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Growing Legacies

IMI KOLKATA

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19th ISDSI-Global Conference 2025

Tech for Net Zero: Digital Solutions for a Sustainable Planet

Editors: Dr. Rohit Kumar Singh
Prof. Mohua Banerjee

CONFERENCE PROCEEDINGS



26 - 29 December 2025

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Tech for Net Zero: Digital Solutions for a Sustainable Planet
ISBN : 978-81-982989-5-9
eISBN : 978-81-982989-3-5
DOI : https://doi.org/10.64558/bllp/578764mssmfe
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BALLPEN MEDIA PRIVATE LIMITED

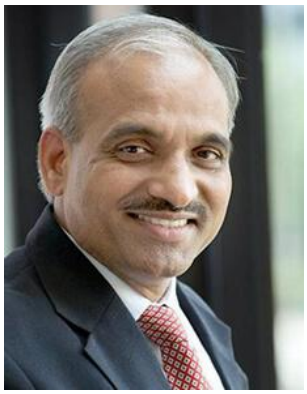


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Typest by
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Message from the President, ISDSI-Global



It gives me immense pleasure to welcome you to the 19th ISDSI-Global Conference. ISDSI-Global was founded with a clear purpose—to create a truly international platform where academia, industry, and the research community come together to generate ideas that shape a sustainable and innovative future. Over the years, the ISDSI community has worked tirelessly to foster research as a culture, especially among young academics, nurturing curiosity, rigor, and the confidence to contribute to global scholarship.

One of our enduring missions is to celebrate Indian scholars on the world stage, showcasing their research excellence and strengthening India's presence in global knowledge networks. We are equally committed to encouraging aspiring scholars from the margins, helping them find their voice, build networks, and emerge at the forefront of academic discourse.

As we convene under the theme "Tech for Net Zero: Digital Solutions for a Sustainable Planet," I am confident that the conversations here will inspire collaborations that transcend disciplines, geographies, and generations. Together, let us continue to build a vibrant, inclusive, and globally engaged ISDSI community FROM INDIA FOR THE WORLD.

Prof. Bhimaraya Metri
President, ISDSI Global

Message from the Chief Patron, ISDSI-Global



It is a pleasure and an honour to welcome all delegates to the 19th ISDSI-Global Conference at IMI Kolkata. This year's theme, "Tech for Net Zero: Digital Solutions for a Sustainable Planet," resonates deeply with our institutional commitment to fostering responsible leadership and innovative thinking for a sustainable future. As the world navigates complex environmental challenges, the integration of technology, data-driven decision-making, and managerial insight becomes indispensable.

At IMI Kolkata, sustainability is embedded in our institutional ethos. Our campus actively promotes green practices – ranging from the use of solar panels for electricity generation to the adoption of paperless operations wherever possible. Even for this Conference, we have ensured that schedules and key materials are accessible through QR codes, reducing our environmental footprint and encouraging digital-first engagement. These initiatives reflect our belief that Business Schools must lead by example in advancing environmentally responsible behaviour.

Hosting ISDSI-Global allows us to strengthen our collaborative ties with a vibrant, multidisciplinary community of academicians, scholars, practitioners, and industry experts. We are delighted to provide a platform where cutting-edge research, impactful dialogue, and forward-looking ideas can flourish. I extend my sincere appreciation to all contributors, organisers, and participants for enriching this academic endeavour. Together, let us advance knowledge that supports a sustainable, inclusive, and technology-enabled world.

Prof. Mohua Banerjee
Director, IMI Kolkata

Message from the Secretary General, ISDSI-Global



It is my privilege to welcome all distinguished scholars, practitioners, and industry leaders to the 19th ISDSI-Global Conference, hosted at IMI Kolkata. This year's theme, "Tech for Net Zero: Digital Solutions for a Sustainable Planet," reflects our collective commitment to advancing research and action toward a climate-resilient future. As the world accelerates its transition to net-zero pathways, the role of data sciences, digital technologies, and innovative managerial practices becomes more crucial than ever.

The conference brings together a vibrant community of thinkers to deliberate on breakthrough ideas across sustainability, technology, operations, analytics, and social impact. Through scholarly presentations, doctoral colloquium sessions, workshops, and global networking opportunities, we aim to foster meaningful collaboration and inspire actionable insights.

I extend my heartfelt appreciation to all contributors and participants for enriching this intellectual platform. Together, let us shape knowledge that propels a sustainable, inclusive, and digitally empowered future.

Prof. Ravi Kumar Jain
Secretary General, ISDSI-Global

Message from the Conference Patron



We welcome you to the ISDSI Global Conference 2025 at IMI Kolkata with a profound sense of purpose that aligns with this erudite collection of original abstracts addressing various facets of sustainability. In this age of interconnected global challenges with the requirement of balancing local priorities, the United Nations Sustainable Development Goals (SDGs) provide a comprehensive lens for examining complex issues and a framework for implementation. The brief snippets of research within this book of abstracts explore the complex dynamics of these goals. With a collection of both global and Indian papers, the objective has been to emphasize local contextual underpinnings and their global implications.
India and many other nations are subject to expectations of rapid economic growth while living up to expectations around sustainability. With the net-zero countdown clock ticking away for nations, many are turning to innovative and digital solutions to address this. The research presented in this book examines themes from the SDGs that have an interface with business or business-related disciplines. The traditional business discussions are also tempered with emissions, circularity, equity and other themes around sustainability. The collection of papers underscores that business research can play a broader role in value creation for people and the planet. We sincerely wish that this wide collection leads to ideations, discussions, and collaborations for co-creating a just and sustainable future.

Prof. Tirthankar Nag
Dean (Research), IMI-Kolkata

Message from the Conference Chair



It is my pleasure to welcome you to the 19th ISDSI Global Conference 2025, hosted by IMI Kolkata, on the theme "Tech for Net Zero: Digital Solutions for a Sustainable Planet." This year's conference arrives at a pivotal moment when nations, organisations, and researchers are collectively seeking data-driven pathways to achieve sustainability targets. With India's commitment to Net Zero by 2070, reducing emission intensity by 45% by 2030, and expanding renewable energy capacity to 500 GW, the role of analytics, optimisation, AI, and digital transformation in managerial decision-making has become indispensable. The 2025 edition marks one of the largest ISDSI gatherings to date, reflecting global confidence in India as a rising hub of research and innovation.

The overwhelming response affirms the growing need for evidence-based approaches to sustainability, and the critical role of decision sciences in accelerating the Viksit Bharat 2047 vision. The papers received, highlight advancements in carbon-efficient supply chains, predictive analytics, optimisation, digital infrastructure, and sustainable business practices. Together, they offer rigorous empirical insights, conceptual clarity, and innovative frameworks that can guide industries and policymakers in the journey toward a net-zero future.

I extend my sincere appreciation to all authors, reviewers, track chairs, keynote speakers, and members of the organising committee for their dedication. I hope the scholarly contributions presented in this volume inspire new collaborations and meaningful advancements for academia, industry, and society.

Welcome to ISDSI Global 2025, and welcome to IMI Kolkata.

Dr. Rohit Kumar Singh
Conference Chair,
ISDSI Global Conference 2025
IMI Kolkata

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DETECTION OF AFRICAN ANIMALS VIA DEEP LEARNING

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DOI: https://doi.org/10.64558/bllp/157851uwivzo

ABSTRACT

In recent decades, deep learning has advanced significantly. Personalized marketing, smart agriculture, facial identification, object detection, healthcare, and many more fields have made substantial use of deep learning in recent years. It has found an extensive usage in the field of detection and classification of animal species, which in turn has proved to be of great help for the preservation and protection of various species. In this work, we propose a YOLOv8 approach for the detection of wildlife species. Experiments have been performed on African Wildlife Dataset. This dataset consists of 1504 images of four animal types —buffalo, elephant, rhino, and zebra— which are primarily found in South Africa's nature reserves. At least 376 photos for every animal type are included in this data collection, which was gathered using Google's picture search feature and labelled for object detection. The proposed model achieved a Mean Average Precision of 0.992 on the dataset across all classes, outperforming previous progressive works and algorithms carried out on this dataset. This work can prove to be very helpful in real-life scenarios for the detection of animals.

INTRODUCTION

The rapid progress of deep learning in recent years has brought transformative changes across numerous domains, including personalized marketing, smart agriculture, facial recognition, and healthcare (Schmidhuber, Juergen 2022). Among these, one particularly impactful application is the automated detection and classification of wildlife species. This has profound implications for conservation efforts, biodiversity monitoring, and ecological research. Efficient and accurate animal detection methods not only aid in preserving endangered species but also contribute to better management of wildlife reserves and the prevention of human-animal conflicts.

Traditional wildlife monitoring techniques, such as manual surveys, camera traps, and aerial reconnaissance (Zwerts, Joeri A., et al 2021), are often labour-intensive, time-consuming, and limited in coverage. The advent of deep learning-based object detection models—particularly the You Only Look Once (YOLO) family (Terven, Juan, et al 2023), has revolutionized this space by offering high-speed and high-accuracy detection in real-time scenarios.

In this study, we propose a YOLOv8-based approach for the detection of African wildlife species. We evaluate the model's performance on the African Wildlife Dataset, which contains 1504 annotated images of four key species: buffalo, elephant, rhinoceros, and zebra. The dataset, curated using Google Image

Search and annotated for object detection, offers a balanced representation of each animal type with at least 376 images per class as described in Section 3.

Our proposed YOLOv8 model achieved a Mean Average Precision (mAP@0.5) of 0.992, significantly outperforming previous YOLO versions and the Faster R-CNN model. Specifically, YOLOv8 demonstrated the highest localization accuracy for the rhino class with mAP@0.5:0.95 = 0.931, and overall superior precision (97.30%) and recall (97.60%). Comparative results across different models are summarized to highlight the progressive improvements—from YOLOv5 (mAP@0.5 = 96.0%) and YOLOv7 (mAP@0.5 = 97.8%) to YOLOv8 (mAP@0.5 = 99.2%).

These results demonstrate the strong potential of advanced object detection models in wildlife conservation applications. Our work not only contributes to the body of research on animal detection using deep learning but also provides a reliable and scalable solution that can be integrated into real-world monitoring systems across wildlife habitats.

The rest of the paper is organized as follows: Section 2 contains an overview of previous work carried out in the field of animal detection; Section 3 describes the dataset. In Section 4, the proposed methodology is presented, and Section 5 provides a comparison between previous work carried out on the African Wildlife dataset and the

proposed method, along with describing results obtained under various test cases performed on the dataset. Finally, the paper concludes with the conclusion and possible future work outlined in Section 6.

RELATED WORK

Automated wildlife monitoring increased into attention over the past decade because conservation tools need to be scalable, efficient, and accurate. Field methods that are customary such as counting manually or trapping via camera and surveys from the air are labour-intensive. Their reach is restricted too. Object detection techniques address these limitations through deep learning's advent especially convolutional neural networks (CNNs).

R-CNN and Fast R-CNN plus Faster R-CNN are region-based CNNs that have been widely employed in object detection tasks. A similar task involves watching wildlife. Norouzzadeh et al. used a ResNet-based Faster R-CNN for species classification within camera trap images while achieving high accuracy across several African mammals (Norouzzadeh et al. 2018). These approaches often infer slowly however so their suitability for field applications declines.

To address this, the YOLO family of models became popular because it finds a balance of speed and accuracy. For bird detection (Schneider et al. 2020) as well as marine animal monitoring (Xu et al. 2021), earlier versions such as YOLOv3 and YOLOv4 have been applied. These models have enabled the real-time detection of species. However, they often struggled in order to classify species with fine granularity in cluttered environments.

YOLOv5 (Jocher, Glenn, et al. 2020) as well as YOLOv7 (Wang, Chien-Yao et al 2023) have pushed the boundaries of real-time detection performance because they introduced architectural innovations like CSPNet and extended ELAN modules. Because of their higher precision and

recall, these models have shown promise in ecological applications. Even with this, detecting of animals still poses some challenges. This is true in the dense vegetation at varying scales in the presence of occlusions.

The African Wildlife Dataset, which includes images of elephants, rhinos, zebras, and buffaloes, has previously been studied using earlier YOLO versions and traditional CNN-based detectors (Ahn and Kweon). While YOLOv5 achieved promising results (mAP@0.5 = 96%), our study shows that YOLOv8 significantly improves performance with a mAP@0.5 of 99.2% and stronger localization, particularly for difficult classes like rhino.

YOLOv8's anchor-free detection mechanism and decoupled head design offer substantial improvements in both accuracy and speed, making it highly suitable for real-time deployment in wildlife monitoring tasks.

DATASET DESCRIPTION

Evaluations were conducted using the African Wildlife Dataset, which is openly accessible on Kaggle (https://www.kaggle.com/datasets/biancaferreira/african-wildlife). The initial purpose of gathering this data set was to train an embedded device to recognize animals in South African nature reserves in real time. The four animal types in this dataset—buffalo, elephant, rhino, and zebra—are primarily found in South Africa's nature reserves. At least 376 photos for every animal type are included in this data collection, which was gathered using Google's picture search feature and labelled for object detection. A txt label file and a jpg image form each sample in the data set. There is at least one specimen of the designated animal class in each image, which has varying aspect ratios. A single image may contain several animal instances. Additionally, instances of the other classes may appear in the same image, such as a buffalo in the file alongside a zebra.

PROPOSED METHODOLOGY

This work presents a deep learning-based object detection pipeline for identifying four key wildlife species using the YOLOv8 architecture. The methodology consists of the following components: dataset preparation, architecture design, training, and evaluation.

DATASET PREPARATION

The study uses the African Wildlife Dataset, comprising 1504 labelled images representing four species: buffalo, elephant, rhino, and zebra. Each class includes at least 376 images, ensuring balanced class representation. The dataset was split into training (80%), validation (10%), and testing (10%) sets. To enhance generalizability, the training data was augmented using random transformations such as:

- Horizontal flipping
- Random brightness and contrast adjustments
- Scaling and rotation
- Mosaic augmentation (for small object detection)

YOLOV8 ARCHITECTURE

YOLOv8 is the latest and most refined iteration in the YOLO series, developed by Ultralytics. It integrates several key improvements over previous models:

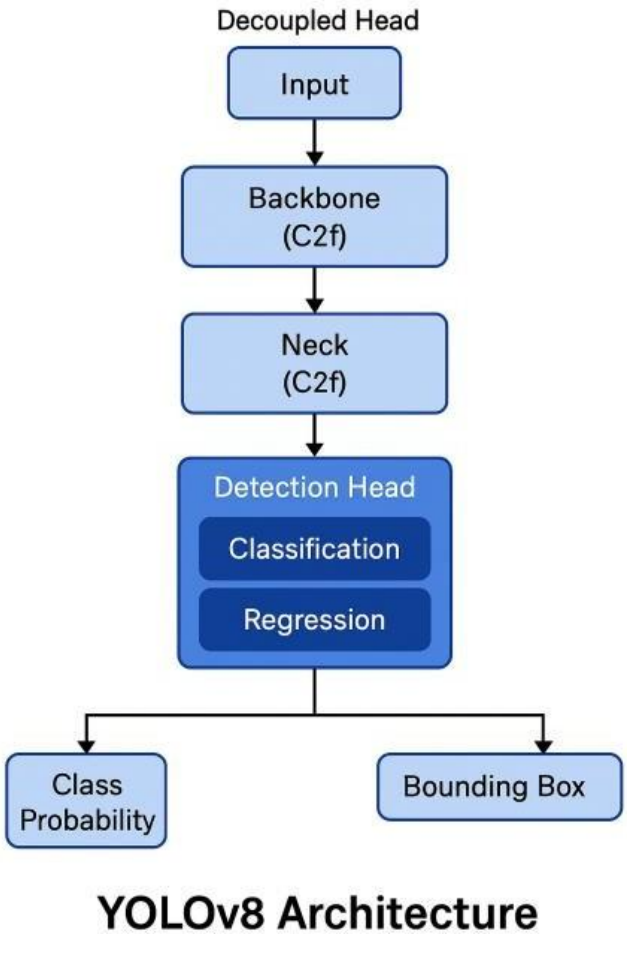
- Anchor-Free Detection: Unlike YOLOv5 and YOLOv7, YOLOv8 eliminates anchor boxes. It predicts object canters directly, reducing computational complexity and enhancing generalization across

object scales.

- Decoupled Head: YOLOv8 employs a decoupled detection head that separately optimizes classification and regression branches. This allows better specialization of tasks, leading to improved accuracy, especially in complex scenes.
- Enhanced Backbone: The model uses a CSPDarknet-based backbone with C2f (Concatenate to Fusion) modules to retain multi-scale semantic information while minimizing computational load. This structure deepens the receptive field while preserving spatial resolution.
- Neural Architecture Search (NAS): YOLOv8 incorporates NAS-optimized components, which contribute to faster inference without compromising detection accuracy.
- AutoShape and Exportable Modules: The model can auto-adjust input resolutions and be exported seamlessly to ONNX, TensorRT, CoreML, and other platforms, supporting deployment in real-time edge computing environments like drones or embedded systems for wildlife monitoring.

In this study, YOLOv8 was initialized with pre-trained weights and fine-tuned on the African Wildlife Dataset using transfer learning. Figure 1 shows the architecture of YOLOv8.

Figure 1 Architecture of YOLOv8



Model Training

The YOLOv8 model was trained for 30 epochs using the following setup:

- Optimizer: SGD with momentum (0.937)
- Learning Rate: 0.01 with cosine annealing
- Batch Size: 16
- Input Image Size: 640×640
- Loss Functions: Binary Cross-Entropy for classification, Distribution Focal Loss for bounding box regression, and Loss for detection confidence

Early stopping and model checkpointing were employed to prevent overfitting and retain the best-performing weights.

Evaluation Metrics

Model performance was assessed using standard object detection metrics:Precision and Recall for class-wise detection quality mAP@0.5: Mean Average Precision at IoU threshold of 0.5 mAP@0.5:0.95: Average precision across multiple IoU thresholds (0.5 to 0.95), capturing localization accuracy These metrics were calculated both per-class and overall to provide a detailed evaluation of the model's robustness.

EXPERIMENTAL RESULTS

To assess the performance of the proposed YOLOv8-based wildlife detection framework, we conducted a series of experiments comparing it against three baseline models: YOLOv5, YOLOv7, and Faster R-CNN. All models were trained and evaluated using the same African Wildlife Dataset under identical preprocessing and training conditions.

Evaluation Metrics

The following metrics were used to evaluate model performance:

- Precision: Measures the proportion of correctly predicted positives.
- Recall: Measures the proportion of actual positives correctly predicted.
- mAP@0.5: Mean Average Precision at IoU threshold 0.5, reflecting overall detection accuracy.
- mAP@0.5:0.95: Averaged mAP across IoU thresholds from 0.5 to 0.95 in steps of 0.05, reflecting localization quality.

Model Comparison

Table 1 Comparison of results obtained by different models

Model	Epochs	Precision (%)	Recall (%)	mAP@0.5 (%)	mAP@0.5:0.95 (%)
YOLOv5	30	93.60	92.20	96.00	75.90
YOLOv7	30	95.90	95.80	97.80	85.60
YOLOv8	30	97.30	97.60	99.20	89.80
Faster R-CNN	12 / 20	70.40	56.60	70.40	52.40

The YOLOv8 model achieved the highest performance across all metrics, significantly outperforming previous versions of YOLO and the traditional Faster R-CNN (Ren, Shaoqing, et al. 2016) model. Notably, YOLOv8 achieved:

- Precision of 97.30%, indicating high reliability in detecting correct wildlife instances.
- Recall of 97.60%, signifying strong sensitivity in finding all target objects.
- mAP@0.5 of 99.20%, demonstrating excellent detection accuracy.
- mAP@0.5:0.95 of 89.80%, reflecting superior bounding box localization.

Per-Class Performance

YOLOv8 also showed strong performance across individual animal classes:

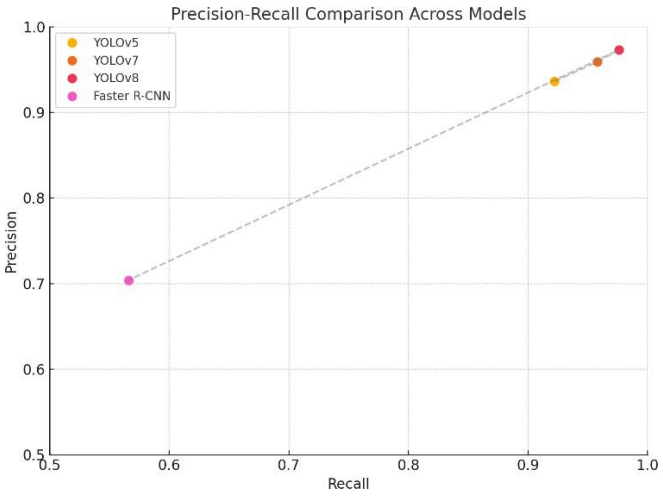
- Rhino: Highest localization accuracy with mAP@0.5:0.95 = 0.931
- Elephant: High object confidence and detection consistency
- Zebra and Buffalo: Detected accurately with minimal false positives

These results illustrate YOLOv8's robustness in detecting diverse wildlife species under variable visual conditions.

Inference Efficiency

In addition to accuracy, YOLOv8 offers real-time inference capabilities with low computational overhead due to its anchor-free and decoupled head design. While Faster R-CNN required approximately 10 minutes per epoch, YOLO models were significantly faster per epoch with lower GPU memory usage.

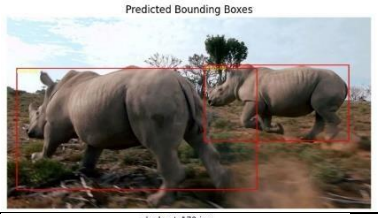
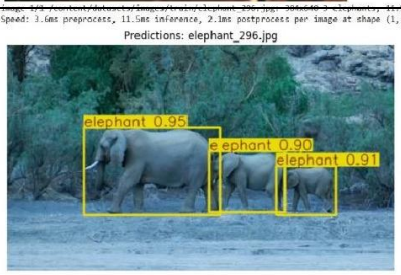
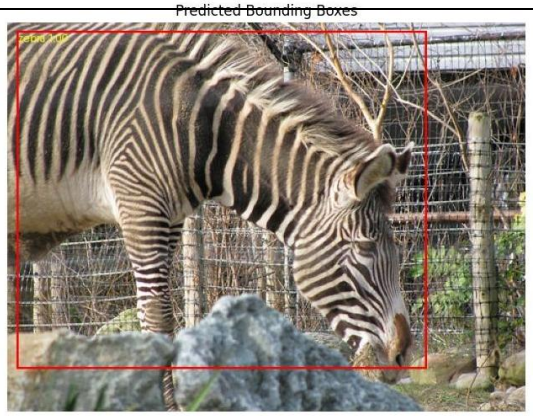
Figure 2 Precision- Recall comparison

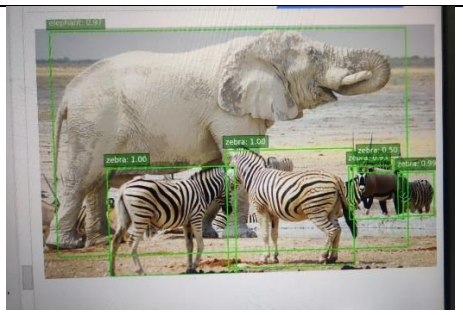
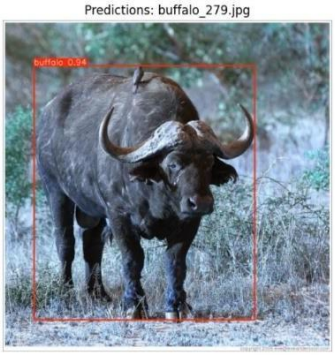


Precision-Recall Analysis

The figure above illustrates the precision-recall distribution for each model. YOLOv8 consistently achieved the highest scores on both axes, confirming its superior balance between precision and recall. YOLOv7 a lso demonstrated high consistency, while Faster R-CNN lagged behind due to higher false positives and missed detections. This visualization reinforces YOLOv8's robustness and reliability for real-time wildlife monitoring applications. Further, results obtained using the approach has been shown in Table 2.

Table 2 Result images obtained from proposed approach.

Result image obtained by the Proposed Approach	Species Detected
	Rhino
	Elephant
	Elephant
	Zebra

	Elephant and Zebra
image 1/1 /content/datasets/images/train/buffalo_279.jpg: 640x640 1 buffalo, 9.4ms Speed: 5.1ms preprocess, 9.4ms inference, 1.8ms postprocess per image at shape (1, 3, 640, 640) Predictions: buffalo_279.jpg 	Buffalo

CONCLUSION AND FUTURE WORK

This study presents a deep learning-based framework for the automatic detection of large terrestrial animals. The proposed method demonstrates promising results, achieving accurate localization and identification of target species across varying terrains and oceanic conditions. By leveraging convolutional neural networks (CNNs) and data augmentation techniques, the system has shown resilience to variations in lighting, scale, background complexity, and animal pose. The experimental results highlight the potential of remote sensing combined with AI in supporting wildlife conservation, population monitoring, and ecological research at scale—especially in remote or inaccessible regions.

This work also addresses a critical gap in automated monitoring by contributing to the limited pool of annotated datasets in this domain.

Future Work

While the current approach achieves competitive performance, several avenues remain for improvement:

- Expansion of Dataset and Label Diversity: The model's performance can be enhanced with a larger, more diverse dataset spanning different seasons, locations, species, and imaging platforms. Incorporating semi-supervised or self-supervised learning techniques could help scale labeling in data-scarce environments.
- Multi-Species Detection Framework: Future efforts will aim to generalize the pipeline to support multi- species detection, including smaller mammals or endangered species such as walruses and seals, which pose unique challenges in satellite imagery.
- Integration with Temporal Monitoring: Incorporating temporal imagery to analyze animal movement patterns, habitat change, or population trends over time can provide dynamic ecological insights and improve model adaptability.
- Model Explainability and Human-in-the-Loop Systems: Enhancing interpretability of the deep learning predictions and incorporating expert feedback in a looped framework can aid in better decision-making and trust-building among conservation practitioners.
- Deployment in Conservation Tools: Ultimately, the model can be integrated into real-time conservation dashboards or mobile applications to assist wildlife authorities, NGOs, and researchers in ongoing monitoring and management efforts.

In summary, this research provides a foundational step toward automated, scalable wildlife detection from space and sets the stage for more intelligent and impactful ecological monitoring systems.

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REVOLUTION IN ENERGY UTILITY IN THE PHASE OF INDUSTRY 5.0

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ABSTRACT:

In terms of industry 5.0, a change of human focus, stability and flexibility through the widespread assimilation of advanced technologies (ie Artificial Intelligence (AI), Internet of Things (IoT), Robotics and Human-Machin Cooperation) examines a change to the transforming energy utility industry. The primary production of this study is to present traditional, decentralized, intelligent and adaptive systems and procedures to present the trajectory of the development of energy utilities for adaptive systems and processes that follow the industry 5.0 principles.

This study shows that the major changes are detected by increasing advance maintenance and green energy innovation by using smart grid adoption, prosecutor partnership, AI. Inspiration for this study arises from an insistence around the world that transitions in permanent energy systems that are efficient and flexible for social-environmental disruptions. The industry brought digital automation of processes for 4.0 energy systems, while the industry emphasizes
5.0 human intelligence and values in the development of technology.

This development energy presents opportunities and challenges to the utility field, which contributes to the need to check the roles. The contribution of this study is a consolidated analysis of the role of industry 5.0 in energy utility strategies that drives efficiency, stability and consumer satisfaction, while governments also benefit from utilities and technology organizations that want to renew the industry 5.0 to facilitate cleaner energy futures and energy utility systems.

Keywords: Industry 5.0, Energy Utility Transformation, Human-Centric Innovation, Smart Grid Technology, Sustainable Energy Systems, AI in Energy Management, Decentralized Energy Networks

INTRODUCTION:

Energy landscape technology is developing considerably by the convergence of development, urgency of climate change and convergence of social and economic factors. The development of central traditional, centralized utility structures to smart, decentralized and durable energy systems for more

intensive changes in energy markets. Industry 4.0 determined a thick phase with automation, digitization, technology and connectivity. The emerging industry is restructuring a route by restoring the 5.0 framework human references and intentions of technical context and action, restructuring a route, and holding back as flexibility, stability and humans in the central condition of the Industrial Pratim (European Commission (2021)).

Industry 5.0 is not only an increase in technology advancement, the progress towards industry 5.0 indicates an intensive transition that will add its development according to society and environmental interests. Industry 5.0 aims to achieve human and machine supplement in advanced technical procedures using the latest techniques such as Artificial Intelligence (AI), Internet of Things (IOT), Blockchain, and Robotics, achieving human and machine supplement in advanced technical procedures, which carry forward human decision making, enhance adaptability and flexibility of essential systems, and increase permanent growth at the same time. In this regard, energy utility references, which generally provide rigid structures and high fossil fuel dependence, are also seen as a major area for innovation; Integration in many regions, and the industry requires a re - combination within 5.0 vision.

As reported by the International Energy Agency (IEA, 2023), the demand for energy worldwide is estimated to increase by 2040 by 2040, such as urbanization, digital consumption and electrification of transport systems as a result of factors. At the same time, the United Nations is wiring the ability to decarbon energy systems, keeping in mind the Sustainable Development Goals (SDG) and the Paris Climate Agreement, stroking the investment in renewable technologies and intelligent infrastructure simultaneously. It has ended in a situation that can be called "game-changing", from now on the energy system should be completely reconsidered in terms of methods that generates, manages, distributes and consumes.

The era of industry is related to energy utility fields, technical intelligence, human-focused design and sustainable development in the era of 5.0, including three interconnected columns. Historical tendency for energy utilities is in existence to lag behind in case of transformational energy change, as there should be a change in the direction of becoming digital, data-powered and customer-excellent service. Whether it is a smart grid technology, intelligent integration of demand-side management innovations, AI-SAPHAD for Energy Consumption, and Blockchain-Saksa colleague-to energy trading, future science fiction of energy utility, but in the form of real deployment and implementation, Germany, Japan and Netherlands (Iea, 2022; 2022.)

With technical capabilities, the industry encourages adaptation of energy experiences by assisting 5.0 consumers as they infection in "professionals" (ie producers and consumers of energy). With democratization of energy enabled by rooftop solar, battery storage and smart meters, which allow domestic energy monitoring and control in real - time. Domestic energy solutions are rarely as simple as keeping an eye on your energy consumption; However in Denmark with "Smartnet" initiative, they

are integrating domestic energy systems with grid networks. Danish citizens can also feed surplus renewable energy in the grid, improve access to renewable energy sources and a suit of AI algorithm abilities to properly load energy and reduce energy waste (European Smart Grid Task Force, 2022).

Importantly, the industry's human-focused approach addresses a long-standing issues of 5.0 energy inequality and reaches more globally. Many emerging economies across Asia, Africa and Latin America are now equipped with opportunities to adopt decentralized microgrids and off-grid renewable energy solutions, jointly with smart monitoring systems to jump these more stringent, heritage infrastructure and jump to local communities and include them within an energy infections.

Nevertheless, many challenges still exist. The privacy of the data, cyber security, bottlenecks with regulators, and lack of currency with skills, in all energy utilities, industry 5.0 principles have considerable obstacles to the mainstream. Additionally, this infection needs to change the way the concept of its purpose of capital investment, coordination with stakeholders, and providing extended energy to organizations; All of which are naturally complicated, especially in the resource-script environment.

This study determines to fully assess how the energy utility field industry can be suited to the principles and technologies of 5.0. By discovering global trends, technological innovations and examples of real world, research aims to identify major factors that contribute to success, face challenges, and policy recommendations that can assist governments, private utilities and researchers who prefer human needs and environmental stability.

Through the use of secondary data received from international energy reports, policy documents and industry white papers, this study checks how the fields are creating fields in the energy sector. The book detects adopting trends, examines the spread of technology, and evaluates regulatory settings that either convenience or obstruct this change. 'Meditation is not only on the technical aspects of technology, but also' how 'is on' how 'the governance models, processes and human-centric designs for the creation of strong energy utility systems in the industry 5.0.

This letter briefly discusses the development of energy utilities as an important aspect of industry 5.0, which emphasizes stability, technological advancement and its important impact on the empowerment of people. By fusing theoretical concepts with practical implementation, it collectively offers an important opportunity to create our energy future, following the principles of the fifth industrial revolution.

LITERATURE REVIEW:

The ongoing change of global energy utility sector is deeply in the development of industrial paradigms. While Industry 4.0 introduced automation, data exchange and interconnected systems, the industry has been redefined and the 5.0-human-focus conceptual foundation has been implemented, stability and flexibility- This is again defined that energy systems

are imagined and applied (European Commission, 2021). This literature reviews have severely synthesized academic, policy and industry-based contributions, who have examined the energy utilities and intersections of technological development with a focused lens on industry's ability and performance.

Theoretical Foundations: Industry 5.0 and Energy Utility

The concept of industry 5.0 departs by re -organizing human values in technological progress from its predecessor. As Dameer et al. (2021) Note, Industry wants to coordinate personal and permanent results between 5.0 cognitive computing and human intelligence. In terms of energy, it is not only to digitize energy operations, but also to do so that prefers social needs, moral ideas and ecological balance (Naavandi, 2019; Joo et al., 2021).

Under industry 5.0, theoretical grounding of energy system innovation is designed by the principles of cyber-physical systems (CPS), human-measin cooperation and inclusive infrastructure design (Leo et al., 2017). The transition refers to a systemic change from centralized energy supply chains towards decentralized, partnership and future energy ecosystems (Siyamela et al., 2022).

Smart Grid and Digital Energy Infrastructure

Smart grid industries have emerged as a core technological foundation for 5.0-based energy utilities. These grids integrate digital communication, IOT and machine learning to enable Real -Time Monitoring, Dynamic Load Balance and Bidire Energy Flow (Home and Gafurian, 2011).

Study by Zhang et al. Alhakoon and U (2016) emphasize that future analytics in smart grids enable active maintenance, their implementation is often limited by data silos and the infrastructure of heritage. Integration of blockchain technologies - Endi at al was mistrust in works. (2019) and Gai et al. (2021) -Geus was proposed as a solution for safe, transparent and decentralized energy transactions.

Artificial Intelligence in Energy Management

AI is definitely the most transformative promoter of industry 5.0 in the energy sector. It enables real -time forecast, discrepancy detection, consumer behavior modeling and automatic grid operations (mines and zhang, 2021). Machine Learning algorithms are used to predict energy consumption patterns, optimize renewable energy use and detect defects before growing (Wang et al., 2020).

Banse et al. (2011) This shows how AI applications have reduced energy intensity in construction by 20%. In addition, the study of recent case by Lee et al. (2023) A-in-managed demand in urban areas of Chinese values the operational cost earned through such deployment on the response system and validate environmental benefits. Nevertheless, moral concerns about data privacy and algorithm bias are under-edressed (Passcuvatti, 2020).

Decentralization, Prosumerism, and Citizen Participation

The democratization of energy production is another important aspect of this revolution. Citizens are rapidly becoming "prosecutors" who not only consume, but also produce and share energy through microgrid and community solar initiatives (Parag and Sovakool, 2016). Research by Volsink (2020) has highlighted how such participants have increased the social acceptance of renewable energy projects.

Decentralized energy system, as reviewed by Pudineh et al. (2020), are particularly impressive in developing economies where centralized grid expansion is economically unattainable. Smart metering and distributed laser technologies reviewed by Han et al. (2019), enabling transparent and equitable energy exchange among homes and small-scale producers.

Sustainability and Environmental Integration

Hirschhausen et al. (2018) Stress that regulatory and institutional reforms should create permanent energy infections. In addition, progress in energy storage technologies, as is investigated by Dun et al. (2011) and Taro et al. (2016), are important in the race in management. Recent successes in the lithium-sulfur and solid-state battery system have the ability to address the bottleneck of storage in the decentralized grids (Goodeno and Park, 2013).

Human-Centric and Ethical Considerations

Industry 5.0 is the most fundamentally separate, its obvious human centenary orientation. This includes access to access to areas of marginalized areas, power and energy equity (Sachs et al., 2022). Study by Sovakool et al. (2019) A lawyer for energy infection only, where the deployment of technology is aligning with social inclusion and local capacity building.

Literature also indicates moral risks. Utility operations can cause job displacement from high- automatic jobs without adequate human monitoring or can cause dependence on the proprietary AI system (Brianjolphson and McAfi, 2014). For example, researchers such as Zuboff (2019) are cautious against "monitoring of capitalism", where utility becomes a tool for manipulation in behavior rather than data empowerment.

Policy and Regulatory Frameworks

In energy utilities, further policy framework is required for successful implementation of industry 5.0. According to Ropeke (2022), multidimensional energy flows, dynamic pricing models and governance structures should be developed to accommodate cross-sector integration. The European Union Green Deal (European Commission, 2021) and India's Smart Cities Mission (NITI Aayog, 2022) offer a template for case study regulatory modernization and multi-two-two-to-two-two to-two-two to-twos.

In addition, regulatory sandbox and public-private innovation laboratories have proved to be effective in testing and scaling of emerging energy technologies (ofgem, 2020; Unido, 2021).

RESEARCH METHODOLOGY:

Research is purely done on secondary data as has been received from the

government. India's website on MNRE (Ministry of Renewable Energy) []. Renewable resources such as hydro, solar and air have been studied for comparative analysis with energy production and non-renewable. Capacity production (GW) has been analyzed from FY 2014-2025 and an estimated generation is calculated using MPA (moving point average method).

In the latter part, the correlation and regression analysis has been done for the following objective:

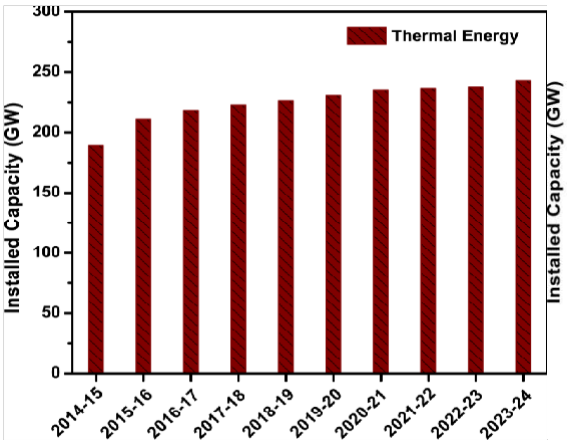
Table 1 Justification on data analysis

S. No.	Method	Variables	Reason
1	Correlation	Energy types	Dependence strength of one energy on another
2	Regression	Share and total	Relation on share and total energy generation capacity
3	Moving Average	Energy type	Estimate the projected generation capacity (GW)

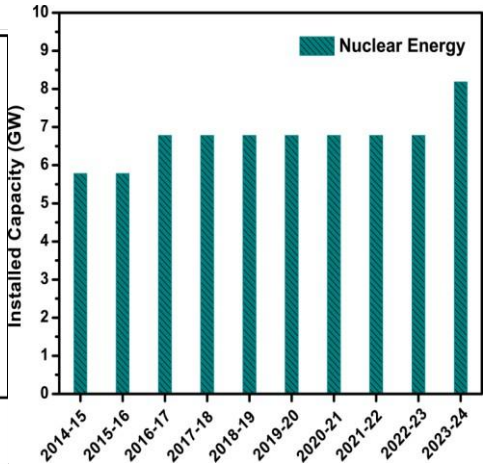
Data Analysis and interpretation

Table 2 Generated Energy Capacity (GW) and projected generated energy capacity (GW)

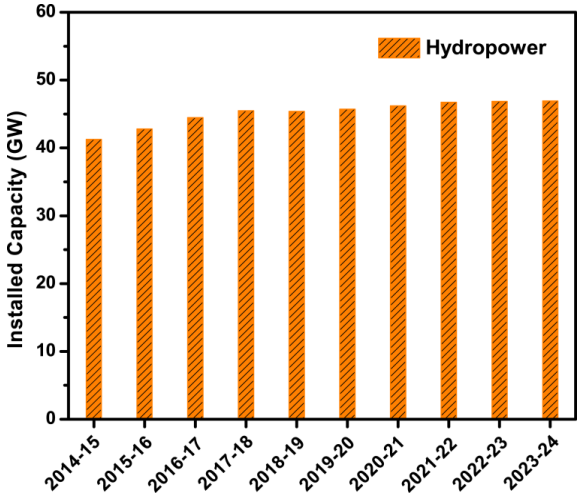
INSTALLED RENEWABLE ENERGY (GW) IN INDIA (2014-2024)								
Year	**Thermal**	**Nuclear**	**Hydro**	**RES**	**Total RE**	**Grand total**	**Growth (%)**	**Share of RE (%)**
2014-2015	188.9	5.78	41.27	39.95	81.22	275.9	10.62	29.44
2015-2016	210.68	5.78	42.78	47.09	89.87	306.33	11.03	29.34
2016-2017	218.33	6.78	44.48	58.56	103.04	328.15	7.12	31.40
2017-2018	222.91	6.78	45.49	70.65	116.14	345.83	5.39	33.58
2018-2019	226.28	6.78	45.4	79.41	124.81	357.87	3.48	34.88
2019-2020	230.6	6.78	45.7	88.26	133.96	371.34	3.76	36.07
2020-2021	234.73	6.78	46.21	95.8	142.01	383.52	3.28	37.03
2021-2022	236.11	6.78	46.72	109.89	156.61	399.5	4.17	39.20
2022-2023	237.27	6.78	46.85	125.16	172.01	416.06	4.15	41.34
2023-2024	243.22	8.18	46.93	143.64	190.57	441.97	6.23	43.12
Growth Rate	28.7559555	41.52249	13.71456	259.5494				
CAGR	2.55969783	3.533894	1.293507	13.65168				
2024-2025	**205.97**	**6.113333**	**42.84333**	**48.53333**				
2026-2027	**217.306667**	**6.446667**	**44.25**	**58.76667**				
2027-2028	**222.506667**	**6.78**	**45.12333**	**69.54**				
2028-2029	**226.596667**	**6.78**	**45.53**	**79.44**				
2029-2030	**230.536667**	**6.78**	**45.77**	**87.82333**				



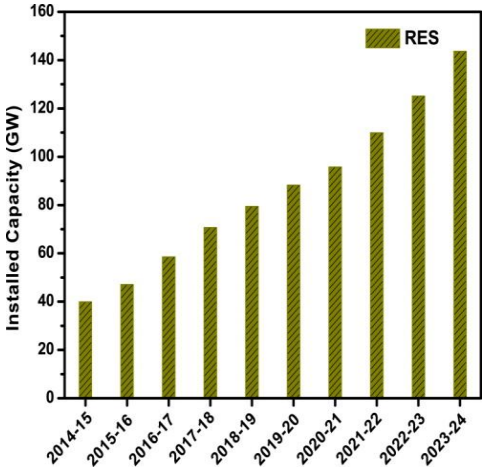
Graph 1: Thermal Capacity (GW)



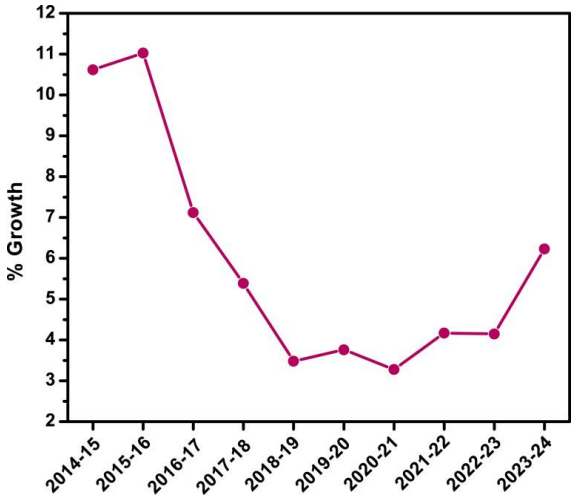
Graph 2: RES Capacity (GW)



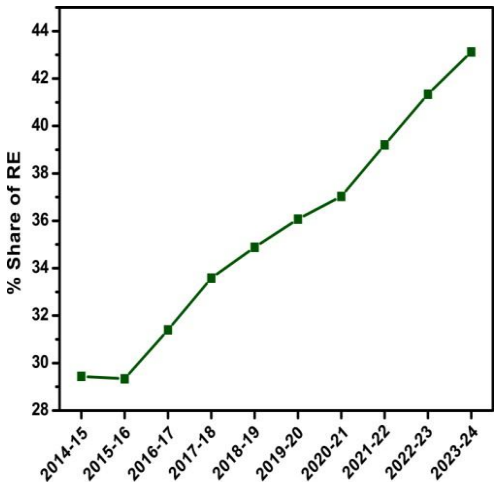
Graph 3: Nuclear Energy Capacity (GW)



Graph 4: Hydro-power Capacity (GW)



Graph 5: Percentage (%) of growth



Graph 6: Percentage (%) of share for RE

Table 3 Regression Statistics on Renewable energy and thermal capacity generation (GW)

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	1.27808*10-^{14}
Observations	10

Table 4 ANOVA statistics on Renewable energy and thermal capacity generation (GW)

Parameter	**df**	**SS**	**MS**	**F**	**Significance F**
Regression	4	11226.87564	2806.719	1.71823E+31	4.99621E-78
Residual	5	8.16748E-28	1.63E-28		
Total	9	11226.87564			

Table 5. Regression Co-efficient on different types of energy generation capacity (GW)

Parameter	**Coefficients**	**Standard Error**	**t Stat**	**P-value**
Intercept	-7.10543E-14	2.64431E-13	-0.26871	0.798890546
Thermal	2.67586E-15	1.41942E-15	1.885182	0.11808832
Nuclear	4.17489E-15	1.18325E-14	0.352833	0.738600839
Hydro	1	1.16617E-14	8.58E+13	4.09359E-69
RES	1	3.14755E-16	3.18E+15	5.86368E-77

Data Interpretation:

Now, the above exhibits show the distribution pattern of few sources of energy capacity generation (GW) in India from 2014-2024. The below table has been presented as summarized format for better understanding of the above data as analysed:

Table 6: Statistical tool with justification

Method	Statistical Tool	Software	Justification
Graphical Potting	Scatter Plot	MS Excel	Pictorial year-wise comparison
Projection	Moving Point Average (MPE)	MS Excel	Prediction helps in preparation of budget for resources
Inter-dependence	Regression	MS Excel	Dependence strength of one type of energy on another

Integration of industry 5.0 and energy transition era

The convergence of industry 5.0 with global energy infection indicates a transformational leap of how modern society attaches the generation, distribution and consumption of energy. This integration only reflects a decisive development from automatic and digitizing energy processes, as seen in industry 4.0, towards the systems that are human censible, intelligent, adaptive and durable. As nations around the world struggle with the twin mandatory of dikrbonization and energy equity, the principle of the industry 5.0- A compelling framework to resume the 5.0-human-mind cooperation, moral innovation, and systemic flexibility centered on systemic flexibility. Instead of looking at energy as a commoditized product flowing unilaterally from the consumer from the consumer, the industry recognizes 5.0 paradigm systems as dynamic socio-technical ecosystems where humans activate machines, algorithms and infrastructure as well as decision-making roles.

Industry 5.0 technologies such as Artificial Intelligence, Blockchain, Internet of Things (IOT), and cyber-physical systems are being designed not only for performance efficiency, but also for flexibility, equity and cognitive adaptability in energy utilities. These technologies support intelligent forecasts, real-time grid adaptation, and colleagues from colleagues, allowing communities to manage energy in decentralized, demand-ex-and environmentally sensitive ways. Countries such as Germany, Denmark and Japan have pioneered such changes through their national smart grid programs, but emerging economies like India are benefiting to jump these techniques to leap the old centralized infrastructure. For example, in Indian pilot projects, blockchain-based peer energy trading platforms are being paired with roof solar and smart metering systems to empower local prosecutors-which not only consumes, but generate and share energy. These innovations originally align with India's broad energy transition goals under the National Hydrogen Mission, Smart Cities Mission and Self -reliant India structure.

From the perspective of a professional analytics and digital design, the integration of the industry 5.0 allows to reduce waste to adapt to user interfaces in energy management systems, improve decision making and prevent digital overconsation. Excessive and irregular use of digital devices - frequent power consumption, server load, and increase in network stress have increased the concerns around the Internet addiction

and its related energy demands.

The role of human-focused design in energy utilities reinforced by decentralization of power generation and emergence of localized microgrids. Directed by the AI-Saksham future model, these systems allow remote or undested communities to participate in energy infections through off-grind and hybrid renewable solutions. Smart sensors, low-distraction communication, and autonomous demand-equilibrium mechanisms, ensure continuity of microgrid supply, reduce transmission loss and promote energy democracy. It is particularly relevant in regions such as rural India, sub-city Africa and Southeast Asia, where access to the centralized grid is either

cost-decent or structurally contagious. Industry 5.0 thus creates the route for inclusive innovation by aligning local aspirations, environmental obstacles and technological progress with economic diversification.

In association with decentralized production, the rise of green hydrogen, biogenic energy storage and A-Enhancened Electrolysis shows how the industry promotes 5.0 conversion between biological and digital energy innovations. For example, AI-powered hydrogen plants are being designed to customize resource inputs, reduce environmental effects and forecast energy availability based on weather patterns and real-time grid needs. This reflects a departure for one in a biosphere consciousness from technical-focused industrial argument, where energy systems are designed not only for output maximization but also for the leadership of planets. In addition, these progresses are being deployed with moral ideas at the forefront and transparency, privacy and social inclusion through the-Niyas Sandbox, Multi-Stechold Cum- Design, and Open-Detta Protocol. Such moral-by-design structures are important for protection against algorithm bias, monitoring capitalism and digital exclusion risks that may arise from irregular AI purinogen in significant energy infrastructure.

The policy synchronization plays an equally important role in realizing the full potential of industry 5.0 within policy infection infection. The current regulatory regime, designed for centralized and monopoly energy distribution, must be re -configured to accommodate multidimensional flows, participation markets and cognitive technologies. It asks for institutional innovation, including the agile regulatory environment, transdiplinary taskforce, and integrated governance platforms that align utility operators, technology developers, consumers and environmental manageries. The European Commission's industry 5.0 visions, the United Nations SDG 7 energy access targets, and international structure such as India's climate missions show that the speed for such infections is already running. However, the real success lies in harmonizing global standards with local experiment, allowing countries to scale energy solutions that are not only technically sound, but also socially responsible and environmentally restructural.

CONCLUSION:

Renewable energy, energy storage,

electric vehicles and technology advancement are all anticipated to play a role in the future of India. It will require adventurous policies, technological progress and maximum international cooperation to combat climate change, guaranteeing energy availability for all citizens. Long-term policy stability should be overcome for major challenges such as development of infrastructure, financing dynamics for start-up culture, rapid progress. The major objectives of India's stability and economic progress are closely associated with its energy infection.

FUTURE DIRECTION:

The future direction of India in the energy sector takes shape from the rapidly increasing energy demand of the country in various regions. India is moving towards green and permanent energy resources to achieve pure zero carbon emissions. The significant increase in the installation of RE capacity is clear since the last five years and is expected to achieve 500 GW capabilities by

the end of 2030. The central part of India has a greater risk of sunlight that supplies heavy capacity for solar energy expansion, large coastal regions and river -centric regions play an important role in hydropower generations and are derived from biomass jernner. India is also expanding its wind energy capacity, especially along the beach, which has significant ability to the offshore and coastal wind farms. Smart grid and advanced metering infrastructure will run efficient energy distribution and storage capacity across the country. Government. Initiatives such as rapid adoption and manufacturing of hybrid and electric vehicles (fame) schemes are emphasizing for a change towards EVS. India is developing pollution-free nuclear reactors for diversification of energy, an important part of the energy mixture in the future. As a part of the renewable energy source, India is also focusing on futuristic green hydrogen production that can meet high energy requirements in heavy industries, as well as for long distance transportation and storage. This initiative is promoted by a government scheme like National Hydrogen Mission, which aims to make India as a global center for green hydrogen production. Smart programs such as performance, receipt, and trade (PAT) plan and Energy Conservation Building Code (ECBC) are helping to reduce the intensity of energy in industries and buildings. To speed up sustain

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LOCAL INDIGENOUS FOOD ESTABLISHMENTS AND ENTREPRENEURSHIP IN MEGHALAYA, INDIA: CHALLENGES AND PROSPECTIVE OPPORTUNITIES IN THE EMERGING TOURISM LANDSCAPES

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DOI: https://doi.org/10.64558/bllp/287446lhskts

INTRODUCTION:

From the very beginning, the quest for knowledge has been at the heart of tourism, dating back to the times of ancient explorers. This fundamental idea has endured through the ages, as modern travelers in the 21st century continue to seek out distant and hidden places primarily to deepen their understanding of the social, cultural, traditional, and culinary aspects of the regions they visit. Although bustling megacities and popular tourist destinations hold significant appeal, there is a growing interest in the charm of rural and remote scenic areas. The tourism boom of recent decades has allowed these far-off locations to present their distinctive sociocultural identities to a global audience.

The distinctiveness of the traditional food systems among the indigenous tribal communities underscores a wealth of cultural knowledge regarding their lifestyles, belief systems, spirituality, and overall wellbeing (Kuhnlein, Erasmus & Spigelski, 2009; Wangoola, 2000). The North- Eastern region of India has largely been overlooked and remains underutilized due to its complex social and cultural practices, which pose challenges for easy integration with mainland India. This region consists of eight states, often referred to as the area of seven sisters and one brother, and it shares four international borders with China, Myanmar, Bangladesh, and Bhutan, with 98 percent of its boundaries being international. The geographical and ecological diversity, along with its variety of communities and distinctive landscape, render this region exceptional when compared to the mainland. The total geographical area of the northeastern states is approximately 263,179 square kilometers, accounting for about 8 percent of the country's total geographical area. Among the 427 tribal groups in India, around 130 are residents of the northeastern region.

The north-eastern region of India is characterized by a rich tapestry of ethnic communities, each with its own distinctive culinary traditions that encompass growth patterns, cooking techniques, consumption habits, and preservation methods. Indigenous food specialties are vital to tourism, as they often serve as a significant attraction for visitors to a destination (Getz, Robinson, Andersson & Vujicic, 2014; McKercher, Okumus & Okumus, 2008). Meghalaya is frequently referred to as nature’s gift to humanity, situated amidst a network of towering mountain ranges, lush green forests, expansive water bodies, and magnificent waterfalls, all contributing to a

verdant valley that provides an ideal environment for diverse flora and fauna. Known as the 'Abode of Clouds', Meghalaya stands out as one of the most advanced states in the north-eastern part of India, encompassing approximately 22,000 square kilometers and housing a population of around 2.5 million (Census 2011). The state is home to three primary tribal communities: the Khasis, the Jaintias, and the Garos. The Khasis inhabit the central region, the Jaintias are located in the east, and the Garos reside in the west. While these three major tribal groups have prominently displayed their cultural heritage, festivals, and traditions to both national and international audiences, their indigenous culinary practices have not received the same level of attention as their social and cultural customs. The primary staple for these tribal communities is rice; however, they also favor pork, chicken, beef, and various types of fish, including dried fish. Meat dishes are typically prepared using locally sourced spices and vegetables, and are served alongside rice (Blah and Joshi, 2013).

REVIEW OF LITERATURE:

Food serves as a crucial component within the tourism sector, and recently, it has become evident that the culinary aspect is a significant factor in the promotion of a destination. Fields (2002) elucidates that food is integral to the overall satisfaction derived from the tourist experience. Telfer and Wall (1996) explored the complex relationship between food and tourism, noting that food can be perceived merely as a necessity or, at times, as a major attraction of a destination. In the past decade, the role of food in tourism has been elevated from a mere input to a vital element of the tourism product. Indigenous food tourism presents substantial opportunities for destination marketing and enhancing tourist experiences. According to Jones and Jenkins (2002), the food component is an essential link in the promotion of tourist destinations. Food is consistently viewed as a significant tool for enriching tourist experiences. The local indigenous culinary specialties of a region reflect its cultural traditions, dietary practices, and biodiversity, thereby contributing to the identity of the place and fostering tourism development (Singh et al., 2007). There exists a diverse array of traditional foods among indigenous communities (Nongrum & Dohtdong, 2018); however, scientific documentation of the ethnic foods from northeastern communities is limited, with only a few local delicacies, such as Tungrymbai from Meghalaya, being noted (Sohliya, I. et al., 2009). Research indicates that many locals do not recognize local delicacies as potential tourist attractions, leading to their general undervaluation and infrequent inclusion in promotional and marketing materials for tourist circuits, especially when compared to natural and man-made tourism resources (Du Rand, Heath, and Alberts, 2003, pp. 99–101). Tribal regions are typically regarded as challenging climatic ecosystem zones. There appears to be a connection between consumption patterns and the cooking methods employed using iron-based utensils to mitigate anaemia within these communities (Albert, 2017). The ethnic groups residing in these difficult environments must utilize

diverse traditional cooking methods and storage techniques to maintain their food and preserve its aroma and flavor. (Anup Kumar Das, Nako Laling, and Wishfully Mylliemngap, 2017).

RESEARCH OBJECTIVES:

The aims of this research are as follows:

- To emphasize the traditional indigenous cuisines of the primary tribes in Meghalaya, specifically the Khasis, the Jaintias, and the Garos.
- To investigate and assess the factors contributing to the limited number of visitors to these local indigenous food courts.
- To motivate entrepreneurs to establish these local indigenous food courts in areas frequented by tourists and to adopt a more tourist-oriented strategy.

RESEARCH METHODOLOGY:

The research is empirical, incorporating both primary and secondary data through a qualitative lens. Primary data was gatheredvia discussions with the proprietors and personnel of local indigenous food courtThe investigation focused on local indigenous food courts across four districts in Meghalaya: East Khasi Hills (including Shillong, Mylliem, and Sohra), Ri Bhoi (Nongpoh), West Jaintia Hills (Jowai), and West Garo Hills (Tura). A total of 26 local indigenous food courts were examined. Through comprehensive structured interviews, the author was able to gain insights into the operational dynamics of indigenous food courts and the factors contributing to their lack of tourist appeal. Additionally, some tourists were interviewed in popular tourist destinations such as Umiam (Ri Bhoi district), Shillong Peak, Mylliem, Sohra (East Khasi Hills District), and Tura (West Garo Hills district). The secondary research involved a thorough review of journals, research papers, newspaper articles, and relevant literature.

RESULTS AND DISCUSSIONS:

Khasi delicacies: The culinary traditions of each nation, region, culture, or tribe are shaped by centuries of historical development. Factors such as climate, geographical location, and topography significantly affect the dietary practices of the local ethnic groups. The Khasi tribe boasts a rich variety of indigenous food specialties. The Khasis utilize local raw ingredients and traditional cooking techniques to preserve the authenticity of their indigenous cuisine. Historically, food was primarily prepared over firewood, imparting a unique flavor; however, such traditional methods are now predominantly observed during large social and community events. In the northeastern region, boiled dishes featuring bamboo shoots are quite common; nevertheless, in Khasi cuisine, boiled items do not constitute the primary indigenous delicacies, and bamboo shoots are typically utilized in pickled form. In addition to the main course, which usually includes a non-vegetarian dish served with rice and boiled sides, the community has a custom of enjoying rice-based snacks alongside their evening tea (Shylla, R.G. & Ramdas, S. 2014). The food can be categorized into traditional Khasi snacks (Jing bam) and

main courses. Khasi cuisine tends to emphasize meat over vegetables. Rice red sticky rice being the preferred known as Ja, and it forms the foundation of most traditional Khasi snack items, locally referred to as 'Ki Kpu,' meaning rice cakes, which come in various forms and are made using indigenous knowledge (Umdor, M. et al, 2016). However, meat, particularly chicken, pork, and beef, constitutes the essence of the meat delicacies; meat is referred to as Doh, while vegetables are called Jur. The preparation of food involves the use of basic spices such as pepper, ginger, garlic, turmeric, bay leaves, sesame seeds, and chilies.

Jaintia delicacies: The Jaintia Hills, located in the eastern region of Meghalaya, are primarily populated by the Jaintia tribes, who are locally referred to as Pnars. The culinary traditions of the Jaintia and Khasi tribes exhibit significant similarities; both groups share comparable dietary preferences, cooking techniques, and food selections. Traditional cooking methods employed include steaming, boiling, and sautéing, with a moderate level of spiciness.

Garo delicacies: The Garos represent the second largest tribal community in Meghalaya, following the Khasis. Primarily, the Garos inhabit the southern region of the state, which borders Assam; as a result, Assamese cuisine, particularly that of the Bodo tribe, has a significant influence on their culinary practices. The Garos exhibit a broad-minded approach to their dietary preferences, with meat and fish being central to Garo gastronomy. Nevertheless, they also consume a substantial amount of vegetables and roots, with bamboo shoots being particularly prominent in their traditional dishes. Most indigenous Garo foods are enhanced by the incorporation of potash or cooking soda. Traditionally, potash or ash water is derived from the combustion of dried plantain stems or tender bamboos, locally referred to as Kalchi or Katchi. After burning, the ashes are collected, immersed in water, and then strained.

DATA ANALYSIS AND ITS FINDINGS:

The information gathered through comprehensive structured interviews with the proprietors and personnel of local indigenous food courts has unveiled numerous insights regarding the reasons these establishments have struggled to showcase their regional tribal delicacies on regional, national, and global platforms, as well as to attract tourists in general. To begin with, the local delicacies of the Khasi, Jaintia, and Garo tribes have not been systematically documented or promoted at tourist centers. Notably, many of the A-category hotels in Shillong city lack dedicated restaurants specializing in tribal indigenous cuisine, despite the popularity of certain tribal dishes. Some front-line reception staff have reported frequent inquiries from in-house guests regarding local indigenous food options. Indeed, several guest comment cards have highlighted the absence of local tribal food delicacies or indicated that only a limited variety is available. Most authentic tribal indigenous food courts are situated in marketplaces, which primarily cater to local residents, resulting in a minimal percentage of tourist foot traffic, as these markets

primarily sell groceries, vegetables, meat, spices, and general goods. Another challenge faced by these indigenous food courts in general markets is the issue of space constraints, as noted by some stall owners; the rental costs in these marketplaces are prohibitively high, forcing them to opt for smaller spaces to keep operational costs manageable. Due to these spatial limitations, these food courts resemble small shops or stalls, where seating arrangements typically consist of benches or stools, accommodating patrons in close proximity to one another. Such seating arrangements may render tourists or visitors uncomfortable, thereby discouraging them from entering these food courts located within general markets. The menus available in these local food courts do not feature ala carte or table d'hôte options; instead, all food items are pre-cooked and arranged in display racks. Patrons must indicate their desired selections from the displayed offerings, which typically include a rice dish as the base, accompanied by a choice of vegetable, meat, or fish preparations, along with a wide variety of local indigenous chutneys. The food is served on steel oval plates using a ladle, and pricing is determined by each item served. The meals in these local food courts may be prepared on-site or at a different location. Generally, food items are sold out by the afternoon, after which cleaning and mise en place occur. These marketplaces typically close between 7 PM and 8 PM, although local indigenous food courts may close earlier or even shut down when food supplies are depleted. The primary visitors to these local indigenous food courts are the tribal residents of the state. The quality of food served in these establishments is high, adhering to authentic recipes during the cooking process.

In the districts predominantly inhabited by the Khasi and Jaintia tribes, the marketplaces primarily feature Khasi and Jaintia indigenous food courts. Similarly, in Garo-dominated districts, one can exclusively find Garo indigenous food courts. It is quite uncommon to encounter a food court that offers all three types of tribal indigenous delicacies. Although a few tribal food courts have recently been established in tourist-oriented areas such as East Khasi Hills (Shillong), Ri Bhoi (Nongpoh), and West Garo Hills (Tura), the number of tourists visiting these locations remains relatively low compared to the local tribal population. These food courts typically feature a restaurant-like atmosphere, offering either an a la carte menu, a thali system, or a combo arrangement. Some of these establishments have also included a variety of Indian and Chinese culinary options alongside traditional indigenous tribal dishes in their offerings to attract a broader audience. The proprietors of these food courts in tourist hotspots have expressed similar sentiments, noting that visitors are generally unfamiliar with the local indigenous culinary specialties, with the exception of a few Khasi dishes such as Jadoh, Dohkhleh, Tungrymbai, Doh nei iong, and Dohjem. Upon further inquiry, these business owners indicated that Meghalaya has been effectively marketed as a tourism destination in the northeast, highlighting its picturesque landscapes, tribal festivals, handicrafts, ethnic

garments, accommodations, and dining options. However, the ethnic tribal indigenous cuisines of the Khasis, Jaintias, and Garos have not received the same level of documentation and promotion as the scenic attractions of Meghalaya in both domestic and international forums. Given that most tourists lack knowledge about the local tribal delicacies, it is essential for both government and private agencies involved in the conservation and promotion of local tribal ethnic food to organize workshops with key tourism stakeholders, including hotels, restaurants, travel agencies, tour operators, transport providers, and entrepreneurs. This collaborative effort would help ensure that the tribal indigenous cuisines of the three tribes are preserved, promoted, and marketed effectively, thereby increasing tourist awareness of these unique culinary offerings and their availability.

One of the entrepreneurs has proposed that the tourist itinerary should incorporate a visit to the cottage industry where local rice-based snacks are made, and perhaps tourists could also engage in a hands-on experience of cooking these snacks. Additionally, the tour itinerary ought to include at least one or two lunch stops at traditional ethnic indigenous restaurants, which would encourage entrepreneurs to establish local tribal food courts in tourist-centric areas, ensuring a steady flow of visitors. Currently, there are numerous Indian and Chinese cuisine restaurants, along with small Maggie joints; if stakeholders are genuinely committed to promoting local tribal indigenous food, these same entrepreneurs could operate establishments featuring local tribal cuisine. Furthermore, some form of local legislation is necessary to reinforce tribal interests. If stakeholders are earnest about advancing tribal indigenous food delicacies, existing or new entrepreneurs could be motivated to create tribal food courts with a pleasant restaurant ambiance, offering authentic tribal cuisine recipes. From discussions with tourists at several prime tourist-centric locations, visitors from Assam, Bengal, South India, and North India expressed significant interest in local tribal food, yet only a few had the opportunity to sample a limited selection of Khasi delicacies. Some tourists suggested that their itineraries could include lunch or dinner featuring tribal indigenous food. A few tourists also noted the absence of tribal specialty restaurants in tourist-centric areas, or perhaps the signage was inadequate and not visually appealing. Information regarding tribal indigenous food was largely unavailable to most tourists, and hotels or guest houses offered very limited food options.

RECOMMENDATIONS:

Based on discussions with entrepreneurs managing local tribal indigenous food courts, as well as interactions with staff at these establishments and tourists visiting notable destinations in Meghalaya, the researcher has drawn several conclusions. It has become evident that there exists a disconnect between tribal indigenous food products and tourists. This gap suggests that the relationship between tribal food offerings and tourists can be improved through the following recommendations:

- Tourists should be informed about the

local delicacies available, and tribal indigenous food should be promoted alongside the region's scenic attractions.

- It is advisable to include food stops at tribal indigenous outlets within tourist itineraries.
- Language barriers represent a significant disconnect; staff at these tribal food courts often speak tribal dialects. Therefore, it is essential for staff to be more responsive to tourists' needs and inquiries. Capacity-building refresher courses should be organized by industry experts in collaboration with stakeholders to enhance the tourist-centric approach of the staff at these tribal indigenous outlets.
- Government stakeholders should provide special subsidies to local tribal entrepreneurs for establishing and managing indigenous food courts in tourist-heavy areas. Additionally, regular workshops should be held to preserve the authentic recipes of various Khasi, Jaintia, and Garo delicacies, while also exploring ways to adapt these recipes to enhance their appeal to tourists in terms of taste, flavor, and presentation.
- Small cottage industries that produce a variety of tribal indigenous snack delicacies should be integrated into self-help groups or cooperatives, allowing for a more efficient management of operational, production, and distribution processes. Additionally, these cottage industries could be promoted as tourist attractions within travel itineraries.
- Familiarization tours organized by stakeholders for travel agents, tour operators, and travel writers should include traditional tribal indigenous cuisine, enabling travel agencies and tour operators to market these culinary delights alongside the state's scenic attractions at various events.
- Financial institutions, in collaboration with the directorate of tourism, ought to devise and promote initiatives that encourage local host communities to actively engage in the expanding tourism sector, thereby fostering more tourism entrepreneurs within the tribal food industry.
- Local food writers should be motivated to author books on indigenous tribal food delicacies to revive forgotten recipes and preserve the rich heritage of tribal indigenous food culture.
- Given the presence of government and private culinary institutes in the state, it is essential to integrate regional tribal indigenous cuisine into the educational curriculum, facilitating extensive research on tribal food and ultimately promoting local cuisine within the state's tourism circuits.
- A food festival showcasing local ethnic cuisines will be organized in conjunction with the primary traditional festivals of the state, thereby emphasizing the local culinary offerings to both domestic and international tourists.

CONCLUSION:

A tourist, visitor, or excursionist travels to a location distinct from their usual residence for leisure, business, or various other reasons. Regardless of the motivation

behind the journey or visit, food plays a crucial role; thus, it can often serve as a significant factor in the decision to visit a particular place. Traditional indigenous cuisine possesses immense potential to become a prominent tourism product; however, it has yet to attain the recognition it deserves, despite its uniqueness. One contributing factor may be the influence of globalization, convenience foods, and the evolving dietary habits of the general population. Nevertheless, within the tourism industry, travelers are typically eager and curious to sample diverse traditional indigenous dishes. It has been noted that traditional indigenous food courts are present worldwide and are quite popular among the local populace. Recently, an increasing number of tourists have shown a keen interest in experiencing traditional indigenous culinary delights, prompting many local tribal food courts to engage with tourists. However, a significant gap remains. The primary reason for the low number of tourists frequenting these indigenous food establishments is the language barrier, as many employees or owners are native tribal individuals who do not operate with a tourist-centric approach, primarily serving the local tribal community. Additionally, these indigenous food outlets often lack adequate signage, which may deter tourists from confidently entering and ensuring they receive value for their money. Lastly, it has been observed that these native indigenous outlets are typically located in marketplaces where the local tribal population predominates, resulting in less visibility and accessibility for tourists. Finally, another significant reason noted is that these native indigenous outlets are typically located in market areas where there is a greater flow of the local tribal population compared to tourists. In Meghalaya, regional and local stakeholders, in collaboration with primary tourism providers, can develop concrete strategies to address this gap and promote the indigenous culinary specialties of the Khasis, Jaintias, and Garos, thereby creating a robust tourism product that appeals to visitors through its food and scenic beauty.

LIMITATIONS AND FUTURE SCOPES OF STUDY:

The research focused on a select group of districts in Meghalaya, which was primarily influenced by constraints concerning time and the available resources. Despite this limitation, it presents a significant opportunity for researchers and various stakeholders to advocate for and support the indigenous tribal cuisine of Northeast India. Promoting this unique culinary heritage could be instrumental in boosting the tourism industry, not just in Meghalaya, but also in adjacent regions, ultimately leading to a deeper appreciation for the area's distinctive food culture.

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ALIGNING SDG & ESG: SHAPING COMMON GOOD HRM AND ORGANIZATIONAL CONSCIOUSNESS FOR SUSTAINABLE DEVELOPMENT IN THE INDIAN POWER GENERATION SECTOR

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ABSTRACT

The Indian power generation sector, as a cornerstone of national growth, faces an extreme challenge to balance rapid growth and sustainability issues. This research explores the possibility of aligning Sustainable Development Goals (SDGs) and Environmental, Social, and Governance (ESG) frameworks to shape Common Good Human Resource Management (CGHRM) practices and Organizational Consciousness to drive sustainable development. SDG priorities and ESG-driven accountability can prepare HRM dimensions of organizations to go beyond efficiency to ensure equity, ethical responsibility, and long-term resilience. The role of organizational consciousness with values, culture, and leadership orientation in designing sustainability into workforce policies, talent strategies, and decision-making has been highlighted in this study. Such alignment is extremely important for the power sector. Transition to renewable energy and reducing the use of non-fossil fuels are some of the important solutions to reach the net-zero target by 2070. This study adopts an explorative qualitative approach as research methodology. Research methods include an in-depth study of literature, journals, policy frameworks, and thematic insights from power sector experts to identify patterns linking SDG-ESG alignment with CGHRM and organizational consciousness. Findings suggest that SDG-ESG-driven CGHRM rooted in sustainability and consciousness can ensure social justice, environmental consciousness, in addition to corporate purpose.

Keywords: Indian power generation sector, SDG, ESG, Common Good HRM, Organizational Consciousness.

INTRODUCTION

The evolving dynamics of globalization and rapid technological advancements are reshaping the world, presenting both opportunities and challenges for achieving decent work and sustainable development. As industries integrate artificial intelligence, automation, and digital platforms, labour and industrial relations are undergoing a profound transformation. While these innovations enhance efficiency and productivity, they also disrupt traditional employment structures, raising concerns about job security, fair wages, and workers' rights in developing economies like India, where the power generation sector plays a crucial role in economic progress. These challenges become even more pronounced. It examines the obstacles to advocating for decent work, the impact of emerging technologies on employment, and the role of policy interventions in fostering ethical labour practices. By analysing innovative HRM strategies and regulatory measures, the study aims to provide insights into how conscious power-generating organizations can drive change management and sustainable developments while ensuring workers' rights and well-being in a rapidly evolving global economy.

The Indian power generation sector plays a critical role in shaping the country's economic development, while also being a significant contributor to environmental challenges. As the global emphasis on sustainability intensifies, the sector faces mounting pressure to transform its operations, embrace renewable energy, and align with the principles of sustainable development. In this context, the concept of a conscious organisation – one that prioritizes ethical practices, social responsibility, and long-term environmental stewardship – has gained momentum. This shift is supported by the emerging framework of CGHRM, which focuses on the collective well-being of employees, communities, and the environment, creating a workforce that is more engaged, responsible, and aligned with sustainable practices. This workforce can take part in the Government of India's national action plan on climate change, National Solar Mission, and the National Mission for Enhanced Energy Efficiency.

By integrating conscious organizational values and CGHRM, power generation companies can drive change management initiatives that foster operational efficiency, economic growth, and environmental sustainability. This approach not only leads to better resource management and energy efficiency but also enhances employee satisfaction and company performance, offering a path towards long-term resilience and profitability. The sustainability dimension of this transformation is crucial, as it ensures that the sector contributes to India's broader goals of reducing carbon emissions, supporting renewable energy adaptation, and promoting socio-economic development.

This research explores the intersection of these dimensions – conscious organization, CGHRM, change management, and sustainable development – to understand how they collectively drive transformation with India's power generation sector so that greenhouse gas generation can be reduced to limit global temperature rise in this century 2 degree centigrade (preferably 1.5 degree centigrade) compared to pre-

industrial level by phasing out fossil fuel and limiting cutting of trees and displacement of local people for installation of power generation plant.

LITERATURE REVIEW

Globalization and Decent Work

Globalization has significantly altered labor markets, creating both opportunities and challenges for workers worldwide. Studies suggest that while globalization fosters economic growth and job creation, it also exacerbates inequalities and job insecurities (Rodrik, 2018). The International Labor Organization (ILO) emphasizes that achieving decent work within a globalized economy requires robust policies to mitigate wage disparities and precarious employment (ILO, 2021). Particularly in developing economies like India, the power generation sector faces challenges in labor protections amid the pressure of global competition (Sharma & Gupta, 2020).

Technological Advancements and Labor Market Transformations

The rapid integration of artificial intelligence (AI), automation, and digital platforms is reshaping industrial relations. Brynjolfsson and McAfee (2017) argue that while automation enhances productivity, it leads to job displacement, especially in routine-based occupations. In the power generation sector, smart grids and predictive maintenance systems reduce the demand for traditional roles while creating new opportunities for highly skilled workers only. (Kumar & Patel, 2019). However, the challenge remains in ensuring fair wages and job security for those at risk of displacement (Autor, 2019). The transition requires comprehensive workforce reskilling programs and government policies that promote labor market adaptability (World Economic Forum, 2022).

Labor Rights and Global Supply Chains

Despite international frameworks like the United Nations Guiding Principles on Business and Human Rights, many workers in global supply chains face poor working conditions, wage suppression, and lack of collective bargaining rights (Barrientos, 2020). Studies indicate that multinational corporations often prioritize cost efficiency over ethical employment practices, particularly in developing nations (Nolan & Bott, 2018). In the Indian power sector, subcontracting and informal employment arrangements further complicate the enforcement of labor rights (Ghosh & Ranjan, 2021). Strengthening governance mechanisms and enforcing corporate accountability are essential to safeguarding workers' rights.

Common Good HRM and Conscious Organizations

Recent research highlights the role of ethical HRM in promoting sustainable development. The CGHRM framework, which emphasizes fairness, well-being, and long-term socio- economic benefits, has gained traction as an effective strategy for balancing corporate success with employee, social, community, and environmental welfare and thus makes the organization conscious or aware to drive positive change towards a clean and green future. Implementing HRM strategies that prioritize workers' rights not only enhances job quality but also

fosters resilience in industries facing rapid technological shifts (Budd & Zagelmeyer, 2020). This approach fosters employee participation in decision-making, ensures job security, and promotes practices benefiting all stakeholders, thereby contributing to the common good. In the Indian power generation sector, conscious organizations that integrate CGHRM practices can drive equitable growth while contributing to the broader goals of Sustainable Development Goals (Mishra & Verma, 2022).

Policy Interventions for Sustainable Employment

Governments, international organizations, and corporations play a crucial role in addressing labor market disruptions. The ILO (2021) advocates for comprehensive labor laws that ensure fair wages, social protections, and safe working environments.

Policy measures such as minimum wage regulations, union rights protections, and investment in worker resilient programs have been successful in fostering decent employment in several economies (Freeman, 2020). In India, initiatives like Skill India and Make in India aim to bridge the skill gap and enhance workforce adaptability to technological changes (GoI, 2021). However, effective implementation remains a challenge due to regulatory inefficiencies and resistance from corporate stakeholders (Chakraborty & Banerjee, 2021).

Relevance of Artificial Intelligence (AI), Artificial General Intelligence), SDG 8, SDG 9, and SDG 12

SDG 8: Decent Work and Economic Growth

The goal aims to promote sustained, inclusive growth, full and productive employment, and decent work for all. CGHRM practices by implementing fair labor practices, providing opportunities for professional development, and ensuring equitable compensation, thus fostering a work environment conducive to economic growth and employee well-being (United Nations Sustainable Development Goals, 2015).

AI contributes to economic growth by enhancing productivity, optimizing business operations, and fostering innovation. However, ensuring fair labor practices, equitable access to AI-driven opportunities, and inclusive workforce policies is essential to mitigate job displacement risks (UNDP, 2021)

SDG 9: Industry, Innovation and Infrastructure

This goal focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. By encouraging a culture of continuous learning and innovation, CGHRM practices enable employees to contribute effectively to industrial advancements and industrial development, essential components of a sustainable power generation sector (United Nations Sustainable Development Goals, 2015).

AI accelerates industrial innovation through smart manufacturing, predictive maintenance, and digital transformation (Brennen & Kreiss, 2016). AGI, if realized, could revolutionize R&D, driving unprecedented advancements in infrastructure and industrial sustainability.

SDG12: Responsible Consumption and Production

This goal aims to ensure sustainable consumption and production patterns. CGHRM can influence this by promoting environmental awareness among employees, encouraging sustainable practices, and integrating eco-friendly policies into organizational operations, thereby reducing waste and optimizing resource use(United Nations Sustainable Development Goals, 2015).

Ai enables sustainable production by optimizing supply chains, reducing waste, and supporting circular economy initiatives. Meanwhile, learning models help monitor environmental impact, enhancing sustainable resource management (Jarrahi, 2018).

Role of ESG for introducing CGHRM in a conscious power generation company

As obtained from https://www.esgthereport.com/what-is-sdg-and-esg/ (2024), ESG stands for Environmental, Social, and Governance, and it refers to the way a company performs in these critical areas. It evaluates a company's impact on the environment, how it treats its employees and other stakeholders, and its governance practices. Investments that focus on ESG prioritize not just financial returns, but also ethical and sustainable business practices. Companies are increasingly under pressure to consider the social good when making operational decisions, and ESG helps them track and measure sustainability efforts. Research shows that adopting responsible environmental and social practices is vital for long-term success. While ESG reporting has traditionally been required for public companies like the power sector, middle and smaller level companies may not have focused on sustainability as much. What was once seen as optional has now become essential. Consumers and stakeholders are becoming more conscious and demanding more transparency. So, this is the high time to for companies to start prioritizing ESG.

ESG is a set of guiding principles that business adopts to ensure that they operate in a way that is sustainable in the long run. Implementing an ESG framework offers several significant advantages for businesses, investors, other stakeholders, society, the community, and the planet.

ESG encourages companies to take a more holistic approach to their operations with the help of CGHRM. Strategic HRM is to be elevated to the stage of CGHRM. By adopting Common Good practices and focusing on resource management, businesses can gain a competitive edge in today's market. ESG practices are also beneficial to investors and other stakeholders

because companies that follow these principles tend to be better governed, offering greater transparency and accountability. Especially in the light of recent global events, ESG has become an essential tool in the fight against climate change. The ongoing world events further accelerated the push towards green and clean energy investments and energy- conservation efforts.

ESG holds power and other industries accountable for their environmental and social impact, and serves as a roadmap for a more conscious and sustainable future.

Why aren't SDGs enough?

The Sustainable Goals (SDGs) alone are not enough to ensure true sustainable development because there are many complex challenges that still need to be addressed. Some of these issues include:

- Poor working conditions in supply chains, like unfair wages and long working hours.
- Corruption and bribery, which can lead to the suppression of workers' rights, especially in corrupt governments and organizations.
- Child labor, which continues to be a significant problem in the outsourced jobs of the power industries.
- Water scarcity, driven by droughts, climate change, or other factors.
- Mismanagement and corruption in the handling of natural resources like forests, minerals, coal, and oil used in the power generation sector. As obtained from https://www.esgthereport.com/what-is-sdg-and-esg/ (2024), without addressing these critical issues, it's impossible for any company to fully achieve the SDGs. For example, a company that outsourced its operation and that outsourced agency employs child labor is indirectly contributing to the exploitation of children. This is where ESG (Environmental, Social, and Governance) comes in - it holds companies accountable for their actions, ensuring they follow ethical and sustainable practices.

AI, AGI, and the Future Workforce

AI encompasses a range of technologies, from machine learning and neural networks to natural language processing and robotics. Current AI systems exhibit narrow intelligence, excelling at specific tasks but lacking human-like cognitive abilities (Russel & Norvig, 2021).

In contrast, AGI, often envisioned as a system capable of general reasoning and problem- solving, remains a theoretical construct with ongoing research (Goertzel, 2014).

Impact on Employment

AI-driven automation is transforming labor markets by displacing routine jobs while creating new roles that require advanced digital skills (Brynjolfsson & McAfee, 2017). Studies suggest that AI will augment rather than replace most jobs, with workers needing reskilling to remain competitive (Autor, 2015).

Workforce Adaptation and Skill Development

With AI's growing presence, education systems and corporate training programs must prioritize lifelong learning and digital literacy (World Economic Forum, 2020). Initiatives focusing on STEM education, soft skills, and human-AI collaboration are crucial for workforce sustainability.

CHALLENGES AND ETHICAL CONSIDERATIONS

The ethical implications of AI and AGI include bias in algorithms, data privacy concerns, and the potential for job polarization (Bostrom, 2014). Policymakers and organizations must establish regulatory frameworks to ensure AI aligns with human- centric values and sustainability goals.

Role of Change Management in the Power Generation Sector

Change management is an essential practice for navigating the complexities of organizational transformation towards

the conscious power generation sector. Emotional and psychological aspects of change emphasize that true change occurs when people transition through an internal process (Bridges, 2003). He argues that organizations often neglect these aspects, leading to resistance and inefficiency.

(Cameron & Green, 2004) provides a structured. Research-based approach to understanding and implementing change, highlighting models and techniques that help leaders guide their

teams through transitions. Their work synthesizes both theoretical frameworks and practical insights, offering a roadmap for successful change initiatives.

(Johnson, 1998) present a simple yet profound parable that underscores the importance of adaptability. Through the story, characters seeking cheese in a maze, Johnson explores the human tendency to resist change and the value of embracing it for personal and professional growth. His work resonates widely for its straightforward yet powerful message on the importance of adapting to change.

(Kotter, 2006) provides a compelling narrative around his 8-step change model, which is widely regarded as one of the most effective frameworks for leading change. His fable about a group of penguins trying to save their melting iceberg highlights the importance of creating a sense of urgency, building a coalition, and communicating a vision for change, among other principles. His work outlines the practical steps leaders can take to ensure sustainable, positive transformation in their organizations.

Together, these authors offer a multifaceted approach to managing change – focusing on emotional resilience, structured frameworks, adaptability, and leadership strategies. Their combined insights form a comprehensive guide to navigating the complexities of organizational change.

Application in the Indian Power Generation Sector

India's power generation sector is pivotal for the country's economic development and industrial growth. However, it faces challenges such as environmental concerns, technological obsolescence, and workforce management issues (NITI Ayog, 2021). Implementing CGHRM in this sector can address these challenges by:

Enhancing Employment Engagement and Retention

Involving employees indecision-making processes an recognizing their contributions can boost morale and reduce turnover rates (GOI, 2020).

Promoting Sustainable Practices

Educating and training employees on environmental sustainability can lead to the adoption of greener technologies and processes, reducing the sector's carbon footprint (GOI, 2020).

Fostering Innovation

A supportive HRM framework encourages creativity and innovation among employees, leading to the development of efficient and sustainable power generation methods (GOI, 2020).

RESEARCH GAP

Lack of integration between SDGs and ESG in HRM practices

Existing literature discusses SDGs and ESG separately, but lacks empirical research on how HRM strategies can effectively integrate both frameworks to enhance corporate sustainability There is limited research on how power sector companies in India align HRM practices with both SDGs at the macro level and ESG at the corporate level for sustainable workforce management.

Impact of AI and AGI-related change management on Workforce transformation in the power generation sector

While studies highlight AI's role in automation, productivity, and smart grids, there is limited research on AGI's potential for workforce adaptation and job displacement in the power generation sector.

The literature lacks comprehensive frameworks for reskilling and upskilling programs tailored to power generation sector employees in the wake of AI-driven transformations. The research also lacks the need for necessary change management in the AI and AGI environment of the power generation sector.

CGHRM strategies for sustainable employment amid technological advancements

Research primarily focuses on economic and technological factors influencing employment, but lacks insights into how CGHRM can address workforce challenges in a rapidly evolving digital economy. There is insufficient empirical data on the effectiveness of CGHRM in India's power generation sector, particularly concerning employment retention, workforce well-being, and innovation in sustainable energy practices.

Challenges in implementing ESG-driven HRM policies in developing nations

Existing studies focus on ESG in corporate governance and investment decisions, but do not extensively explore how HRM policies can address ESG concerns in workforce management, particularly in the Indian power generation sector.

Regulatory inefficiencies and corporate resistance to ESG-aligned HRM practices remain unexplored, requiring case studies and policy recommendations.

Ethical and policy considerations for AI & AGI in workforce sustainability

AI-driven automation's ethical implications, such as bias, privacy, and job displacement, have been discussed broadly, but there is limited research on ethical AI governance specifically for the power generation sector workforce.

Policies ensuring fair wages, job security, and equitable AI integration in labor markets remain fragmented and require structured frameworks for the power generation sector implementation. How can organizational consciousness help to develop ethical and policy considerations for the AI and AGI workforce? This needs further research.

Role of CGHRM in enhancing decent work (SDG 8) and sustainable industry (SDG 9) in power generation

The literature mentions SHRM as a key driver for workforce transformation, but empirical studies on SHRM's impact on SDG 8 (Decent work) and SDG 9 (Industry and innovation) are limited. How organizational consciousness can be developed using CGHRM practices needs further research.

The connection between HRM digitization (HR analytics, AI-powered hiring, and employee engagement) and sustainability in power generation is not well established.

RESEARCH QUESTIONS

- How does Common Good HRM influence sustainable development in the Indian power generation sector?
- What role do employee engagement, ethical leadership, and value-based governance play in promoting conscious organizational practices through CGHRM?
- How can CGHRM integrate sustainability into core HR functions such as talent acquisition, performance management, and employee development?
- What are the impacts of CGHRM practices on environmental conservation and socio-economic equity in India's renewable, pumped-storage, and conventional power generation initiatives?

RESEARCH OBJECTIVES

- To examine the influence of CGHRM on sustainable development in the Indian power generation sector.
- To investigate the potential of CGHRM in transforming profit-centric organizations into purpose-driven, conscious organizations in the power generation sector.
- To identify the best practices in CGHRM that contribute to achieving sustainable development goals in Indian power generation companies.
- To explore the role of employee engagement, ethical leadership, and value- based governance in promoting conscious organizational practices through CGHRM.
- To evaluate how CGHRM fosters an inclusive organizational culture and promotes holistic employee well-being.
- To explore the role of CGHRM in enhancing corporate social responsibility initiatives within India's power generation sector.
- To assess the impact of CGHRM practices on environmental conservation and socio-economic equity in India's renewable, pumped-storage, and conventional power generation initiatives.

RESEARCH PROPOSITIONS

H1: CGHRM has a positive influence on sustainable development in the Indian Power Sector.

H2: CGHRM practices significantly contribute to transforming profit-centric organizations into purpose-driven, conscious organizations in the Indian power sector.

H3: The implementation of best practices in CGHRM is positively associated with the achievement of SDGs in Indian power generation companies.

H4: Employee engagement, ethical leadership, and value-based governance play a significant role in promoting conscious organizational practices through CGHRM.

H5: CGHRM significantly enhances inclusive organizational culture and promotes holistic employee well-being.

H6: CGHRM practices have a significant impact on improving corporate social responsibility initiatives in the Indian power generation sector.

H7: CGHRM practices have a positive

impact on environmental conservation and socio-economic equity in India's renewable, pumped-storage, and conventional power generation initiatives.

RESEARCH DESIGN

This exploratory research will adopt a qualitative approach, focusing on collecting rich, in- depth insights from individuals who are experts in the field of power generation, sustainability efforts, and engineers and HRM professionals involved in the power generation sector. Data collection will be done through document review of the power generation companies, interviews, and focus group discussions.

The qualitative methodology within a cross-sectional framework allows for exploring experiences, perceptions, and a nuanced understanding of HRM practices related to sustainability and the Common Good, aiming to explore and understand the underlying phenomena of CGHRM practices as a driver of change management in the context of sustainable development in the Indian power generation sector.

RESEARCH METHODOLOGY

Research Approach

Phenomenological Approach

To understand the experience of individuals who are experts in the field of power generation, sustainability efforts, and engineers and HRM professionals involved in the power generation sector with respect to CGHRM practices, consciousness, and their impact on sustainability factors.

Case Study Methods

To explore specific instances where CGHRM and consciousness have been successfully integrated into the operations of power generation companies in India, multiple case studies from different companies will be included to explore a range of practices and contexts.

Sampling

Population

Experts in the field of power generation, sustainability efforts, and engineers and HRM professionals involved in the power generation sector.

Sampling Techniques

Positive Sampling will be used to select companies that are known to implement innovative HRM practices or have shown a commitment to sustainability.

Snowball Sampling will also be employed to identify further participants through initial interviewees who are well-versed in the subject matter.

Sample Size

The research will involve in-depth interviews with 23 participants across multiple organizations. This sample size is sufficient for gathering a wide range of qualitative insights while managing data analysis.

Data Collection

Document Review

Organizational reports, including HR policies, sustainability initiatives, and related documents, will be analyzed to understand how sustainability is integrated into HRM practices at a policy level.

Semi-structured Interviews

This will be conducted with the experts in the field of power generation, sustainability eff, including HR policies, sustainability initiatives, and related documents, will be analyzed to

understand how sustainability is integrated intoort, and engineers and HRM professionals involved in power generation sector to gather their perceptions, experience, and insights into CGHRM practices and sustainable development and how do these factors steer a power generation utility into a conscious organization.

Focus Groups

Group discussions will also be arranged to get a clear idea of the role of HRM practices in sustainability efforts and the concept of Common Good in the power generation sector.

Data Analysis

Thematic Analysis

This primary method will be used to analyze the interview transcripts, focusing on identifying recurring themes related to CGHRM, sustainability, and challenges in implementing these practices in power generation companies.

Coding Process

Transcripts will be coded manually, and the initial code will focus on emerging themes such as "employee well-being", "environmental sustainability", and "ethical leadership". These codes will then be grouped into higher-level themes.

Triangulation

Data from documents, interviews, and focus groups will be cross-checked to ensure consistency and increase the reliability of findings.

Ethical Considerations

Informed Consent

All participants will be provided with clear information about the research purpose and their role in it. After receipt of consent only, the interview process will be started.

Confidentiality

The identity of the participant and their responses will remain confidential. Data will be anonymized and securely stored.

Voluntary Participation

Participation will be voluntary, and participants can withdraw their consent at any time.

Validity and Reliability

Validity

As concepts have been clearly defined and comprehensive data collection has been ensured by selecting participants from a relevant background, construct, content, internal, and external validities have been maintained to reflect the true role of CGHRM in sustainable change in the Indian power generation sector.

Reliability

In this research, data collection has been done using a standardized method, and all the data have been cross-checked through the triangulation method to ensure data reliability.

FINDINGS AND IMPLICATIONS

After thematic analysis, the following points have emerged as findings:

Coal-based thermal generation is to be substituted by renewables for a smooth journey to a carbon-neutral destination.

Although the Pumped Storage Project (PSP) is a good option, it cannot be called fully renewable till the fuel mix in power generation includes less fossil fuel, as in PSP, the raw material is not water, but grid electricity. PSP pumps water from the lower reservoir when the cost of grid power is less due to high frequency, and generates electricity with 75% efficiency by releasing water from the upper

reservoir when the cost of power is high/very high. This will become clean energy only when we can generate renewable energy in higher capacities and use PSP as a storage medium by pumping water with the help of renewables, when the same will be available. Moreover, deforestation, changing the natural flow of water, three to

four PSP in one hilly region, resulting in land slippage and destruction of biodiversity, and the displacement of local people from that hill.

A hydel power station generates clean and green power, but is totally dependent on the availability of water flow. Of course, during the construction period, several issues were generated as stated above for PSP.

Solar power and wind power generation depend on the weather. Moreover, solar generation is available only during the daytime. The cost of installation is declining day by day, and these generations can be distributed through a microgrid using distributed generation. A battery can be used to make these available in a 24/7 mode. Remote rural villages can be served with the help of this arrangement.

Biomass, a clean energy source, is a cheap and implementable option and can generate in a 24/7 mode. There is a huge, promising area to implement this at a very low cost. Hydrogen is also coming as a very useful source of clean energy.

All power-generating companies must think about increasing overall efficiency and plant load factor, along with optimal use of scarce resources.

All government, power-generating companies of India, and the entire ecosystem must collaborate, in line with SDG 17, in such a way that the goal of the country to generate 500 GW and 200GW of non-fossil energy can be achieved by 2030 and 2050, respectively, to ensure the net-zero goal of India by 2070. Although the interim goal of generating 500 GW is not a distant dream, as we have already achieved 218 GW, and another 150 GW are in the pipeline. But to ensure 2000 GW by 2050 is a tough target in terms of land for construction, transmission grid, and development of energy storage devices. To address land-related problems, solar is to be installed on every dam, upper and lower reservoirs of PSP, on the river, etc. To solve the storage problem, pending PSPs are to be constructed within the time without further delay.

A few respondents have installed a 3.6 KW solar rooftop panel with 25 25-year lifespan at Rs 2 Lac. They have to make another expenditure of around Rs 2.25 lac for the change of the inverter and battery within these 25 years. They have calculated NPV also as +ve, and the cost of power after 25 years will be Rs 85/- per month in NPV terms, which is now Rs 925/- per month. One such respondent also told that he is following the guidance of Mother Teresa, who said, “We ourselves feel that what we are doing is just a drop in the ocean. But the ocean would be less because of that missing drop”. He also says that he feels very happy and relaxed when he notices solar panels are supplying power in distributed mode in agriculture, small businesses, and public places.

As greenhouse gas is increasing, the world is getting hotter, and droughts, storms, and floods are now regular phenomena.

CONCLUSION

The adoption of conscious organizational practices and CGHRM in the Indian power sector is crucial for driving change management initiatives that contribute to sustainable development. The operational, economic, and sustainability dimensions are interconnected, and aligning HRM practices with these goals ensures that power companies can not only meet their immediate business objectives but also contribute positively to environmental stewardship and social welfare. By fostering a culture of responsibility, these companies can drive long- term success and play a pivotal role in India's sustainable energy future.

All power generation companies must remember that they have to promote all 3Ps – not only prosperity, but they also have to nurture people and planet, with due care for their holistic growth and long-term success.

Govt. of India (GOI) has to play a significant role in framing sustainable energy policies in this line for a cleaner and greener future. Although GOI has targeted two-third of resource towards a green recovery, including around USD 3 billion in battery and solar PV development, lowering emission by 33% to 35% below 2025 level by 2030 level, increase share of non-fossil fuel based energy source to 40% of installed power capacity by 2030 (with international support), and create an additional carbon sink of 2.5GtCO2e through additional forest cover by 2030, but at the same time, coal-based energy will be increased by about 266 GW as a part of coal-expansion plan – this will drive the change in negative direction, As a result of that, temperature is expected to increase by 2.7 degree centigrade by another 2 to 3 years. This will be a direct threat to our future generation as disease will increase and life expectancy will be greatly decreased. So, the central and all state governments. has to come together to make a policy for a truly pollution-free, green, clean, and sustainable India. Let us start the revolution from India with a vision to keep the temperature rise of the world within

0.5 to 0.7 degrees centigrade rise compared to the pre-industrial level temperature by the end of this century. If the Covid virus can show us the way, we, human beings, can positively do that if we commit from the core of our hearts.

The findings of the study are industry-specific, focusing on the Indian power generation sector, and may not be suitable for other industries. The research is qualitative in nature, and

as such, the results may not be generalized to all organizations in this sector, although the study provides deep insights into the issue of the power generation sector.

However, this topic is vast and multifaceted. The study can focus on sector-specific case studies to evaluate how different power generation companies are adopting these practices to measure effects on sustainability metrics. Research could also investigate how leadership styles that prioritize sustainability and ethical practices influence organizational culture, values, and employee engagement in the power sector. Researchers could also explore the correlation between long-term profitability and investment in sustainable technologies. Cross- sectoral comparisons could also offer insights into how the Indian power generation sector can learn from other industries or global leaders in

sustainable development, providing a roadmap for scaling these practices nationally and globally.

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A QUALITATIVE STUDY OF FACTORS INFLUENCING CONSUMER PURCHASE BEHAVIOUR FOR GREEN PACKAGED PRODUCTS

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ABSTRACT

Green packaging refers to using packaging materials that minimise the adverse effects on the environment. These materials are reusable and have the ability to biodegrade or be composted. Businesses and institutions are increasingly adopting green packaging to highlight their dedication to the environment and fulfil governmental as well as consumer demands. However, terms like 'green packaging', 'eco-friendly packaging', and 'sustainable packaging' can confuse consumers trying to grasp the underlying notion. Furthermore, factors such as environmental consciousness, product availability, and price are expected to influence consumer purchasing behaviour towards environmentally friendly packaged items. The primary goal of this study is to identify the elements that impact consumer buying behaviour towards green packaging by examining past research studies and available literature. The study is qualitative in nature based on 20 research papers from reputed journals. The papers were identified from various online digital libraries such as EBASCO. The critical independent and sub-variables were identified from the research papers to develop the proposed research model. The study findings are anticipated to offer valuable insights to packaging material suppliers and diverse businesses for their forthcoming sustainability endeavours. The findings may also provide valuable input for future scholars interested in conducting similar studies in various geographical locations.

Keywords–*Green packaging, sustainable packaging, eco- friendly packaging, consumer purchase behaviour*

INTRODUCTION

Two-thirds of the 430 million tons of plastic generated every year is used for very brief periods of time [1]. This includes products like PET water bottles and shopping bags, straws, and food containers made of plastic. Fortunately, there is an increasing desire for sustainable consumption, including non-plastic alternatives like green packaging.

According to United Nations Environment Programme (UNEP), Green packaging, otherwise known as sustainable packaging

refers to packaging, which limits the harm done to the environment. In academic study, green packaging is sometimes known as sustainable or eco-friendly packaging; nonetheless, the fundamental understanding is that green packaging reduces environmental pollution while providing sustainable value without compromising the functioning of traditional packaging [2]. Across the globe, governments and non- governmental organisations are advocating for the use of environmentally friendly packaging materials to mitigate environmental damage.

For many stakeholders, using green packaging materials has presented both benefits and challenges. Determining if end users are aware of and concerned with the environment is crucial. Many items in the market claim to use sustainable or green packaging. This research aims to comprehend how consumers perceive and choose green packaged goods. This study aims to provide novel variables, such as price sensitivity and brand image that are expected to impact consumers' purchasing decisions regarding environmentally friendly packaging. In addition, unlike other articles, this study has not only identified sub-variables but also anticipated outcomes from the proposed model, along with the measures needed to ensure its comprehensiveness. The research gaps, questions, and objectives of the study can be summarised as follows.

RESEARCH GAPS AND OBJECTIVES

Research Gaps

An initial literature review for this study identified four independent variables based on the research gaps observed: i) brand image, ii) price sensitivity, iii) cultural norms, and iv)environmental benefits. The related literature study helped identify the following research problems and questions.

- What is the impact of brand image on consumer purchasing behaviour for green packaged products?
- How does price sensitivity influence consumer purchase behaviour for green-packaged products?
- How do cultural norms impact consumer purchase behaviour for green packaged products?
- How does consumers' perception of environmental benefits affect their decision to buy green packaged goods?

Research Objectives

The objectives of this study are as follows:

- To identify the variables that enhance brand image, resulting in consumer loyalty and influencing consumer purchase behaviour for green packaged products.
- To determine the factors that impact price sensitivity leading to consumers' willingness to pay for green packaged products.
- To identify the factors that affect cultural norms while purchasing green packaged products resulting in social acceptance.
- To identify the factors impacting consumers' perceived environmental benefits of green packaged products that ultimately result in a better

ecosystem.

This study aims to investigate and analyse existing

RESEARCH METHODOLOGY

Qualitative research entails the collection and analysis of non-numerical data, such as text or video for understanding ideas or real-life experiences. It has the potential to be employed to develop novel research ideas. Observations, interviews, focus groups, surveys and secondary research are some of the most common qualitative research methods used in research studies. For the purpose of this study, secondary research method was adopted, which involved screening of various existing research papers. From the many articles screened, 20 were shortlisted to establish the research gaps and create the research framework as mentioned in the Figure 1 above. The keywords provided above were used to search for papers in reputable Journals. Only the articles that explicitly stated limitations and areas for future research were further examined. The articles were analysed using Dr. A. Seetharaman's patented (2021) excel worksheet format to ascertain the research gaps and discern the independent and sub-variable.

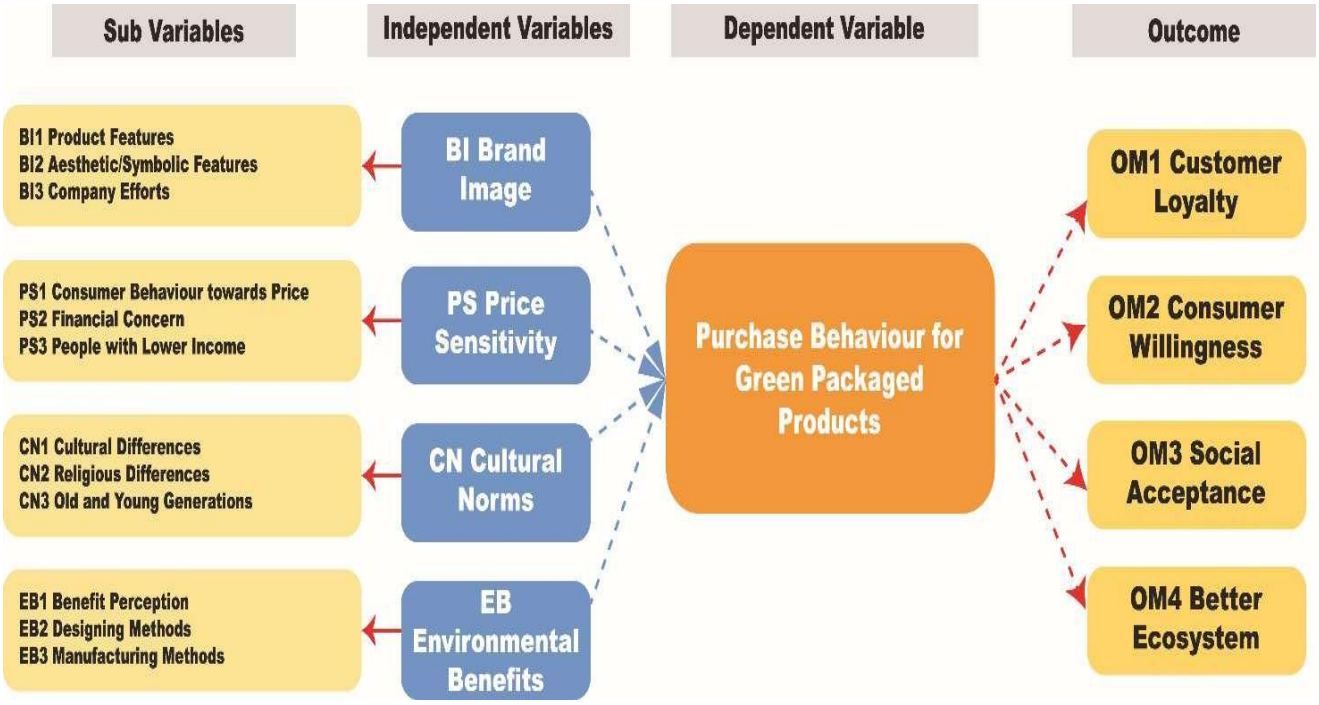


Figure 1 Research framework (Source: Author)

Research's limitations and issues to determine the factors impacting consumer purchase behaviour for green packaged products

Research Framework and Scope

This study focuses exclusively on consumer purchase behaviour for green packaged products. It does not explore the technical aspects of green packaging; hence, the research scope is limited to investigating and analysing the various factors that impact the consumer purchase behaviour of green packaged products.

Additionally, it examines the potential results or outcomes of green-packaged product purchases and outlines some measurement criteria that might be used to evaluate these outcomes. This study used research papers from the last five years from various online digital libraries such as EBASCO. The scope of this research is qualitative in nature.

DISCUSSIONS, OUTCOME AND PROPOSITION

Brand Image

According to the study conducted by reference [3], green packaging and branding have a significant impact on green purchase intention. This is supported by substantial prior research about how a green brand image can positively influence purchasers' decisions because it makes the brand distinctive [3]. Findings also confirm that perceived green value boosts reliability and trust together with purchase intention [4]. The company's perceived environmentally friendly reputation acts as a mediator between many elements and consumers' inclinations to make environmentally conscious purchases. An extensive examination of the pertinent literature reveals that the following elements are essential for creating a brand image:

- Product features
- Aesthetic/symbolic features
- Company efforts

Product features

According to reference [5], consumers were unwilling to sacrifice product quality for more environmentally friendly food packaging. In addition, some consumers were not completely satisfied with the food packaging's reduced shelf life when it was more environmentally friendly. These findings indicate a need for a balance; furthermore, customers are not entirely prepared to make compromises in certain areas to facilitate the use of sustainable packaging [6].

Aesthetic/symbolic features

The product's aesthetic features sometimes influence consumer's perception of brand image. According to a study, packaging material not only affects the perception of sustainability but also affects other views, such as the aesthetic quality of the product and its perceived ability to preserve the contents [7].

Company efforts

According to Waites et al., consumers are more inclined to purchase from companies that effectively implement green marketing strategies than from those that do not prioritise their environmental impact. The correlation is facilitated by trust in the

company. Moreover, demonstrating prosocial behaviour seems to validate the organisation's efforts and promotes the development of trust [8].

Outcomes and measures

Consumer satisfaction is achieved when individuals obtain desired items and services at an appropriate price and quality. This, in turn, contributes to establishing a favourable brand perception in customers' minds. Brand image is a predecessor to consumer loyalty [9]. Consumer loyalty has the potential to result in higher revenue and greater client lifetime value over an extended period. Consumer loyalty can be measured with the help of metrics such as Customer Lifetime Value and Repeat Purchases.

Proposition 1

Brand image significantly influences consumer purchase behaviour of green packaged products, leading to consumer loyalty supported by product features, aesthetic/symbolic features, and company efforts.

Price Sensitivity

Buying environmentally friendly products has been demonstrated to be substantially influenced by their economic value [10]. Price sensitivity has a negative moderating effect on the conversion of purchase intention into actual purchase of green items [11]. Therefore, firms may want to adjust the prices of their products according to the purchasing power of consumers. A comprehensive review of the literature indicates that the following factors significantly influence price sensitivity:

- Consumer behaviour towards Price
- Financial concerns
- People with lower income

Consumer behaviour towards price

The intention to purchase green products is significantly influenced by the premium and pricing of green products. However, according to research, it is anticipated that a substantial number of consumers are prepared to pay a premium for environmentally friendly products [3].

Financial concerns

Contrary to popular opinion, a study has demonstrated that consumers, purchase intention for green products is not adversely influenced by their higher prices. They regard the price premium as an additional measure of environmental worth [5].

People with Lower Income

Individuals with lower incomes exhibit less inclination towards buying products with environmentally friendly packaging due to the perception of higher costs and heightened price sensitivity [12].

Outcome and measures

While some consumers are ready to pay a higher price for environmentally friendly packaged products, others prioritise good value for their money. By considering the consumer's price sensitivity and effectively communicating the environmental advantages of green products, firms can anticipate consumers' willingness to pay the asked price for their products. This can result in increased revenue and accelerated growth.

Proposition 2

Price sensitivity significantly influences consumer purchase behaviour of green packaged products, resulting in consumers'

willingness to pay, supported by consumer behaviour towards price, financial concern, and income level.

Cultural Norms

Cultural disparities between nations impact the perceived efficacy of consumers and hence influence their environmentally conscious purchasing behaviour. A thorough comprehension of the psychological and behavioural factors that influence green customer behaviour is crucial for successfully implementing a green marketing mix [5]. Cultural norms are significantly influenced by the following factors, as evidenced by a comprehensive examination of the literature:

- Cultural differences
- Religious differences
- Old and young generations

Cultural differences

Cultural characteristics, such as individualism and collectivism, are significant factors in comprehending green consumer behaviour as they influence individuals' perception of their ability to contribute to social issues [5].

Religious differences

Religion significantly influences cultural distinctions in several regions of the world. Businesses must comprehend and exhibit a high level of awareness towards consumer sentiments to succeed in these regions. For example, according to one study it was found that incorporating religious symbols into advertising in Egypt might have negative effect and be ineffective [13].

Old and young generations

A study revealed significant differences in both the level of collaboration and the inclination to uphold societal norms of collaboration between two adult generations: individuals in their twenties and individuals with an average age of 67 years [14]. The young consumers' decision to transition from synthetic plastics to biodegradable ones is mainly influenced by novelty seeking, adventure, and concern for the environment rather than their knowledge, particularly about environmental issues [15].

Outcome and measures

Businesses must understand cultural aspects to make their products socially acceptable in a particular area. For instance, despite considerable benefits from their protein content, consuming insects in whole or powder form is still not widely accepted in Western countries, according to studies [16]. As mentioned in various studies, tools such as a stakeholder survey or analysis may be helpful to measure social acceptance of a product.

Proposition 3

Cultural norms have a significant influence on the consumer purchase behaviour of green packaged products, resulting in their social acceptance with the influence of cultural and religious differences and old and young generations.

Environmental Benefits

Consumers must possess knowledge about the specific environmental advantages offered by a product in order to make an ecologically mindful purchasing decision. Environmental awareness enhances the association between environmental concern and a company's perceived green image [17]. A thorough examination of the

literature indicates that the following criteria determine the perception of environmental benefits of green packaged products:

- Benefit perception
- Designing methods
- Manufacturing methods

Benefit perception

A study demonstrates that the type of packaging material not only significantly influences the perception of sustainability but also has an impact on other aspects, such as the perception of aesthetic quality and the potential ability to protect and maintain the contents [7]. As per Waites et al., companies that effectively use green marketing strategies experience more intentions to purchase compared to those that do not prioritise environmental impact. Furthermore, trust in the company influences this connection [8].

Designing methods

Designers possess a distinct capability and obligation to utilise their abilities, knowledge, and impact to promote beneficial environmental transformation. Design methodologies that prioritise efficiency, minimalism, and using ecologically sustainable materials experience increased popularity [18].

Manufacturing methods

Implementing environmentally friendly production practices can not only reduce waste and mitigate climate impact but also enhance firms' reputation for sustainability and positively influence consumers' purchasing decisions, thus increasing future sales [17].

Outcome and measures

According to Zhu et al., packaging is traditionally designed, manufactured, consumed, disposed of, and burnt or buried in landfills. The circular economy strives to minimise waste by preserving resources in a closed loop, minimising the negative impact on the environment. This necessitates packaging design innovations, as 80% of environmental impacts are determined during design, including material selection, production, consumption, reuse, and recycling [19]. Green product knowledge positively affects green product buying behaviour and customer attitudes toward green products [20], which can help improve the ecosystem. The indicators of a healthier ecosystem include decreasing air and water pollution and landfill waste, and increasing recycling rates.

Proposition 4

Environmental benefits perception has a significant impact on consumer purchasing behaviour for green packaged products, leading to a better ecosystem, influenced by benefits perception, designing methods and manufacturing methods.

RESEARCH.IMPLICATIONS, LIMITATIONS, AND SCOPE

Research implications

- Contribution to theory

The research model proposed in this study endeavours to incorporate innovative factors, such as brand image and price sensitivity and their influence on customer buying behaviour. Based on the identified criteria, future researchers might formulate and test various hypotheses to statistically validate the research findings.

- Contribution to practice

The study findings can assist businesses in devising appropriate packaging strategies towards their sustainability efforts. For example, companies can use study findings to develop appropriate "green" packaging as well as position their brand against competition with the help of right marketing strategies. The study highlights importance of other aspects such as price sensitivity and cultural norms which the businesses need to take care of in their green initiatives.

Limitations

The following are the limitations of this study.

The study is qualitative in nature and based on a restricted review of research papers. Therefore, the results of the investigation lack statistical verification.

- The findings may not be generalizable since the research model is based solely on the reviewed research articles. Moreover, consumers from different parts of the world are expected to exhibit varying purchase behaviour towards green packaging due to various factors such as cultural or subjective norms, availability or price sensitivity.
- Due to limited evaluation of papers and time constraints, the study has discovered only four independent variables and three sub-variables per independent variable. It may have failed to consider the effects of other significant variables that have not been evaluated.

SCOPE FOR FUTURE RESEARCH

Future researchers can consider the following suggestions.

- Conduct a comprehensive study by thoroughly reviewing more research publications.
- Perform primary research and statistically validate the results.
- Conduct a study focusing on a particular product category or geographic location to enhance the accuracy of the findings. Consider other factors such as government interventions and green packaging availability that may influence consumer behaviour.

CONCLUSION

Environmental awareness is growing. Businesses are using sustainable techniques to meet consumer demands, government laws, and corporate social responsibility. This study revealed consumer-focused characteristics that can help companies create eco-friendly packaging. The findings also showed how each element might considerably affect critical outcomes. Businesses should improve their green brand image while considering price sensitivity. It is vital for them to analyse how consumers perceive the environmental advantages provided by their products and how cultural standards influence this view.

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PIEZOELECTRIC MATERIALS FOR ENVIRONMENT SUSTAINABILTY

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ABSTRACT

Piezoelectric materials can be used as an unconventional sustainable source of green energy, an urgent need at present. The present paper reviews the potential of these smart materials to sustain the environment. Applications are based on the energy extracted from our day to day life events like vibrations from cars on highways, bridges or footballs on floors. Piezoelectric energy harvesting process with its minimal maintenance requirement, clean operation, scalability and renewable nature are emphasized in this paper. Its potential for green energy future in the renewable energy market is also discussed here.

Keywords: Piezoelectric materials, green energy, renewable energy, sustainability

INTRODUCTION

An energy crisis is now coupled with the unprecedented and accelerating impacts of climate change. Global population growth and increases in urbanization and industrialization have spurred the demand for energy across multiple sectors like transport, manufacturing and household consumption. Unfortunately, a large part of this demand is still supplied by fossil fuels - coal, oil and gas - which are environmentally harmful, finite and ever-more costly [1], [2]. The generation of huge carbon dioxide and other greenhouse gases from the burning of fossil fuels creates global warming, extreme weather, and rising seas. The carbon emissions produced from energy generation is the largest and most harmful pollutant leaving the sector in a technological, social, and ecological crisis that endangers public health, climate, and the whole of living biodiversity on the planet [3].

The immediate transition to renewable and sustainable forms of energy is now a global imperative. [4].The renewable sources of energy like solar, wind, hydro and biomass are all developing, but have limitations that include intermittency, geographic dependence, and expensive storage and infrastructure. Therefore, the unconventional exploration of other energy alternatives that can complement existing renewable systems is critical.

Promising new technologies such as Mechan synthesis and especially, piezoelectric energy harvesting technologies have the capacity to convert the wasted mechanical energies of human and environmental activities into usable electrical energies.

The term 'piezoelectricity,' has its roots in the Greek words for press (piezein) and amber (elektron), was first explained in 1880 by the Curies. They noticed that certain crystals like quartz would build up a charge when mechanical stress was applied [5].This curious effect is not one way: applying stress mechanically and obtaining a charge is reversible, and applying a charge mechanically deforms the body. For decades, this effect has been used in devices like sensors, actuators, and oscillators. The integration of materials science and nanotechnology into the field of piezoelectricity has begun to allow the harvesting of piezoelectric energy, making piezoelectricity a candidate for decentralized, sustainable energy generation [6].

The ability to convert even small vibrations and movements to energy makes piezoelectric materials crucial to contemporary sustainability efforts. Many everyday activities, including chalking a score, dribbling a football, and even foot traffic, can be tapped into to generate electrical energy. Piezoelectric devices can therefore be used as part of “smart” infrastructures, along with self-chargeable electronics and wearable tech, to form a key part of future smart cities and the IoT. Unlike piezoelectric systems, which can be localized to street lights, sensors, and even biomedical devices to power them, renewable energy systems are large and offer little flexibility [6].

Piezoelectric materials provide a novel way to enhance traditional forms of renewable energy [5]. They also assist in the environmental goals of energy conservation and sustainability. Piezoelectric energy harvesting presents opportunities to decentralized power generation while diminishing reliance on fossil fuels. This paper discusses principles, applications, and prospects of piezoelectric materials, especially on their potential to resolve the climate change issue and energy crisis.

Piezoelectric Effect and Material Basis

Some crystalline materials have the unusual feature of producing an electric charge when under mechanical pressure. They also change shape when a mechanical pressure is electrically charged. The converse of this pressure is also able to be achieved in electricity. A crystal lattice is able to maintain this feature when they are non-centrosymmetric. In the most common terminology, when piezoelectric crystals are subjected to stress, the pressure generates an electric potential difference, or polarization. This is caused by the separation of charges. The most common applications of this unusual coupling of electromechanical features are in crystals, but they also in sensors, and energy harvesting [5].

The explanation of the piezoelectric effect can be approached from the macro and micro perspectives. Crystals piezoelectric at the atomic level do not have centre of symmetry which means the arrangement of the constituent ions and the structure will not be the same

when inverted. Hence, any deformation caused by applied stress results in an imbalance which can be turned into a measurable voltage. On the macro level, embedding such materials into functioning mechanical systems which vibrate, compress, or bend, results in the generation of an alternating current which can then be harvested, rectified, and stored [5]. This is one of the reasons piezoelectricity is so useful for harvesting renewable energy as it can collect mechanical energy that would otherwise be wasted [7].

Classes of Piezoelectric Materials

Several natural and synthetic materials exhibit piezoelectric properties, each of which shows unique advantages in terms of performance, durability, and processability. The most notable classes include [8]:

- Quartz (SiO_2): Quartz is one of the oldest natural piezoelectric materials, and is still one of the most widely used in oscillator, resonators, and time keeping devices. Despite the low piezoelectric coefficient, materials thermal stability and availability in the market, quartz remains a usable for many electronic devices.
- Lead Zirconate Titanate (PZT): As a ferroelectric ceramic material, PZT is one of the most widely used synthetic piezoelectric materials due to its high piezoelectric coefficients, strength, and low cost. It is heavily used in actuators, ultrasonic transducers and energy harvesting devices. However, its environmental impacts due to the lead content in PZT have sparked the search for lead-free PZT.
- The Flexible Piezoelectric Polymer - PVDF. PVDF is effortless to manufacture and lightweight. PVDF is not as rigid as ceramic and thus is incorporated in wearable technology, biomedical sensors, and lightweight electronics. PVDF is adaptable to conform to surfaces or under body movement [9].
- Barium Titanate ($BaTiO_3$). This is a ferroelectric-piezoelectric ceramic. $BaTiO_3$ is used in capacitors, sensors, and actuators. Also because $BaTiO_3$ does not contain lead, and is therefore less harmful to the environment than PZT, it is becoming more popular.
- Gallium Orthophosphate ($GaPO_4$): Because of its strong piezoelectricity and outstanding thermal stability as a synthetic crystal, $GaPO_4$ is excellent for use in Acoustic sensors, and ultrasonic transducers for high frequency and high temperature applications.
- Rochelle Salt: Although less commonly used today due to stability issues, Rochelle salt historically played a significant role in the early development of piezoelectric devices.

Characteristics Enabling Energy Harvesting

The energy harvesting capabilities of piezoelectric materials is derived from specific physical and electrical characteristics of the materials. Materials having high piezoelectric coefficients (d_{33} and g_{33} values) show significant conversion efficiencies from mechanical stress to electric charge. For long term cyclic loading applications in transportation or industrial machines,

mechanical robustness and fatigue resistance are critical. For wearable and biomedical devices, flexibility of materials such as polymers (e.g. PVDF) is invaluable rather than the rigid ceramics. The ability to develop advanced nanocomposites and the fabrication of piezoelectric thin films has allowed significant downsizing of piezoelectric harvesters for incorporation into micro electromechanical systems (MEMS) and IoT devices.

Additionally, piezoelectric materials can be incorporated into various structures from big projects like bridges and highways to little portable electronics. Their low maintenance demand and functionality in different environments strengthen their status as energy harvesters ready for sustainable energy harvesting.

Energy Harvesting Mechanisms

Piezoelectric energy harvesting depends on the piezoelectric effect and the conversion of mechanical stimuli into electrical energy [5],[10]. Because there is a multitude of natural and anthropogenic environments composed of vibrations, movements, and impacts, energy can be captured through piezoelectric materials. Piezoelectric systems are highly versatile, ranging from the large scale of highway vehicle vibrations to the small scale of oscillating biomedical devices.

Sources of Piezoelectric Energy Harvesting

Vibration-Based Harvesting:

Vibrations are one of the most common sources of mechanical energy. Practically every automobile, train, bridge, industrial machine, and even household appliance produces some ambient vibration. Piezoelectric energy harvesters can be tuned to the frequency of these vibrations for optimized energy conversion [9],[11]. For instance, piezoelectric transducers can be embedded in roadways to capture the vibrational energy of traffic to power roadside sensors and even street lights [1].

Impact or Shock-Based Harvesting:

Sharp shocks or impacts, including the sound of footsteps on a pavement, the bounce of a football, or the stamping operations in an industry, lead to rapid and intense mechanical stress. This energy type is well suited to piezoelectric harvesters since quick and intense mechanical deformations lead to high electrical output in quick intervals [12].

Structural Stress and Oscillations:

Huge constructions like buildings, towers, and bridges bear persistent pressure and vibrations from heavy traffic, wind, and earthquakes. Using piezoelectric materials in these constructions makes it possible to do energy harvesting and monitor structural health at the same time. The energy captured can operate battery-free wireless sensors for real time monitoring [13].

Human Motion-Based Harvesting:

Industrial Monitoring: Predictive maintenance can be improved and downtime reduced by using piezoelectric harvesters embedded in machinery to power condition-monitoring sensors [10].

Environmental Sensing: For sustainable environmental management, remote

weather stations or devices used to monitor wildlife can operate using harvested vibration energy [10].

Incorporating piezoelectric materials with energy-efficient circuitry and smart algorithms for wireless transmission systems and advanced algorithms makes it possible to optimize and effectively use the harvested energy. This will enhance sustainable energy development and optionally reinforce the vision of self-sufficient intelligent infrastructures.

Fluid Flow Harvesting:

Every time there is liquid or gas flow, there are pressure changes and possible turbulence. These fluctuations can be captured and transformed [9]. Electrical energy can be created when inserting piezoelectric films or composites into pipelines or channels. These materials generate power when fluid moves and forces them to change shape. This is the case when there is smart water distribution or during other processes where there is industries [14],[15].

Environmental Vibrations:

There are energies, in the form mechanical energy, in our natural surroundings. The pressure fluctuations caused by the wind blows, the action of waves in the ocean, or the impact of falling rain are all potential sources of energy. Piezoelectric harvesters can be deployed to remote areas in these situations and provide localized power to small sensors, weather monitors, or environmental IoT systems, where there is no conventional power supply [16], [17].

Energy Conversion and Storage Process

Piezoelectric materials initially emit an alternating current (AC) which has to be processed further to be useful. The energy harvesting cycle typically following steps:

Rectification:

Piezoelectric devices produce AC signals which have to be converted to DC to store or power most electronic devices. This is achieved through the use of rectifier circuits which are usually designed with diodes.

Voltage Regulation:

The output voltage generated by piezoelectric harvesters might be unstable and reliant on the level of stress applied. Damage can occur to downstream components or storage devices, so voltage regulation circuitry is essential to ensure that output is stabilized and contained within a safe and usable range.

Energy Storage Devices:

Rechargeable Batteries: The rectified DC output can be stored in advanced batteries like lithium-ion or other rechargeable batteries. They facilitate long-term storage with controlled discharge to power portable electronics, lighting, or wireless systems.

Supercapacitors or ultracapacitors are incorporated for use cases that need fast charging and discharging capabilities. These devices are appropriate for powering sensors, actuators, and circuits that need quick bursts of energy since, while they are less energy dense than batteries, they have a much greater power density.

Charge Control and Management:

To improve system efficiency, overcharging may be avoided, charging cycles may be regulated, and additional circuitry may be incorporated, including charge controllers. This guarantees that the rechargeable piezoelectric harvesters and the batteries or piezoelectric devices are safeguarded.

Integration with Electronics and IoT

A significant advantage of piezoelectric energy harvesting is the ease with which it can be combined with today's electronics and the Internet of Things (IoT) ecosystem. Self-powered IoT devices can function independently in remote locations where batteries cannot be replaced [15],[17],[18]. For example:

- Smart Cities: Piezoelectric surfaces can energize smart illumination, surveillance, and traffic control systems.
- Healthcare: Body-worn biomedical monitors, like heart-rate sensors and glucose monitors, can harvest energy from movements to power the devices, which minimizes the need to replace the batteries often
- Industrial Monitoring: Predictive maintenance can be improved and downtime reduced by using piezoelectric harvesters embedded in machinery to power condition-monitoring sensors.
- Environmental Sensing: For sustainable environmental management, remote weather stations or devices used to monitor wildlife can operate using harvested vibrational energy.

Incorporating piezoelectric materials with energy-efficient circuitry and smart algorithms for wireless transmission systems and advanced algorithms makes it possible to optimize and effectively use the harvested energy. This will enhance sustainable energy development and optionally reinforce the vision of self-sufficient intelligent infrastructures.

APPLICATIONS ACROSS SECTORS

Initially, piezoelectric materials were considered functional materials for niche applications [2]. With the ability to convert vibrations and mechanical stress within the environment to usable electric energy, the scope for functional integration of these materials and technologies to capture energy grew considerably. Now, piezoelectric materials and technologies are integrated within the systems of numerous high energy consuming and unsustainable applications. Their integration within systems that span from civil and transportation infrastructure to biomedical engineering and devices improves not only their performance but also their energy use and overall environmental impact [19].

Transportation and Infrastructure

Transportation systems create a great deal of mechanical vibrations and dynamic stresses, making them perfect candidates for piezoelectric integration. The constant flow of vehicles and trains offers an opportunity for energy harvesting. for energy harvesting. By embedding piezoelectric transducers into highways, bridges, and railway tracks, this energy can be used to power street lights, traffic signals, toll gates, and wireless monitoring systems, thus

reducing dependence on the conventional power grid. In addition, piezoelectric sensors can be used to monitor the structural health of a bridge or pavement and help track the formation of cracks, stress, and fatigue to improve safety and decrease maintenance costs. Projects in Israel and in Japan, for example, have demonstrated piezoelectric roads and street lighting to help model smart transportation networks [17],[20]

Public Utilities

The city life offers numerous possibilities for the use of piezoelectric technology as a result of human activity. Floors that harvest energy from footsteps can be put in places with a lot of foot traffic like train stations, airports, shopping malls, and stadiums. The energy produced from millions of footsteps every day can be used to power ambient lights, security cameras, and advertising billboards. Besides energy generation, these tools also amplify public engagement. People can visualize the power generation from their foot movements, making them understand the concept of energy movement in a more practical way and use it as a tool to educate people on the value of renewable energy. Airports and sports arenas around the globe use piezoelectric tiles made by Pavegen [21],[22].

Industrial Sector

Industries involve the use of heavy equipment, machines, and vehicles which produce consistent operational vibrations. Normally, these vibrations are lost as heat or sound, but with the use of piezoelectric harvesters, they can be converted into electricity. The electricity produced can be used to power the monitoring system, remote sensors, actuators, and other devices used for predictive maintenance that are also powered by electricity like piezoelectric knock sensors which are used in the automotive industry. Ultrasonic cleaning systems are other examples which use piezoelectric transducers. Other industries also use piezoelectric actuators for advanced robotics, automated assembly lines, and additive manufacturing for precise position, control, and system to improve the overall efficiency and reliability of the system [21].

Medical Field

Given the increasing need for miniaturized, self-powered, and non-invasive devices, the medical sector is one of the most promising fields for the applications of piezoelectric. For instance, piezoelectric materials are used in ultrasound imaging systems, which generate detailed images of internal organs by converting electrical pulses into sound waves and back. Furthermore, piezoelectric implants and wearable biomedical devices are able to capture the infinite energy provided by the body during movements such as walking, breathing, and even the heartbeat, which removes the hassle of battery replacements. Examples are chest powered pacemakers and hearing aids using piezoelectric bone conduction. In addition, the integration of piezoelectric actuators on drug delivery systems will enhance the effectiveness of treatment using controlled and precise release of medication [23],[24].

Consumer Electronics

Analysis of consumer electronics show

how piezoelectric devices are incorporated into everyday licensed electronics items [21]. Every piezoelectric models, toys, smart phones, timepieces, and appliances have sound generating components that use piezoelectric devices [6]. Piezoelectric devices gain a unique role with the piezoelectric actuators as they become a part of the advanced inkjet printers which have a precise control over the ejection of ink droplets. Piezoelectric materials are also advanced as they provide nano-positioning capabilities within the AFM and STM devices which are advanced research devices. Small dimensions of these devices, reliability, and low operational power are some of the reasons for its applicability to power contemporary consumer electronics [6].

Defence and Aerospace

In the sectors of defence and aerospace, piezoelectric materials play an important role in applications that are high-performance and critical to the mission. These materials are implemented in solar systems, used for submarines detection, aircraft vibration sensor systems, and aerospace engine actuators. The piezoelectric materials in micro-robotics and adaptive munitions that are emerging in defence technologies assist self-powered sensors and precision motion control. As an example, the piezoelectric actuators in bullets that can change course assist in micro-adjustments during the bullets flight. Also, energy-harvesting systems in communication and sensor devices incorporated into military boots and gear assist compressed powered bulky mission batteries [6],[25].

Indian Scenario

India, one of the world's fastest growing economies, is dealing with two challenges at the same time - escalating energy needs and the decreasing environmental impacts of reliance on fossil fuels. Around 70% of the power generated in India is from coal, and the coal energy sector supplied India's power for many decades, while also, the greenhouse gases, air pollution and land degradation caused predominantly by coal energy. India's power needs will continue to grow fast with the rate of urbanisation, industrialisation and growing middle- class making the diversification of energy sources and the adoption of sustainable energies extremely crucial to India [26],[27].

India's Government has been proactive in responding to these challenges with ambitious goals for the adoption of renewable energy. As per the NAPCC and the National Electricity Plan, India is targeting over 200 GW of solar, wind and hydropower renewable energy capacity by 2025. This is an integral part of the NAPCC and India's commitment to the world and the Paris agreement to ensuring India's energy sector with low carbon intensity. However, while mainstream renewable have made significant progress, there is still an urgent need to explore non-conventional and decentralized renewable sources, particularly for localized applications where large-scale installations are impractical.

In this scenario, piezoelectric energy harvesting can be used as an alternative solution. Consider an urban environment where the population density and daily human activity are enormous; footstep-powered systems are a potential source of

clean electricity in places such as railway stations, airports, shopping malls, and stadiums. Piezoelectric tiles can be integrated into metro stations or public pathways and be used as power sources for LED lights, digital billboards, and wireless sensor networks. Likewise, piezoelectric harvesters can be embedded into roadways and used to capture energy from the constant vehicle vibrations to power street lighting. This approach can ease the pressure on the national grid while saving municipalities on operational costs [27],[28].

Multiple factors indicate that such systems could be market feasible in India. The first reason is urban public venues' high foot traffic creates a great deal of mechanical energy that can be captured economically. The second reason is that, in addition to sustaining smart city initiatives, the government is also providing support for the implementation of these projects, and citizens with an increasing awareness of sustainability. The third reason is that, due to the developing thin flexible piezoelectric ceramics, piezoelectric polymers and other policies strengthening the electronically controlled devices; these systems are much better economically feasible. Additionally, such systems have greater potential to provide decentralized remote power for semi-urban and rural regions where the expense of electricity is high and access to electricity is infrequent.

The adoption of piezoelectric technology in India will require demonstration of their functional reliability and real-world scenario cost effectiveness. As a proof of concept in the early stages of adoption, piezoelectric floors in busy transit hubs and harvesters in national highways can be installed. Over decades, with a reduced use of coal and cleaner energy to the India, piezoelectric energy harvesting will help with the goal of emission reduction and balance with the other renewable technology coming from solar and wind energy.

ADVANTAGES AND CHALLENGES

Incorporating piezoelectric materials into energy harvesting technologies highlights their significance during the current shift to renewable energy. These smart materials do present a number of unique benefits in comparison to traditional energy sources; however, the technical and economic issues will need to be resolved to allow greater integration, which should not be overlooked [29],[30].

Advantages

Eco-Friendly and Renewable:

Piezoelectric energy harvesting does not emit greenhouse gases, pollutants, or toxic byproducts during operation, and since it relies on mechanical energy, that would otherwise be wasted, it contributes directly to minimizing negative environmental consequences and upholding the sustainable energy continuum [30].

Decentralized Power Generation:

In contrast to solar farms or wind parks, renewable systems like piezoelectric harvesters can be integrated more freely on a smaller scale. This flexibility allows them to produce power on-site for immediate use, including roadways, public buildings, or even portable devices. Distributed energy generation

can lessen reliance on centralized power systems, strengthening energy resilience [9].

Adaptability across Applications:

The different uses of piezoelectric materials include transportation, healthcare, personal electronics, and military applications. They can be used in large constructions like highways and bridges as well as small devices like sensors and medical implants [9],[10],[30],[31].

Low Maintenance Requirements:

After the initial installation, piezoelectric systems need little maintenance. Many systems have no moving parts, which means they have lower chances of mechanical deterioration and can run for long periods without incurring major maintenance expenses. This feature is especially advantageous for use in remote areas, where regular maintenance is impossible [32].

Integration with Smart Technologies:

In general, powering low-energy devices works in tandem with the expanding Internet of Things (IoT) and the development of smart cities directly. Piezoelectricity facilitates the provision of self-powered sensors and devices, unlocking real-time data capture, and environmental surveillance, and automating the smart infrastructure [33].

Challenges

Low Power Density:

Piezoelectric energy harvesting has yet to match the power output of more established renewables-- wind and solar. It works, however, to power sensors and small electronics, LEDs and other lightweight technologies. Unfortunately, the technology has yet to reach the scalability needed for high-demand uses, including home appliances and industrial plants [34].

High Installation Costs:

Integrating piezoelectric materials into roadways, pavements, or even industrial machinery can be a costly endeavour. This is even more pronounced in developing economies, where budget constraints can limit the integration of materials and energy storage components [34].

Durability and Reliability Issues:

Many piezoelectric harvesters have to withstand extreme temperatures and repetitive stress and strain and may even have to endure mechanical degradation over time. Assessing the efficiency and mechanical failure over time is most likely to remain a perpetual engineering challenge [33],[35].

Energy Storage and Integration Complexities:

Piezoelectric systems produce small amounts of energy in short bursts and, thus, require efficient energy rectification, voltage regulation, and storage. This increases system complexity and cost when integrated with batteries or supercapacitors, which inhibits the large-scale adoption of the technology.

FUTURE PROSPECTS

Unlocking and overcoming the current restrictions will determine the future of piezoelectric energy harvesting and characterizing it as a complementary and

scalable reconciliation energy source. With current developments in materials science, electronics, and construction of sustainable infrastructure, piezoelectricity will occupy a prominent position in the energy spectrum of the future.

Development of Lead-Free Ceramics and Nanocomposites

The material choice is a big challenge in this field. The most popular material used is PZT (lead zirconate titanate). PZT is very piezoelectric and functional, but the use of lead poses environmental health dangers. The materials of focus in current research include lead-free barium titanate, potassium sodium niobate, and lithium niobate. These lead-free materials are more temperature stable, have fatigue resistance, and are more environmentally friendly. The research on polymer nanocomposites (specifically PVDF polymer and carbon nanotubes or graphene) showed significant promise [36],[37],[38]. The piezoelectric nanocomposites being lightweight and flexible form the basis of piezoelectric harvesters used in wearables.

Such materials expand the use of piezoelectric devices in biomedical implants and other more flexible and biocompatible devices.

Integration with IoT and Smart Cities

With the expansion of the Internet of Things (IoT), billions of self-powered sensors and devices will need dependable autonomous sources of power. For self-sustaining IoT nodes, piezoelectric harvesters are the best fit since they transform human activity and environmental vibrations into electric power. In smart cities, piezoelectric floors can lighten walkways, bridges with embedded sensors can autonomous monitor structural health, and roadside harvesters can fuel traffic management systems—all without dependence on centralized electrical grids. The move toward autonomous self-powered electronics perfectly matches the vision of sustainable data-driven urban development. This makes piezoelectricity essential for smart infrastructure [36].

Large-Scale Adoption in Infrastructure Projects

In the future, the potential for piezoelectric technologies, especially in infrastructure, is extraordinary. For example, the ‘smart highways’ of the future will have piezoelectric sensors that monitor real-time updates to road conditions and generate electricity from traffic. Airports, train stations, and sport facilities will use piezoelectric systems to capture and generate electricity from footsteps. Urban planners and the government are seeing the value in piezoelectric systems from an integrated design approach. This technology not only offers energy sustainability, but also real-time monitoring of the structure, leading to improved safety and operational efficiencies. Declining costs of materials and proven feasibility of initial projects will lead to piezoelectric technology becoming more widespread in road construction [22],[39],[40].

CONCLUSION

Piezoelectric materials provide new possibilities in providing alternative sources of green energy by capturing mechanical energy from vibrations, impacts, structural stresses, and even human activities. It avoids extracting

energy from the environment. The wide range of applications, including, transportation, civil structures, biomedical devices, and consumer electronics demonstrate the versatility and flexibility of the technology. They also require little maintenance and work independently without centralized energy supply systems, thus, providing a sustainable energy source for smart cities and IoT devices.

However, the low power density of the piezoelectric harvesters challenges their use as primary energy sources. Small scale or auxiliary energy applications are the best uses for these technologies. Cost, limited life, and lead ceramic pollution are all big issues for its large scale use. The use of hybrid piezoelectric and other more used renewable systems, along with reasonable priced manufacturing systems will help in the final cost of the project.

The potential incorporation of piezoelectric energy harvesting into infrastructure, smart city initiatives, and wearable technology would form self-sustaining, self-powered ecosystems that would be sustainable. Piezoelectric systems harness energy that would otherwise be squandered, which builds an attitude of taking accountability towards the environment and diminishes the amount of carbon emissions. Piezoelectric systems strive towards global sustainable development and ensure that the planet remains healthy, green and robust for future generations.

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CLICKING TOWARDS SUSTAINABILITY: THE ROLE OF SOCIAL MEDIA MARKETING AND MOTIVATIONAL DIMENSIONS IN DRIVING GREEN PURCHASE BEHAVIOR

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ABSTRACT

Social media has transformed green marketing from a tool for awareness into a catalyst for action, serving as a bridge that links promotional efforts with sustainable consumer lifestyles. This study investigates the role of social media marketing in shaping three key motivational drivers—environmental motivation, hedonic motivation, and utilitarian motivation and examines how these factors influence consumers' green purchase attitude (GPA), green purchase intention, and green purchase behavior. In addition, the moderating effect of price consciousness on the relationship between intention and behavior is explored. Using survey data from 312 participants, the findings confirm that SMM has a significant influence on consumer motivations, which serve as critical mechanisms connecting attitudes to intentions and behaviors toward green products. The results underscore the importance of understanding motivational drivers in the context of social media engagement, highlighting the pivotal role of SMM in fostering sustainable purchasing habits and promoting green consumption practices. For practitioners and managers, these insights suggest that effective green marketing strategies should combine these motivations, while also addressing barriers such as cost and convenience. By doing so, firms can strengthen consumer trust, translate positive attitudes into actual purchases, and ultimately promote both sustainable

consumption and long- term brand loyalty.

Keywords: Social media marketing, environmental motivation, hedonic motivation, utilitarian motivation, green purchase attitude, green purchase intention, green purchase behavior.

INTRODUCTION

Social media platforms like Facebook, Twitter, YouTube, Instagram, and Pinterest have gained significant popularity, influencing the lives of around 5.24 billion people globally, equating to more than 60% of the total global population (DataReportal, 2025a). Present-day consumers allocate a substantial portion of their time to interacting with social media (Windels et al., 2018), spending an average of 141 minutes per day on these platforms (Statista, 2025). As a result, social media has become an integral aspect of individuals' lives. Moreover, in India, there are an estimated 806 million internet users, with 491 million actively engaging on social media (DataReportal, 2025b). This surge in social media usage has captured the attention of marketers (Irshad and Ahmad, 2019), giving rise to a burgeoning e-commerce delivery platform known as social commerce (Liang et al., 2011). These platforms offer a vast market for individuals and organizations to promote their products (Tazeen and Mullick, 2023). Consequently, boosting businesses to leverage social media to connect with their existing and potential customers, share information, introduce new products, and advertise their offerings.

It is against this background that social media has come out as an important medium of communication in creating content, sharing ideas and views (Denegri Knott, 2006). It has changed the way consumers relate to companies especially in advertising green products and provide consumers with an entertaining purchasing experience (Singh and Sonnenburg, 2012). Over the last several years, the awareness of sustainable consumption and the use of the eco-friendly or green product has grown significantly and is designed to satisfy the needs of the current generation without compromising the needs of the future generations and nature integrity (Nguyen Thi et al., 2022). This has permanently influenced the purchase intentions and attitudes of consumers to green products (Nekmahamud et al. 2022). Due to this fact, marketing of environmentally friendly products has become a priority of many businesses in the world (Lavuri et al., 2022; Dangelico et al., 2022), and a marketing strategy (social media marketing) is used that helps consumers learn more about the environmental problems, as well as promote the marketing of green products through this marketing technique (Lavuri et al., 2023). As India becomes one of the most rapidly

developing economies, companies within the country have started paying attention to environmental issues that hold importance in consumer attitudes and thus have reorganized their enterprise models to include ecological values (Sharma et al., 2020). Such a change has resulted in an increase in the appeal of green products in the Indian consumer market, creating a favorable attitude and prospects in the recognition of such products (Singh, 2013; Paul et al., 2016; Jaiswal and Kant, 2018). Further, the Indian customers are becoming more picky when determining the products and services offered by the environmentally friendly businesses (Nath et al., 2012). They are fond of green products, quality of products and competitive pricing in their buying process (Singh et al., 2012). The trends discussed give significant emphasis to the need to carry out studies in the Indian context to appreciate green consumer behavior and preferences.

Furthermore, in spite of the rich literature on social media, consumer behavior and motivations on green products, there are a few gaps in research. To begin with, the impact of social media marketing (SMM) on this process has been a little explored topic. This paper will fill this gap by examining the effects that SMM has on the environmental motivation (EM), hedonic motivation (HM) and utilitarian motivation (UM) of consumers. Second, existing research has paid limited attention to the inclusion of diverse dimensions within environmental, hedonic, and utilitarian motivations. Specifically, dimensions such as environmental concern, perceived environmental effectiveness, novelty seeking, and adventurous spirit within environmental and hedonic motivations have been largely overlooked, as prior studies have predominantly emphasized altruistic and egoistic motives (Ghazali et al., 2017; Pop et al., 2020). Addressing this gap, the present study is the first to integrate all three categories of motivation, along with their respective dimensions, into a single model to examine their implications for consumers' green purchase attitude (GPA). Third, although the role of social media has increasingly become significant in the formation of green purchase intentions (GPI), it has not been studied on its influence on green purchase behavior (GPB). Another one is the discrepancy or attitude-behavior gap between the attitudes of consumers and the purchasing behavior. Therefore, this study seeks to fill this gap by examining the relationship between GPA, GPI and GPB. Lastly, price is a critical factor influencing green purchasing decisions that requires consideration (Ahmetoglu et al., 2014). Hence, this study incorporates the moderating role of price consciousness (PC) in the relationship between GPI and

GPB.

Considering the identified gaps, the novelty of this study lies in examining the influence of SMM on environmental, hedonic, and utilitarian motivations, which subsequently affect consumers' attitudes, intentions, and purchase behavior of green products among Indian consumers. Additionally, the study incorporates the moderating effect of PC on the relationship between GPI and GPB (Figure 1). The subsequent sections of this paper outline the literature review and hypotheses development, research methodology, research findings and discussions, and provide theoretical and managerial conclusions, also addressing the limitations and offers future research directions.

Theoretical Framework of the Study

Theory of Planned Behavior (TPB)

The TPB has emerged as one of the most influential frameworks for understanding and predicting human actions across diverse behavioral domains (Ajzen, 1991). It explains behavioral intentions through three core determinants: personal attitude toward the behavior, subjective norms, and perceived behavioral control (PBC). Attitude reflects an "individual's favorable or unfavorable evaluation of a particular action", suggesting that when people perceive their behavior as beneficial, they are more likely to engage in it (Das et al., 2023). This tendency is reinforced by a positive evaluation of possible results, which leads to the development of a greater readiness to act (Huang et al., 2021). Subjective norms are what one perceives as expectations and pressures of others upon them and this influences their actions (Arora and Varah, 2025). These are external forces that are influential in the decision making process of consumers because in most cases, people tend to make decisions that are similar to the ones they observe within their social setting (Mishra and Kaue, 2025). To add to these aspects, the perceived behavioral control is the perception of the person as to how easy or difficult the behavior is, and this aspect directly influences both intention and action (Johe and Bhullar, 2016).

TPP being a powerful tool, it has been used in various fields including tourism (Luong, 2025; Liu and Park, 2024), green consumption (Wang et al., 2024), credit card adoption (Jawaid et al., 2024), organic food (Nguyen et al., 2024), and fast fashion (Ramadani and Dwita, 2025). Nevertheless, the theory is adaptable and flexible and can incorporate other constructs to increase its power of explanation. Interestingly, the same research points out that increased motivational variables significantly contribute to pro-environmental behavior, especially when it comes to the formation

of positive attitudes towards buying green product (Alam et al., 2023; Ng et al., 2024; Hermalia and Kuswati, 2025; Rouf et al., 2025). It is based on this reality that the current paper builds on the TPB by integrating three different motivational dimensions namely utilitarian, hedonic and environmental on the foundation of social media to enhance the predictive ability of TPB. Additionally, by conceptualizing price consciousness as PBC, the model accounts for the fact that higher costs of green products may weaken the path from intention to behavior, whereas affordability may strengthen it. Thus, in the extended framework, social media marketing and motivational dimensions (environmental, hedonic, utilitarian) shape **attitudes**, while price consciousness as **perceived behavioral control** influences not only intentions but also the intention–behavior link. This integration ensures that the model remains aligned with TPB's theoretical foundations while addressing a critical real-world factor in sustainable consumption. In this way, it aims to furnish a subtle insight into the influence of the digital platforms in consumer decision-making and in encouraging sustainable consumption habits. This combination of classical theory and modern drivers of behavior, in the end, provides a more detailed framework with which to describe the complexity of consumer decisions in the digital age.

Consumer Motivation Theory

The conceptualization of motivation by Westbrook and Black (1985) is that of precipitating forces of a behavior change in order to achieve certain needs. Developing this, Tauber (1972) stated that consumers do not just shop to obtain products or services but also to fulfill certain personal and social needs. Activities that are included in personal motives are role-playing, diversion, self-gratification, learning new trends, physical activity and seeking sensory stimulation. On the contrary, social motives are related to interaction, communication, attraction to the peer group, social status, and even pleasure in bargaining (Kumar and Sadarangani, 2018; Belwal et al., 2025). This view signifies that shopping behavior goes beyond utilitarian payoffs to include the pleasure and satisfaction held in the process per se, which is frequently based on fantasy, sensory, and emotional gratification aspects that form the core of HM (Kumar and Yadav, 2021). Moreover, in the modern environment, buyers are becoming more environmentally aware and tend to buy recyclable and resource-saving products, thus, having environmental motives reflected in their buying behavior (Li, 2025; Mehmood and Khan, 2025).

Consequently, UM absorbs pragmatic and rational advantages that consumers would

have with eco- friendly products, including some features like efficiency, durability, and cost-effectiveness (Sonkar et al., 2025). Utilitarian values help consumers sustain sustainable behaviors and boost personal standards as soon as they see some actual benefits, which can be either monetary benefits, health-related benefits, or quality of life benefits (Millar et al., 2016). Conversely, HM is a result of the enjoyment, excitement, and pleasure of the shopping experience per se and not due to the accomplishment of the task (Hayat et al., 2025). Environmental motivation, however, gives an indication of the moral issues of consumers and their ecological responsibility, which direct them towards making decisions with minimal environmental impact. Therefore, this paper will be informed by the Consumer Motivation Theory by making SMM an outside influencer that elicits these three motivational areas that ultimately contribute to the level of GPA, GPI, and GPB. Providing informational stimuli that attracts utilitarian motives, experiential content that satisfies hedonic needs, and value-driven messages that strengthen the sense of environmental responsibility, SMM is at the heart of stimulating consumer motivation and closing the intention-action gap. Thus, this theory is especially appropriate to be applied to this study since it considers the multidimensionality of consumer decision-making in addition to integrating the digital effect of social media to deliver a comprehensive explanation of sustainable consumption.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

Social Media Marketing and Environmental Motivation (Environment Concerns and Perceived Environment Effectiveness)

The concept of environmental motivation (EM) is the enthusiasm or urge to practice activities that have positive environmental impacts and is categorized into two components: Environmental Concerns (EC) and Perceived Environmental Effectiveness (PEE) (Choi and Johnson, 2019). EC refer to concerns or anxieties of the environment and the issues by individuals (Kim and Choi, 2005; Singh and Bansal, 2012). According to previous research by Wu and Chen (2020), SMM campaigns that concentrate on environmental sustainability prove to be effective in increasing awareness on matters relating to the environment. These campaigns are informative, educating the consumers and improving their EC by providing informative information and appealing visuals. Moreover, SMM allows building online communities around the environmental concerns, members of

which support and share resources and encourage one another to practice sustainability (Ballew et al., 2015), thus creating awareness about EC. PEE, however, refers to how much the consumption choices, i.e. whether buying green products, they make are specific to particular environmental problems (Ellen et al., 1991).

The recent literature points out that the correlation between SMM and PEE is positive and significant. As an example, Sun and Wang (2020) established that SMM increases the perceived efficacy in making contributions to environmental sustainability, which contributes to a more favorable perception of green products. Likewise, Bushara et al. (2023) researched the restaurant sector and found out that the perceived effectiveness of followers was considerably increased with the SMM activities, including customization, entertainment, and interaction. This perceived effectiveness mediates the influence of SMM on such behaviors as purchase intentions, willingness to pay a premium, and electronic word-of-mouth (e-WoM). In addition, Ktisti et al. (2022) organized systemic review of green advertising on social media and emphasized the increased significance of green messages in digital marketing, which is more successful in boosting PEE and marketing green products and sustainable behaviors. Altogether, these results demonstrate the role of social media in contributing to the perceptions of the effectiveness of green actions, namely, by augmenting the perceived value of green practices.

Considering this discussion, it is stated that SMM is very important in the improvement of EC and PEE. Through awareness creation, delivery of empowering and educating content, social proof, and community engagement, SMM is a successful way of encouraging consumers to take more sustainable actions. On the basis of which our hypothesis are:

H1a: Social-media marketing positively influences Environmental Concern

H1b: Social-media marketing positively influences Perceived Environment Effectiveness

Social Media Marketing and Hedonic Motivation (Adventurous Spirit and Novelty Seeking) The Hedonic Motivation (HM), or intrinsic/entertainment motivation (Fuller, 2006; Muntinga et al., 2011), is associated with pleasure and play, not with getting things done. According to Boedeker (1995), it includes the experiential side of the shopping, which includes enjoyment, curiosity, fantasy, escape and delight. This motivation is further subdivided into Adventurous Spirit (AS) and Novelty Seeking (NS) (Choi and Johnson, 2019). AS is related to the worth of new and

adventurous challenges to achieve self-fulfilment and NS to the urge to discover new products when buying them (Fraj and Martinez, 2006).

The social media sites employ innovative marketing tactics to engage and appeal to the consumers (Jung et al., 2016; Alalwan et al., 2017; Wamba et al., 2017). Kumar and Yadav (2021) explored the role of online shopping motivation in sustainable consumption and they discovered that consumers who were driven by hedonic needs prioritize the shopping experience over the product itself. This makes their experience more exciting and interactive thus triggering AS through social media. Also, Jung et al. (2016) found a high correlation between AS consumers and social media advertisements and, thus, the relevance of HM to determine customer response and perceptions on social media. People who find AS in products and dynamism in life are more inclined to buy trendy products through searching SMM (Choi and Johnson, 2019). On the same line, Consumers motivated by NS and with the inclination toward unique products are greatly influenced by social media in their buying choices (Afshar Jahanshahi and Jia, 2018).

Based on these results, HM is able to push consumers to buy products that are seen as unique, new, trendy, exciting, and distinct (Fraj and Martinez, 2006) where social media plays a key role in convincing them to purchase the products/services. Accordingly, the following hypothesis are proposed to test the significant relationship between the two subdimensions of HM (i.e., AS and NS) and social media marketing:

H2a: Social-media marketing positively influences Adventurous spirit H2b: Social media marketing positively influences Novelty seeking

Social Media Marketing and Utilitarian Motivation

Utilitarian Motivation (UM) is characterized as mission-critical, rational, decision-effective, and goal-oriented (Hirschman and Holbrook, 1982; Batra and Ahtola, 1991). It indicates that shopping begins with a specific task or mission, and the benefit derived depends on the mission's completion or the efficiency of its completion (To et al., 2007). Consumers driven by UM purchase products for their utility or functional benefits (Kumar and Yadav, 2021). Social media advertisements significantly influence these consumers' product choices, attitudes toward products, perceptions, and decision-making processes from pre-purchase information gathering to post-purchase behavior (Williams and Cothrell, 2000; Mangold and Faulds, 2009; Tazeen and Mullick, 2023).

Research by To et al. (2007) conducted a study to explore internet shopping motives, focusing on UM and revealed that UM significantly influenced customers' intentions to search for information online and make purchases, indicating that utilitarian buyers are driven by a specific mission to be completed. Similarly, Putri (2015) demonstrated that online advertising content with information retrieval significantly affects utilitarian consumption on social media platforms like Instagram. Thus, customers with utilitarian values view Instagram as an effective and profitable source of product information (Fernandes et al., 2020). Consequently, when consumers find that product information meets their needs, a purchase is likely to occur. Studies also show that social media platforms facilitate connections between companies and their customers, helping to build and maintain customer relationships, as customers' experiences with products can be easily shared and propagated through these platforms (Kaplan and Haenlein, 2010; Mersey et al., 2015; Tazeen and Mullick, 2023) and can further enhance the UM of the consumers. Therefore, the current study tries to posit how SMM can enhance the UM of the consumers regarding the green products. Based on which we propose:

H3: Social media marketing positively influences utilitarian motivation

Environmental Motivation (Environmental Concerns and Perceived Environmental Effectiveness) and Green Purchase Attitude EM encompasses individuals' desire or inclination to make environmentally friendly choices in their consumption behavior, rooted in concerns for environmental sustainability, conservation, and reducing ecological footprints. It comprises two subdimensions: EC and PEE (Choi and Johnson, 2019), where, consumers with EC tend to purchase goods and services they believe have a positive impact or less negative impact on the environment (Esmaeilpour and Bahmiary, 2017). However, previous studies have provided conflicting evidence regarding the relationship between EC and attitude towards green products (Hanson, 2013; Tang et al., 2014; Yadav and Pathak, 2016; Maichum et al., 2016; Joshi and Rahman, 2017). Whereas EC has been observed as an influential predictor of consumer attitude towards green products by some researchers (Hanson, 2013; Tang et al., 2014; Yadav and Pathak, 2016; Maichum et al., 2016), others (Joshi and Rahman, 2017) have determined that EC was the least influential variable. On the other hand, PEE attempts to solve certain environmental concerns (Ellen et al., 1991), including the perceived consumer effectiveness (PCE) and perceived product effectiveness (PPE) (Choi and Johnson,

2019). According to researchers, PCE may substantially forecast attitudes (Roberts, 1996; Chao et al., 2013; Joshi and Rahman, 2019), which means that increasing PCE levels can result in the emergence of more positive attitudes and behaviors (Wesley et al., 2012). Likewise, it is also important to stress that PPE should be applied to the purchase of green products (Choi and Johnson, 2019) since the prices of the latter are usually higher than those of other goods (Brown and Wahlers, 1998). Thus, based on the discussion presented above, the present study holds that environmentally motivated individuals have a greater tendency to focus on EC and effectiveness with respect to decision-making process when it comes to green product purchases. On this premise, we have hypothesized:

H4a: EC positively influence green purchase attitude H4b: PEE positively influence green purchase attitude

Hedonic Motivation (Adventurous Spirit and Novelty Seeking) and Green Purchase Attitude

Attitude (AT) defines how the relationship is perceived as either negative or positive towards the individual purchasing the products or services (Chen and Deng, 2016). It is a psychological channel that influences whether a person will be in favour or dislikes a certain product or object (Nekmahmud et al., 2022). On the same note, GPA includes the predisposition and positive assessment of consumers with regards to purchasing products that are considered to be eco-friendly, leading to sustainable consumption behavior (Kim and Choi, 2005).

The analysis of HM has been conducted previously by dividing it into two aspects AS, and NS (Choi and Johnson, 2019; Kumar and Yadav, 2021). On the other hand, it has been analyzed by other people as a coherent whole (To et al., 2007; Irshad and Ahmad, 2019). However, there are various studies that have drilled into this. For instance, Fraj and Martinez (2006) discovered a positive correlation between consumers exhibiting HM and GPA. Later Biswas and Roy (2015), studied the influence of hedonic shopping values on consumers' GPA, revealing that consumers with strong HM are more likely to purchase green products if they find the shopping experience enjoyable and fulfilling. Similarly, Choi and Johnson (2019) examined the effect of HM towards GPB, finding that it positively influences GPA, especially when consumers perceive green products as novel and exciting. Additionally, Lin (2022) also investigated the roles of green enjoyment and HM in shaping GPI, revealing that hedonic elements such as enjoyment and emotional connection with green brands significantly enhance consumers' attitudes toward green

purchases. This suggests that the pleasure derived from these products can drive sustainable consumption behaviors. Based on the above discussion about HM and GPA, it can be argued that although extensive research has linked general HM to positive consumer attitudes towards green products, the specific impacts of AS and NS on GPA remain underexplored. Since green products often embody novelty and innovation, it is important to investigate how these subdimensions of hedonic motivation influence consumer attitudes towards purchasing such products. Understanding these relationships can offer deeper insights into consumer motivations and aid in developing more targeted marketing strategies to enhance the adoption of sustainable products. Therefore, we propose:

H5a: Adventurous spirit positively influences green purchase attitude

H5b: Novelty seeking positively influences green purchase attitude

Utilitarian Motivation and Green Purchase Attitude

Utilitarian consumers are those who gather information to accomplish a task (Babin et al., 1994; Yu et al., 2018; Kumar and Yadav, 2021). They focus on detailed product information, attributes, specifications, prices, and up- to-date information (Chiu et al., 2014). In line with this, To et al. (2007) empirically tested six utilitarian values that motivate consumer purchase attitudes. Their findings indicated that utilitarian motives positively influence consumer attitudes towards purchasing. Similarly, previous researchers (Kakkar, 2017; Choi and Johnson, 2019; Irshad and Ahmad, 2019; Redda, 2020) have found a significant relationship between utilitarian motives and consumer behavior. However, Nguyen et al. (2023) found that UM, such as practicality and cost-effectiveness, have less impact on GPA, as consumers tend to prioritize emotional and experiential benefits over functional benefits when it comes to green products.

Therefore, consumers who prioritize practicality and functionality may develop a stronger GPA when they perceive green products as offering superior utility compared to conventional alternatives. Thus, we hypothesize that:

H6: Utilitarian motivation positively influences green purchase attitude

Green Attitude- Intention -Behavior

In the Theory of Planned Behavior, “attitude” towards a behavior is one of the three core determinants of intention, reflecting an individual’s positive or negative evaluation of a specific action (Ha and Janda, 2012; Klockner, 2013; Liao et al., 2020). “Purchase intention”, in turn, refers to an individual’s inclination and decision to acquire products (here green products) in a particular situation

(Parengkuan, 2017; Akter and Islam, 2020). It captures the motivational factors that influence the GPB of the consumer (Ramayah et al., 2010). Whereas, "Purchase behavior" are the observable actions and decision-making processes which individuals engage in when acquiring goods or services. This process involves the first phase of identification of the need or desire, evaluation and the actual purchase. There are three steps in the decision-making process: input, process, and output, and purchase behavior is the real action performed at the output stage (Wilson and Tan, 2014). In the present research, it is a more complicated kind of ethical decision-making behaviour and a sort of socially responsible behaviour, by considering the green product consumption that meets needs of consumers without harming the environment and is directed to a more sustainable world (Joshi and Rahman, 2015).

Numerous studies have investigated the relationship between GPI and GPB, demonstrating that a positive attitude leads to successful purchase behavior (Ramya and Ali, 2016; Ghazali et al., 2017; Khalid et al., 2018; Uddin and Khan, 2018; Shimul et al., 2021). These researches have always indicated that positive purchase intention leads to positive purchase action. Positive attitude towards particular behaviors in consumers leads to their increased participation (Chen and Tung, 2014; Ghazali et al., 2017; Yadav and Pathak, 2017; Shimul et al., 2021). As an example, Lee et al. (2011) studied the factors that affect consumer intention to buy green products in South Korea and established that purchase intention and actual purchase of the green products showed a significant positive association. Correspondingly, Chen (2010) concluded that the green brand image will have a positive effect in green satisfaction, green trust and eventually purchase intention of green products. These results imply that attitude, intention and behavior are interrelated where each other affects others. In particular, a positive GPI will be achieved due to a positive attitude green and this will translate to actual GPB.

In light of this discussion, the current study argues that the green attitude-intention-behavior relationship demonstrates that fostering positive attitudes towards the environment is crucial for developing strong intentions to act sustainably, which in turn are necessary for actual green behaviors. By understanding and leveraging this relationship, individuals, communities, and policymakers can more effectively promote and achieve sustainable practices. Therefore, the following hypotheses are proposed:

H7a: Green Purchase Attitude positively influences Green Purchase Intention H7b:

Green Purchase Intention positively influences Green Purchase Behavior

Moderating Role of Price Consciousness (PC)

PC refers to "the degree to which the consumer focuses exclusively on paying low prices" (Lichtenstein et al., 1993), and in the current study, it is considered an important criterion for green purchasing behavior (Ahmetoglu et al., 2014). To put it simply, the price of green products significantly influences consumers' purchase decisions (Gleim et al., 2013). Previous studies have shown that consumers who demand green products are willing to pay a premium price for them as they believe in their value (Chekima et al., 2016).Nonetheless, there are contradictory opinions because Malhotra and Maheshwari (2011) stated that consumers are not ready to pay a higher price to consume green products, and the issue of price is essential in the criteria of purchase behavior (Aschemann-Witzel and Zielke, 2017). In addition, since green products can be more costly than conventional ones (Bezawada and Pauwels, 2013), other researchers have also established that PC has a negative impact on consumer intention to buy green products (Van Doorn and Verhoef, 2015; Sun and Wang, 2020; Zheng et al., 2021). Therefore, it can be argued that a price conscious consumer will never be willing to spend on the addition of special features in a product when they feel that the price of that specific product is excessively high (Lichtenstein et al., 1988). However, when consumers have sufficient resources, their ability to purchase green products increases, thereby reducing their concerns about price (Wang et al., 2018; Sun and Wang, 2020). Hence, we hypothesize that higher price concerns lead to a decrease in the relationship between GPI and GPB. Based on this, we propose:

H8: Price Consciousness negatively moderates the relationship between green purchase intention and green purchase behavior

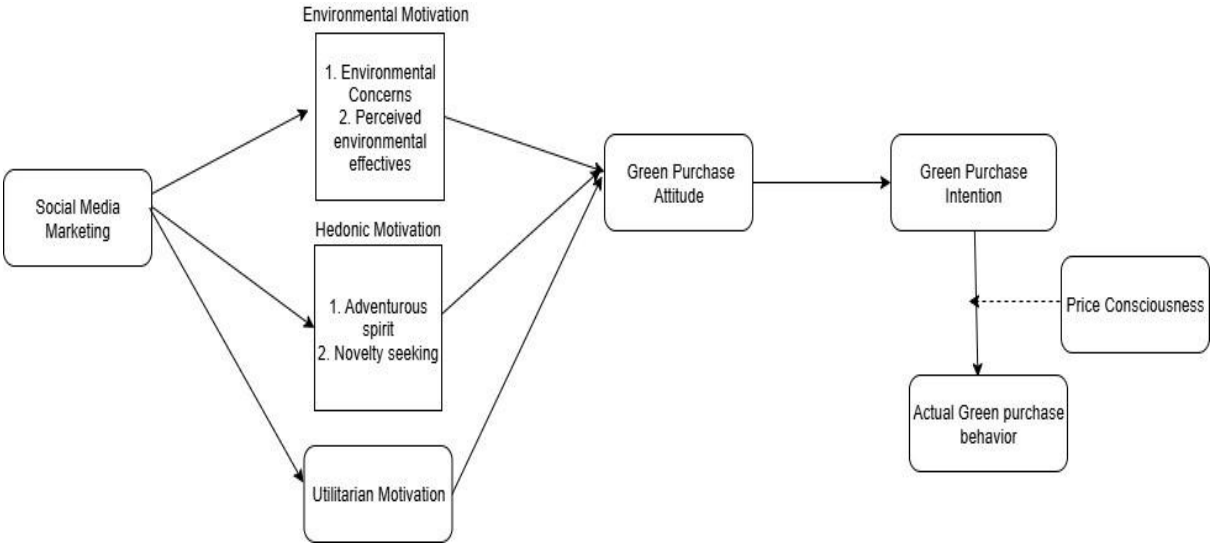


Figure 1 The Research Model

Source: Author(s) own creation

RESEARCH METHOD

Sample Design and Data Collection

India has approximately 491 million social media users (DataReportal, 2025b), making it the country with the second-highest social media penetration rate. Building on this context, the present study adopted a quantitative survey design using a self-administered questionnaire distributed among Indian consumers of green products. Data were collected through a convenience sampling technique via social media pages and groups focused on green products. The questionnaire, prepared in English, comprised four sections following an introductory note. The first section contained two screening questions to ensure respondents' eligibility based on their awareness and purchase experience of green products, with ineligible participants excluded. The second and third sections measured the latent variables of the conceptual framework, while the final section captured demographic information. Prior to the main study, a pilot test was conducted to assess reliability, with all constructs showing strong internal consistency (Cronbach's alpha > 0.7), consistent with Nunnally's (1978) threshold. Data collection was carried out between May and July 2025, yielding 410 responses, of which 78 were excluded for failing the screening criteria. An additional 20 responses were removed due to insufficient variation in answers, a step taken to mitigate potential response set bias, such as acquiescence and extreme

response styles (Baumgartner and Steenkamp, 2001; Iranmanesh et al., 2024).

The study was conducted using 312 valid data sets, which satisfied the required sample size as determined by the "*a priori sample size calculator for structural equation modelling"* developed by Soper (2024). The calculation considered nine latent variables (SMM, EC, PEE, AS, NS, UM, GPA, GPI, and GPB), 51 observed variables, an anticipated effect size of 0.15, a statistical power of 0.8, and a significance level of 0.05. The calculator indicated a minimum requirement of 109 responses, which aligns with Hair et al. (2011), who suggested that "SEM studies should have a sample size at least ten times the largest number of structural paths directed toward a single latent construct". In this study, the construct with the most indicators contained nine paths, confirming that the achieved sample size of 312 is adequate and well above the minimum threshold.

The socio-demographic characteristics of the 312 respondents are presented in Table 1. The sample was evenly split between males and females (50% each). Most respondents were aged 26–40 years (50.3%), followed by 18–25 years (33.3%), and a majority were married (53.5%). In terms of education, graduates (36.5%) and postgraduates (32.7%) formed the largest groups. Occupationally, respondents were primarily private employees (34.3%) and government employees (23.1%). Nearly half reported a monthly income of above ₹100,000 (49.4%), with 29.5% earning between ₹50,001–100,000. Green products were purchased most often once a month (34.9%) or once every three months (29.2%).

Table 1: Sample Composition

Category		**Frequency**	**Percentage**
Gender	Male	156	50.0
	Female	156	50.0
Age	18-25	104	33.3
	26-40	157	50.3
	41-50	29	9.3
	51-60	19	6.1
	Above 60	03	1.0
Marital Status	Married	167	53.5
	Unmarried	145	46.5
Education	Undergraduate	30	9.6

	Graduate	114	36.5
	Postgraduate	102	32.7
	Doctorate	08	2.6
	Professional courses	58	18.6
Occupation	Business	44	14.1
	Government Employee	72	23.1
	Private Employee	107	34.3
	Self employed	29	9.3
	Student	48	15.4
	Housewife	12	3.8
Monthly Income	30,000 and below	23	7.4
	30,0001-50,000	43	13.8
	50,001-100,000	92	29.5
	Above 100,000	154	49.4
Frequency of purchase of green products	Less than once in six months	40	12.8
	Once a month	109	34.9
	Once a week	28	9.0
	Once every six months	44	14.1
	Once every three months	91	29.2

n=312

Measurement Items

The questionnaire utilized a five-point Likert scale (1—Strongly Disagree, 5—Strongly Agree), with measurement scales adapted from prior literature (Appendix A). Social Media Marketing was measured using the scale from Yadav and Rahman (2017). The motivational scale for Environmental Concerns was adapted from Lee (2009); Matthes and Wonneberger (2014). Perceived Environmental Effectiveness was measured using the scale from Choi and Johnson (2019) and Roberts (1996). Scales for Hedonic Motivation Adventurous Spirit was adapted from Choi and Johnson (2019) and Fraj and Martinez (2006) while Novelty seeking was adapted from Choi and Johnson (2019). The Utilitarian Motivation scale was taken from Kumar and Yadav (2021). The Green Purchase Intention scale was measured using studies by Tan et al., (2025); Trivedi et al. (2018). Green Purchase Attitude was adapted from the studies of Taylor and Todd (1995); Chan

(2001), while Green Purchase Behavior was adapted from Lee (2008). Price Consciousness was measured using 6 items scale from the study of Sun and Wang (2020) and Tan et al., (2025).

Results and Analysis

Data Analysis

The present study applied partial least squares structural equation modeling (PLS-SEM) to test the proposed hypotheses, as it is a widely accepted statistical approach in recent research and is suitable for both confirmatory and explanatory modeling (Hair et al., 2017; Benitez et al., 2020). PLS-SEM was chosen given its extensive use in marketing literature (Roy and Shaikh, 2024; Zhou and Jiang, 2025). Moreover, PLS-SEM does not require the assumption of normality and is appropriate for studies with sample sizes below 500 (Hair et al., 2019), making it particularly effective for analyzing complex, prediction-oriented models (Hair et al., 2019; Sarstedt et al., 2021).

Furthermore, the study accessed common method bias (CMB) using Harman's single-factor test, which showed that a single factor explained 24.629% of the variance, well below the 50% threshold (Hair et al., 2014b). In addition, the study employed the full collinearity assessment method through the Variance Inflation Factor (VIF). The results indicated VIF values ranging from 1.324 to 1.907, all below the 3.30 cutoff (Kock, 2017), which could signal potential bias. Hence, these results confirm that the dataset is free from CMB concerns.

Measurement Model

The study applied the PLS bootstrapping method to assess all variables. Convergent validity was examined using factor loadings, composite reliability (CR), and average variance extracted (AVE) (Refer Table 2). Items with factor loadings below 0.50 (AS3, PC1) were removed, following the guidelines of Hair et al. (2014a). Both CR and AVE values exceeded the recommended thresholds of 0.70 and 0.50, respectively (Fornell and Larcker, 1981; Hair Jr et al., 2020). Internal consistency was evaluated through Cronbach's alpha, with all constructs meeting the

0.70 benchmark (Nunnally, 1978; Hair Jr et al., 2020), except for AS5 (0.676). However, this value was still considered acceptable, as α values between 0.60 and 0.70 are permissible when supported by other reliability measures (Hair et al., 2010; Roy and Shaikh, 2024).

Table 2 Reliability and validity

	Items	Loadings	Cronbach's alpha	CR	AVE
SMM	SMM1	0.735			
	SMM2	0.723			
	SMM4	0.733	0.786	0.854	0.538
	SMM5	0.741			
	SMM6	0.736			
PEE	PEE1	0.760			
	PEE2	0.798			
	PEE3	0.760	0.828	0.863	0.559
	PEE4	0.797			
	PEE5	0.774			
EC	EC1	0.897			
	EC2	0.811	0.828	0.874	0.637
	EC3	0.690			
	EC4	0.779			
AS	AS1	0.855			
	AS4	0.883			
NS	NS1	0.767	0.676	0.860	0.755
	NS2	0.798			
	NS3	0.801	0.761	0.848	0.583
	NS4	0.683			
UM	UM1	0.838			
	UM2	0.819	0.784	0.874	0.698
	UM5	0.848			
GPA	GPA1	0.760			
	GPA2	0.798			
	GPA3	0.760	0.837	0.885	0.605
	GPA4	0.797			
	GPA5	0.774			
GPI	GPI2	0.769			
	GPI4	0.788	0.723	0.843	0.642
	GPI5	0.846			
GPB	GPB1	0.813			
	GPB2	0.805	0.738	0.851	0.655
	GPB4	0.810			
PC	PC2	0.701			
	PC3	0.777			
	PC4	0.886	0.817	0.866	0.566
	PC5	0.677			
	PC6	0.701			

***Note*:** CR: Composite Reliability, AVE: Average Variance Extracted, SMM-Social media marketing; PEE- Perceived environmental effectiveness; EC-Environmental Concerns; AS-Adventurous spirit; NS-Novelty seeking; GPA-Green purchase attitude; GPI-Green purchase intention; GPB-Green purchase behavior; PC-Price consciousness

Additionally, discriminant validity was assessed using the heterotrait–monotrait (HTMT) ratio. After removing items such as SMM3, AS2, AS6, UM3, UM4, GPI1, GPI3, GPI6, and GPB3, all HTMT values fell below the 0.90 threshold, confirming construct distinctiveness (Fornell and Larcker, 1981; Franke and Sarstedt, 2019) (see Table 3).

Table 3. Discriminant Validity (HTMT)

	AS	BA	EC	NS	PB	PC	PEE	PI	SMM	UM
AS										
BA	0.739									
EC	0.189	0.136								
NS	0.700	0.822	0.063							
PB	0.162	0.111	0.711	0.110						
PC	0.668	0.880	0.064	0.775	0.097					
PEE	0.080	0.102	0.719	0.052	0.747	0.071				
PI	0.099	0.075	0.621	0.097	0.886	0.082	0.723			
SMM	0.875	0.818	0.075	0.733	0.123	0.739	0.099	0.103		
UM	0.840	0.753	0.116	0.612	0.137	0.661	0.058	0.107	0.787	
PC x PI	0.137	0.094	0.083	0.095	0.149	0.067	0.133	0.081	0.073	0.026

Structural Model

The model fit was assessed using the standardized root mean squared residual (SRMR), which produced a value of 0.057, falling below the recommended threshold of 0.080, indicating a good fit (Henseler et al., 2016). The R^2 values obtained were 0.410 for AS, 0.576 for GPA, 0.445 for GPB, 0.326 for NS, and 0.384 for UM, reflecting moderate explanatory power. In contrast, PEE showed an R^2 of 0.002, while EC and GPI had R^2 values of 0.000, indicating weak explanatory power (Hair et al., 2011; Sarstedt et al., 2014). Effect sizes (f^2) and predictive relevance (Q^2) were also evaluated following Cohen (1988), with f^2 values ranging from 0.000 (negligible) to 0.694 (large) (see Table 4). Hypotheses were tested using path coefficients (β), t-statistics, and p-values at a 5% significance level. The detailed findings of the path analysis and structural model are presented in Table 5 and Figure 2.

Table 4. Explanatory Power

Predictors	Outcomes	R-Square	f-Square
SMM	PEE	0.002	0.002
	EC	0.000	0.000
	AS	0.410	0.694
	NS	0.326	0.484
	UM	0.384	0.624
PEE			0.003
EC			0.028
AS			0.034
NS			0.304
UM	GPA	0.576	0.139
GPA	GPI	0.000	0.000
GPI			0.765
PC	GPB	0.445	0.008

Direct Effects

The study identified SMM as a predictor to influence users' motivation to purchase green products. In line with this, the study observed that SMM significantly influenced AS ($\beta = 0.640$, $t = 16.561$, $p < 0.05$), NS ($\beta = 0.571$, $t = 10.669$, $p < 0.05$), and UM ($\beta = 0.620$, $t = 17.220$, $p < 0.05$), highlighting its strong role in shaping attitudes, social norms, and user motivation. However, its effect on EC ($\beta = 0.012$, $t = 0.138$, $p>0.05$) and PEE ($\beta = –0.048$, $t = 0.517$, $p>0.05$) was not significant. Among the antecedents of GPA, NS ($\beta = 0.431$, $t = 5.951$, $p < 0.05$) and UM ($\beta = 0.316$, $t = 5.660$, $p < 0.05$) exerted the strongest positive influence, followed by AS ($\beta = 0.161$, $t = 2.930$, $p <0.05$), while EC ($\beta = –0.139$, $t = 2.087$, $p<0.05$) showed a significant negative relationship. In contrast, PEE with GPA ($\beta = 0.048$, $t = 0.700$, $p>0.05$) was non-significant. Further, GPA did not significantly predict GPI ($\beta = –0.022$, $t = 0.394$, $p>0.05$), but GPI strongly predicted GPB ($\beta = 0.652$, $t = 16.814$, $p < 0.05$), underscoring intention as a key determinant of behavior (see Table 5).

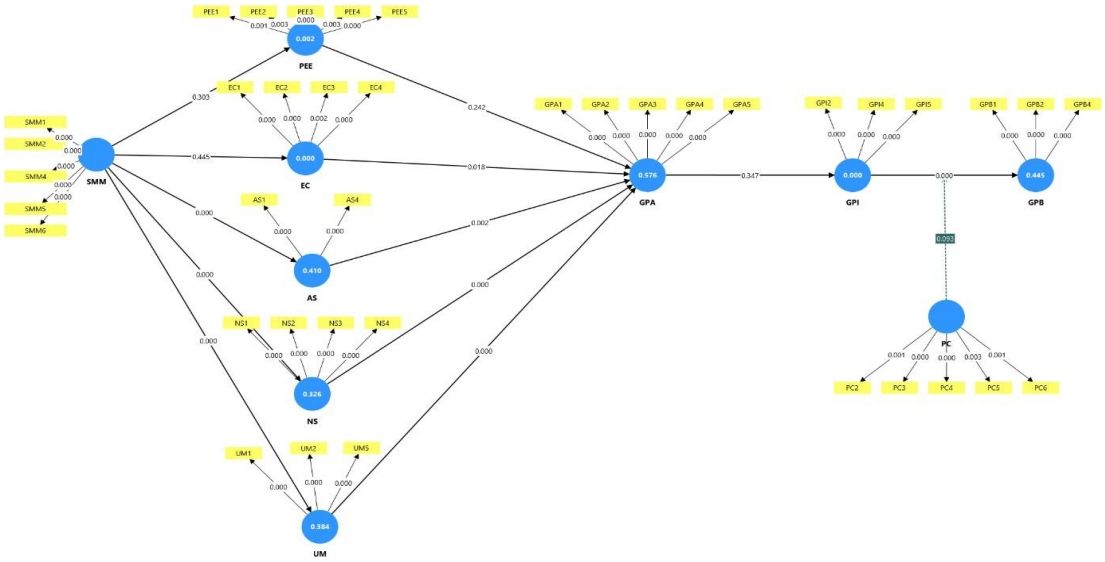


Figure 2 Structural Model

Table 5. Hypothesis Testing

Hypothesis	Paths	Path coefficient	t-Value	P-Value	Result
H1a	SMM→EC	0.012	0.138	0.445	NS
H1b	SMM→PEE	-0.048	0.517	0.303	NS
H2a	SMM→AS	0.640	16.561	0.000	S
H2b	SMM..>NS	0.571	10.669	0.000	S
H3	SMM→UM	0.620	17.220	0.000	S
H4a	EC→GPA	-0.139	2.087	0.018	S
H4b	PEE→GPA	0.048	0.700	0.242	NS
H5a	AS→GPA	0.161	2.930	0.002	S
H5b	NS→GPA	0.431	5.951	0.000	S
H6	UM→GPA	0.316	5.660	0.000	S
H7a	GPA→GPI	-0.022	0.394	0.347	NS
H7b	GPI→GPB	0.652	16.814	0.000	S
H8	PC→GPI*GPB	-0.089	1.321	0.093	NS

$p < 0.05$ is considered to be statistically significant; S-Supported; NS- Not Supported

Moderating Effect

The proposed moderating effect of PC on the relationship between Green Purchase Intention (GPI) and Green Purchase Behavior (GPB) was examined. The analysis revealed in Table 5 revels that the moderation was not statistically significant ($\beta = –0.089$, $t = 1.321$, $p > 0.05$). While the negative coefficient suggested a possible weakening of the intention–behavior link, the result confirms that PC does not exert a meaningful moderating influence on this relationship, thereby rejecting our H8.

DISCUSSION AND CONCLUSION

Drawing on the existing body of work in SMM, a noticeable gap emerges in understanding how such marketing efforts influence consumers' motivation to purchase green products. While prior research has largely examined the role of altruistic and egoistic drivers in shaping green purchasing decisions (Ghazali et al., 2017; Pop et al., 2020), limited attention has been paid to other critical motivational dimensions namely environmental motivation, hedonic motivation, and utilitarian motivation. To overcome this oversight, the current study hypothesize an integrated model that unites these different sources of motivation, evaluate their respective effects on the green attitudes of consumers, intentions to purchase green products, and, finally, their actual consumer behavior. Notably, the available literature also indicates that not every intention can be translated into practical actions, which is typically predetermined by demographic characteristics, including gender, age, income, and education (Wijekoon and Sabri, 2021). Along these lines, the paper goes a step further to provide the discourse with PC as a moderating variable in the correlation between GPI and GPB thus providing a more detailed explanation of the intention-behavior gap.

The outcomes show that the three motivational drivers, including AS, NS, and UM, predominantly define consumer activity regarding the use of SMM in green products. AS became one of the most important forces, which confirms the earlier findings that hedonic consumers are attracted to the delight, discovery, and sensual pleasure of the green buy process (Kumar and Yadav, 2021; Jung et al., 2016). The positive effect was also influenced by novelty-seeking which implies that people prefer to use something new and fresh and the highly innovative people responded to creative and trend-driven green messages in particular (Choi and Johnson, 2019; Nekmahmud, 2022; Hasudungan and Saragih, 2024). On the same note, SMM had a positive effect on UM, which contrasts with the earlier literature that indicates that both hedonic and utilitarian variables determine

consumer intentions in social media (Sharifi Fard et al., 2019; Arul Rajan, 2020). One reason that may be credited to this effect is the character of content shared on such sites. The content of social media is often informative, functional, and practical and draws the attention of consumers and supports the process of informed decision-making (Jiang, 2024). Elements such as comprehensive product descriptions, customer reviews, tutorials, comparison posts, real- time updates, promotional offers, and peer feedback enable consumers to assess the utility and performance of green products (Ngo et al., 2024; Zhao et al., 2024) . Such content enhances the perceived usefulness of information, reduces uncertainty and perceived risk, and thereby strengthens UM. In contrast, SMM demonstrated only a limited influence on EC and PEE, suggesting that exposure to green-related content through SMM does not necessarily strengthen intrinsic environmental motivation or perceptions of individual impact. This outcome may be explained by heightened consumer skepticism toward sustainability claims, largely driven by the prevalence of greenwashing practices, which diminishes message credibility and weakens motivational influence (Fang, 2024; Cg and G, 2025; Nabivi, 2025). Therefore, fostering deeper environmental awareness requires marketing campaigns that deliver credible, authentic, and strategically framed messages designed to resonate with consumers who are environmentally motivated.

The other set of hypotheses examined the relationship between motivational factors and green purchase attitude, revealing several notable findings. EM was observed to have a partial influence on GPA, with EC demonstrating a significant effect. To a large extent, these results can be related to the previous studies that have indicated that environmentally consistent consumers tend to develop more positive attitude to green consumption and thus encourage the actual practice of green purchasing (Nguyen et al., 2023; Kim and Lee, 2023). Nonetheless, in this research, EC was discovered to have the adverse impact on GPA. The first reason that can be put forward is that there is a possibility of the incidence of cognitive dissonance among highly environmentally conscious consumers. These individuals can be more conscious of the constraints of individual action as compared to larger scale systemic environmental problems and this may undermine their attitudinal basis of green purchasing. This increased level of awareness can also bring about a degree of doubt or judgement as to the true nature of green products and strengthen the argument that it will take structural level interventions to change the situations such as government controls or industry-wide

changes and not just individual level consumption decisions. Conversely, PEE exhibited a non-significant impact on GPA, which indicates that certain customers consider environmental preservation not their personal responsibility, indicating a lack of commitment or desire to take responsibility in ensuring the environment is not destroyed (Zheng et al., 2020). However, other researchers found that there is a positive effect of PEE on GPA indicating that the effect can depend on the context and can be weakened by cultural norms and social expectations and access to plausible environmental information (Hussain and Huang, 2022; Zhuang et al., 2021). Taken collectively, these results imply that even though EC is a consistent predictor of green attitudes, the perceived efficacy of individual environmental behavior might need other facilitating factors, including education, awareness campaigns, or social support that would turn it into more GPA. In addition to environmental factors, HM also demonstrated a significant positive influence on GPA. Consumers with an AS are attracted to green products for the exploratory and enjoyable experiences they offer, while novelty-seeking individuals value uniqueness and innovation, which enhances their favorable attitudes toward green consumption (Choi and Johnson, 2019; Matin et al., 2022; Lin, 2022). Together, these hedonic drivers make the consumption experience personally rewarding and reinforce the likelihood of adopting sustainable behaviors. Furthermore, UM was found to strongly shape GPA by emphasizing functionality, efficiency, and essential benefits (Matin et al., 2022). Consumers are influenced not only by EC but also by practical advantages such as health, safety, durability, and cost savings. While hedonic products can attract attention through novelty and enjoyment, it is the rational, benefit-driven appeal of utilitarian products that primarily drives positive attitudes toward green consumption (Wei et al., 2023).

While environmental, hedonic, and utilitarian motivations contribute to shaping GPA, these attitudes do not always translate into purchase intentions. The present study found an insignificant relationship between GPA and GPI, suggesting that certain intervening factors weaken this link. This outcome is consistent with prior research, which highlights the presence of multiple barriers that create a gap between attitude and behavior. For instance, Margariti et al. (2024) argue that heightened concerns over greenwashing diminish the positive influence of favorable attitudes on purchase intentions, as skepticism toward environmental claims undermines consumer trust. Similarly, Essiz et al. (2023) demonstrate that consumers with

lower risk aversion and greater subjective knowledge of green products exhibit stronger attitude–intention alignment, whereas gender differences reveal women to be more positively inclined toward green purchasing. Beyond these psychological and demographic factors, structural barriers such as perceived inconvenience, higher costs, and insufficient information further inhibit the conversion of positive attitudes into actual purchase behavior (ElHaffar et al., 2020). Henceforth, considering the above discussions, the study established a significant and positive relationship between GPI and GPB. Previous studies collectively reinforced that GPI is a robust predictor of GPB, providing empirical support that intentions can translate into actual green consumption. To be more specific, despite challenges such as consumer skepticism, GPI significantly contributes to behavior when consumers perceive green claims as credible (Margariti et al., 2024). Similarly, according to the Theory of Planned Behavior, past behavior and trust in green food not only strengthen purchase intentions but also facilitate their conversion into actual purchase behavior (Witek and Kuźniar, 2023). In line with this stronger intentions consistently predict pro-environmental actions, particularly when supported by social norms and contextual enablers, thereby reducing the intention–behavior gap (Zhuang and Liu, 2022). Collectively, these findings highlight that while intention strongly predicts green purchasing, its translation into behavior is contingent upon factors such as trust, credibility, and supportive social or contextual influences.

Finally, this study investigated the moderating role of PC in the relationship between GPI and GPB. The results revealed that PC did not significantly moderate the GPI–GPB relationship. A plausible explanation for this outcome lies in the demographic profile of the sample, which was skewed toward highly educated and higher- income consumers. Such consumers tend to prioritize sustainability over price considerations, with values, ethics, and EC playing a dominant role in their purchasing decisions. In this context, respondents appeared to demonstrate strong green values that motivated them to engage in sustainable purchases irrespective of price sensitivity. For example, a consumer committed to reducing plastic waste may opt for reusable bags even at a higher cost. This finding aligns with prior evidence that consumers with strong ethical consumption consciousness and favorable attitudes toward eco-friendly products are generally willing to pay a premium for sustainable alternatives (Sun and Yoon, 2022). In conclusion, this study underscores the importance of “value-driven consumer behavior” in the context of GM, suggesting

that ethical and environmentally conscious consumers place greater emphasis on their values than on cost considerations

Theoretical Implications

The current research contributes to the literature of green consumption in a number of ways. To begin with, it contributes to the study of consumer behavior since it combines Theory of Motivation (Westbrook and Black, 1985) and the Theory of Planned Behavior (TPB) (Ajzen, 1991) to describe the behavior in purchase of green products. Through the application of shopping motives, namely, environmental, hedonic, and utilitarian, the study offers a new understanding of sustainable consumption since these aspects are commonly identified as one of the primary factors influencing the decision-making process of a consumer (Kumar and Yadav, 2021; Choi and Johnson, 2019). Also, the research builds upon the TPB theory by looking into the connections between the motivational dimensions and social media marketing, thus fulfilling the objectives of identification of the drivers of GPB in an online environment. Second, the study is a contribution to the interdisciplinary intersection of the topics of social media and green marketing literature (Zeqiri et al., 2025; Banerji and Singh, 2024; Tan et al., 2025; Akram et al., 2024) and supports the study by showing how social media affects different consumer motives and, consequently, GPB. This research adds value to the theoretical knowledge on environmental, utilitarian, and hedonic motivation and the novelty of the study is that the interaction between these motivational dimensions and the contribution to GPB remains a relatively under-investigated area of sustainability marketing research (White et al., 2025; Rastogi et al., 2024; Bulmer et al., 2024). Evidently, social media is emerging as a critical platform for shaping GPI and GPB, highlighting the importance of both digital influence and consumer motivation.

Third, while prior research has examined the attitude–intention–behavior relationship in various contexts (Joshi and Rahman, 2019), this study bridges the "attitude–intention–behavior" gap within the framework of social media and sustainable consumption, offering a more contextualized understanding of consumer actions. Finally, the study proposes a comprehensive conceptual model and investigates the moderating role of PC, making it among the earliest to explore these dynamics. By incorporating PC as a moderator, the research extends TPB by demonstrating that financial considerations can either facilitate or hinder the translation of intentions into actual behavior. This underscores the multi-dimensional nature of consumer decision-making, where

intentions alone may not fully predict sustainable consumption unless contextual and economic factors are accounted for. Overall, the study enhances theoretical knowledge of the barriers to green purchasing behavior, emphasizing that affordability and pricing strategies are pivotal in shaping pro-environmental consumer actions (Li, 2025; Huang et al., 2025; Tosa et al., 2024).

Managerial Implications

The results of the study can also be of significant value to practitioners in the field of SMM and GM as a managerial standpoint. The findings reveal that GPA are greatly influenced by AS, NS and UM, and these attitudes influence GPB. This implies that marketers of social media should ensure that their social media campaign and content resonate with the emotional and rational aspects of consumer motivation. In particular, to appeal to consumers with high AS and NS, hedonic appeals like novelty, excitement, and enjoyment must be emphasised, whereas utilitarian appeals based on cost-effectiveness, durability, health and safety should be used to appeal to rational decision-makers. The high impact of NS shows that consumers will tend to react to marketing tactics that emphasize uniqueness of the product, innovation, and according to the trends. It is on this basis that companies ought to focus more on the messages that highlight product uniqueness and fashionable qualities so that consumers can connect green products with social status and expression of personal identity. This method can be used to reinforce GPA, and consequently purchase intentions.

However, the findings also reveal that SMM does not significantly influence EC or PEE, suggesting that traditional campaigns relying solely on eco-claims may not build intrinsic motivation. To address this, managers should adopt transparent, authentic, and credible messaging that reduces consumer skepticism about greenwashing. Incorporating influencer endorsements, third-party certifications, and user-generated content can enhance perceived authenticity and strengthen trust, ultimately narrowing the gap between consumer attitudes and behaviors. Interestingly, EC negatively but significantly influences GPA, which may indicate that heightened concern can sometimes evoke consumer fatigue or feelings of helplessness. To mitigate this, marketers should frame campaigns around collective efficacy, showing how small, individual actions aggregate to create measurable environmental impact. Communicating concrete outcomes—such as “X tons of waste reduced” or “Y liters of water saved”—and partnering with credible

sustainability organizations can reinforce consumers' confidence in the effectiveness of their actions. Similarly, the non-significant link between PEE and GPA implies that many consumers remain unconvinced that their individual contributions matter. In such cases, social media campaigns should shift the narrative from individual responsibility to shared responsibility and collective success, thereby increasing motivation through a sense of belonging to a wider sustainability movement.

Another important finding is that GPA does not directly translate into GPI, highlighting the role of structural and psychological barriers. Marketers must therefore address constraints such as high costs, perceived inconvenience, and lack of information. This can be achieved through cost incentives, subscription models, convenience-enhancing services, or consumer education initiatives that reduce barriers to action and facilitate the transition from attitude to intention. Once formed, however, GPI strongly predicts GPB, underscoring the importance of strengthening trust and credibility to nsure behavioral conversion. Managers should cultivate consumer confidence by reinforcing the ethical, environmental, and societal value of green products, thereby fostering not only purchases but also long-term loyalty and advocacy. Finally, the results show that PC does not significantly moderate the GPI–GPB relationship, suggesting that consumers with strong environmental values or higher levels of education and income are relatively less sensitive to price. This implies that firms should avoid overemphasizing discount-driven promotions. Instead, they should highlight intrinsic product value, focusing on ethical production, sustainability impact, and social contribution to attract and retain consumers who prioritize long-term benefits over short-term savings. In sum, the findings underscore the need for a balanced and integrative strategy that combines hedonic, utilitarian, and social appeals with authenticity, collective efficacy, and structural support. Such an approach can strengthen GPA, translate them into intentions, and ultimately drive sustainable consumption behaviors.

Limitations and future scope

This study provides meaningful insights into how SMM affects GPB through environmental, hedonic, and utilitarian motivations, yet it is not without limitations. The cross-sectional design constrains the ability to draw causal inferences, suggesting that longitudinal research would better capture shifts in attitudes and behaviors over time. Although PC was included as a moderator between GPI and GPB, other influential moderating factors such as income, cultural

background, or peer influence were not examined and could play a significant role. Additionally, the study's focus on a particular demographic or geographic context may limit the broader applicability of the findings. Future research could employ longitudinal or experimental approaches to determine causal links and assess the enduring impact of SMM on green consumption. Including additional predictors, such as psychological, social, and economic factors, would provide a more comprehensive understanding of GPB determinants. Investigating the effects of different social media platforms and content formats could further refine strategies for promoting green products. Finally, comparative analyses across regions or cultures would shed light on how societal and cultural variations influence green consumption, enabling more tailored and effective marketing and policy interventions.

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GREEN FINTECH & REGULATORY FRAMEWORKS: LEGAL PATHWAYS FOR CREDIBLE DIGITAL SUSTAINABILITY FINANCE

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The rapid expansion of financial technologies (FinTech) is reshaping the global financial ecosystem by opening new channels for mobilizing capital toward climate goals. Green finance instruments such as blockchain-enabled green bonds, tokenized carbon credits, and ESG- scoring tools are increasingly deployed to support projects aligned with net-zero commitments. These innovations promise efficiency, liquidity, and transparency; however, the legal and regulatory frameworks governing them remain fragmented across jurisdictions, creating risks of greenwashing, investor misinformation, and unenforceable cross-border obligations. This paper critically examines the evolving regulatory landscape of green bonds, carbon credits, and ESG-focused digital assets, with a comparative focus on India, the European Union (EU), and the United States (U.S.).

In India, the Securities and Exchange Board of India (SEBI) revised disclosure norms for green debt securities in 2023, requiring issuers to identify eligible green projects and enhance reporting mechanisms. This aligns with India's broader sustainable finance agenda and the Business Responsibility and Sustainability Reporting (BRSR) framework. Yet regulatory clarity is limited for digital platforms that tokenize carbon credits or issue sustainability-linked assets. By contrast, the EU has introduced a more comprehensive regime. The Sustainable Finance Disclosure Regulation (SFDR) and the Corporate Sustainability Reporting Directive (CSRD) impose mandatory sustainability-related disclosures, require companies to report on climate risks, and establish assurance mechanisms for ESG-related information. These measures aim to harmonize sustainability reporting and reduce information asymmetry across member states. In the U.S., the Securities and Exchange Commission (SEC) proposed climate- related disclosure rules in 2022 and is moving toward mandatory reporting of greenhouse gas emissions and climate risks. However, the proposals face significant litigation and political contestation, highlighting the challenges of advancing sustainability regulation in polarized policy environments.

A central concern across these jurisdictions is the credibility of carbon credits and tokenized environmental assets. While tokenization may enhance efficiency and traceability, unresolved legal questions remain around ownership rights, enforceability of smart contracts, and mechanisms to prevent double counting across registries. Without harmonized globalstandards, tokenized carbon markets risk undermining trust in digital green finance. Similarly, the growing reliance on ESG scoring algorithms raises legal

and governance issues related to transparency, data quality, and accountability. As highlighted in scholarship on digital dispute resolution, opaque algorithmic systems can perpetuate bias and erode confidence if not subject to oversight and auditability.

This paper argues that disclosure-based regulation alone is insufficient to ensure credibility in FinTech-enabled sustainable finance. A robust legal framework must integrate mandatory sustainability disclosures with standardized metrics, independent audits, and enforceable accountability mechanisms. Regulators should clarify rules for tokenized carbon credits, including registry interoperability, provenance certification, and property rights. Stronger enforcement against greenwashing is essential for protecting investors and ensuring the integrity of sustainability-linked digital finance. Finally, supervisory cooperation across jurisdictions is necessary to address the extraterritorial reach of digital platforms and to establish coherent global standards that reduce regulatory arbitrage.

By situating green FinTech within a comparative analysis of India, the EU, and the U.S., this paper contributes to the scholarly dialogue at the intersection of digital technology, law, and sustainability. It advances a normative argument for harmonized regulatory frameworks that balance innovation with accountability. Such frameworks would enable FinTech to serve as a credible instrument for financing the global transition to a net-zero economy while safeguarding against risks of greenwashing, misrepresentation, and systemic failures.

Keywords: Green FinTech; Green Bonds; Carbon Credits; ESG Regulation; Greenwashing; Sustainability Disclosure

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CORPORATE SOCIAL RESPONSIBILITY IN INDIAN COMPANIES-A CURRENT SCENARIO

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ABSTRACT

Business organisations has largely been seen as profit-making machines. But since the last one and a half decade, this scenario has been changing. Some business enterprises have realized the importance of giving back something to the society- the phenomenon which is widely known today as Corporate Social Responsibility (henceforth CSR). The top business leaders of the world have also recognized the need to be more responsible towards their stakeholders. The focus of CSR has shifted from charitable contributions to strategic developments in Environmental, Social and Governance (ESG) areas. All the businesses extract different resources from the society for their operations. So, it is expected from them to return something back to the society. Indian companies lack behind their foreign counterparts in this field. Though legal compulsion has been made, the real challenge lies in the successful implementation of the plans and programmes at the ground level to determine how far the effort put forward by the government has borne fruit. This research paper tries to analyse the current scenario of the CSR practices of some of the companies which are listed on the NIFTY Next 50 index on National Stock Exchange of India. These companies are highly regarded with impressive financial performances and impressive careers. This paper also offers some suggestive measures for ensuring wider scope and better compliance of CSR practices in future.

Keywords: Corporate Social Responsibility, business, stakeholders, society

INTRODUCTION

CSR refers to the self-regulation practices of the companies which can contribute significantly to the society and philanthropic activities. In India, the regulations regarding CSR came into existence with the introduction of the new Companies Act in 2013 which replaced the old one of 1956. This is the first time any act in India has mandated CSR through its regulations. Section 135 of the Companies Act, 2013 states that every company whose net worth is rupees five hundred crores or more or turnover of rupees one thousand crores or more or net profit of rupees five crores or more during the immediately preceeding financial year shall constitute a CSR board which will consist of at least three directors. It is the duty of the Board to ensure that every company who fulfills any one of the above- mentioned three criteria shall spend at least 2% of the average net profits of the three preceeding financial

years. The activities which come under the category of CSR are mentioned in Schedule VII of this Act and are as follows: -

- Eradicating hunger, poverty and malnutrition, promoting health care and sanitation
- Promoting education and employment enhancing vocational training and skills among children and young adults
- Promoting gender equality, empowerment of women, setting up of hostels, homes and old age homes for women and orphans
- Ensuring environmental sustainability, ecological balance, protection of flora and fauna, animal welfare
- Any rural development projects
- Slum area development
- Measures taken for the benefits of armed force veterans, war widows and their dependents
- Training to promote rural sports, nationally recognized sports, olympic sports and paralympic sports
- Contributions to public funded universities for the purpose of research and development in science, technology, engineering, medicine, etc.
- Disaster management activities including relief, rehabilitation and reconstruction activities.

CSR is generally subdivided into four parts. These are as follows: -

- Environmental Responsibility- This is the most common form of CSR which includes reducing pollution, greenhouse gas emissions, producing eco-friendly and sustainable products, reduce energy consumption and carbon emission, etc.
- Ethical responsibility- It refers to the practice of fair and ethical policies in an organisation. It indicates the fair treatment of all stakeholders including shareholders, investors, creditors, employees, government, etc. In this regard, many firms have processes to ensure they're not purchasing products resulting from slavery or child labour.
- Philanthropic responsibility- It involves donating a portion of a company's profits to various charitable institutions. A few companies also create their own institutions for doing philanthropic activities.
- Economic responsibility- Economic responsibility is the practice of a firm backing all of its financial decisions in its commitment to do good. The ultimate objective of any business is not just to maximize profits, but also to make sure the business operations positively impact the environment, people, and society.

LITERATURE REVIEW

Parmar and Sindhav (2024) in their article titled "Corporate Social Responsibility in India: Evolution, Compliance, And Future Directions" found that CSR has moved beyond charity to form a key business component which can help the companies in sustainable development. However, the researchers also opined that there are further chance of improvement in the scope of work and stakeholder engagements to achieve benefit to society and ecology. They also suggested future scope of research work across different sectors and states of India. Singh and Yadav (2024) in their research paper titled "A STUDY ON CORPORATE

SOCIAL RESPONSIBILITY (CSR) IN INDIA -ISSUES AND CHALLENGES" studied in details the provisions of the Companies Act, 2013 and the provisions of CSR therein and offered some suggestions. They are of the opinion that the CSR activities should be spread in the rural areas (where government do not have access) as much as possible. CSR should also be taught as a subject to build strong conceptual framework among the young adults.

Transparency and open communication can enhance the perception of a business's credibility and elevate the standards of other organizations simultaneously.

Behal and Gupta (2022) in their article titled "Reporting of Corporate Social Responsibility Practices: An Evidence from Indian BSE-Listed Companies" tested a sample of the Indian listed companies and stated that only some of the corporate social responsibility initiatives have been introduced at the firm level, and still, there are other practices, the disclosure of which has not improved, and thus, they could not report any significant results for such items. According to the authors, their research will offer significant insights for the academicians and policymakers of India to establish appropriate CSR norms to be applicable in India which will further improve CSR reporting.

Nimani et.al. (2022) in their research paper titled "THE IMPORTANCE OF CORPORATE SOCIAL RESPONSIBILITY FOR COMPANIES: THE DEVELOPING MARKET STUDY" collected primary data through a survey of managers of 40 companies of Kosovo and conducted descriptive statistics as well as inferential statistics. Their results found that introduction of CSR practices offered huge benefits to the companies. The companies which were surveyed by the researchers introduced CSR for a variety of reasons such as competitive advantage, pressure from consumers, shareholders, government, media and other stakeholders. They further opined that the sample size of companies can be increased in future and more questions can be added in the primary data to get better results.

Debnath and Chellasamy (2022) in their article titled "An Empirical Study on Issues and Challenges of Corporate Social Responsibility Activities in India" focused on the need to raise awareness about CSR, adopt a comprehensive approach to CSR, and establish clear statutory guidelines and regulations. They also urged the government, corporations, and community to merge their hands in this field to achieve greater success. They also offered some suggestive measures such as teaching CSR as a subject at schools, colleges, universities, and other educational institutions, reaching remote areas for their CSR work, informing public at large, collaborating with Non-Government Organisations (NGO), etc.

Ramgouda and Patil (2021) in their research paper titled "CORPORATE SOCIAL RESPONSIBILITY: A STUDY ON CSR PRACTICES OF SELECT INDIAN COMPANIES" opined that Government has initiated CSR to bring accountability of the companies towards their stakeholders. Business organisations should elucidate and reorient its purpose to help and support the society. The authors also suggested that companies should look into the remote villages for their CSR activities as Government is

sometimes unable to access those areas.

Newman et.al. (2020) in their research paper titled "Corporate Social Responsibility in a Competitive Business Environment" conducted a research based on panel data of 5,000 Vietnamese companies and found that a positive relationship exists between CSR engagement and firm efficiency. The overall findings of the researchers also suggested the evidence that CSR may have an independent positive impact on firm-level efficiency in Vietnam. The increase in the amount of foreign involvement in the economy will automatically bring about positive improvements in the corporate social behaviour of domestic firms through learning and spill-overs from foreign companies.

Sarkar (2019) in his research paper titled "Corporate Social Responsibility: An Indian Perspective" found out that though companies are addressing various issues such as employment generation, community development, etc. through their CSR activities, the lack of coordination among the various stakeholders at the policy framework level has remained as a major challenge to realize the full potential of this activity. He also stated that Government of India is undertaking various steps to convey to the companies the utilities of implementing strategic CSR in creating sustainable businesses.

Benchalli (2018) in his article titled "CORPORATE SOCIAL RESPONSIBILITY: ISSUES CHALLENGES AND STRATEGIES FOR INDIAN CORPORATES" conducted a qualitative study and found evidence that the ethical conduct of companies has a profound influence on the stakeholders' decisions. Companies need to be mature and realize that they must practice socially conscious policies. Companies must practice CSR not from compulsion but from passion to serve the society. Saha (2017) in her research paper titled "An Analysis of the Patterns of CSR Reporting Practices of Indian MNCs" concluded that industries within a same category did not show similar patterns of disclosure with respect to any particular parameter. In human rights parameter the author has also observed pharmaceutical, IT and energy industry-specific results. But the Companies Act, 2013 has resulted in an upsurge of the CSR disclosure practices of the companies selected in her study. Companies have become aware of almost all the parameters and this practice may improve further in the coming years. Roy and Mitra in their article titled "CORPORATE SOCIAL RESPONSIBILITY REPORTING: A REVIEW IN INDIAN PERSPECTIVE" stated that companies should also establish social goals, create strategies to accomplish those goals, put strategies into action, and then monitor, evaluate and improve their social performances. They also said that greater attention needs to be paid to CSR reporting by the top-level management. They concluded that extensive scope of research is available in this area which eventually will help the managers to quantify and evaluate the social benefits and costs.

OBJECTIVES OF THE STUDY

- To offer a theoretical concept of CSR which is present in the Companies Act, 2013.

- To present a list of the activities which fall under the categories of CSR under Schedule VII of this Act.
- To study the amount allotted and spent in CSR activities by the companies which are indexed in NIFTY Next 50.

Sample Collection and Research Methodology

This research paper is entirely based on the secondary data. Simple quantitative analysis has been done using various tables, graphs and charts. The sources of data collection are authentic financial databases, provisions of Companies Act, 2013, CSR reports, corporate governance reports, etc. We have selected the companies which are listed on the NIFTY Next 50 of the National Stock Exchange (NSE) list based on market capitalization. It represents the next rung of liquid securities after the NIFTY 50. The weights of the stocks in the index are based on their free float market capitalization and the value of all the stocks in the index relative to a particular base market capitalization value. The justification of selecting this particular sample is that these set of companies has performed better in terms of returns than the NIFTY 50 companies since its inception on December 24, 1996.

ANALYSIS

Out of the 50 companies indexed on the NIFTY Next 50 list, the CSR data of 47 companies are available. The data of Bank of Baroda, Canara Bank and Punjab National Bank are not available on public domain. Life Insurance Corporation of India did not comply with the regulations of the Companies Act, 2013. The following table shows the budgeted and actual amount of CSR spent by the 47 companies:-

Table 1: Table showing the budgeted CSR and actual amount spent on CSR of the companies listed in NIFTY Next 50 for the three preceding years.

	2024(₹ in crores)		2023(₹ in crores)		2022(₹ in crores)	
NAME OF THE COMPANIES	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR
ABB India Ltd.	21.96	26.23	15.46	10.88	9.88	5.89
Adani Energy Solutions Ltd.	0.09	0.56	N/A	N/A	0.26	0.26
Adani Green Energy Ltd.	0.45	0.46	2.49	2.49	2.76	2.78
Adani Power Ltd.	57.67	39.06	16.35	16.73	N/A	N/A
Ambuja Cements Ltd.	51.26	63.23	45.57	70.58	N/A	N/A
Avenue Supermarts Ltd.	47.04	42.57	37.23	31.11	31.29	29.13
Bajaj Holdings and Investment Ltd.	8.5	10.72	8.68	9.83	8.7	6.32

Bajaj Housing Finance Ltd.	21.31	21.21	12.68	13.32	7.67	7.67
Bharat Petroleum Corporation Ltd.	315.68	158.19	237.59	128.67	183.74	137.78
Bosch Ltd.	22.47	23.39	17.05	20.25	21.58	22.47
Britannia Industries Ltd.	46.72	46.72	41.61	41.61	38.57	38.57
CG Power and Industrial Solutions Ltd.	9	9	N/A	N/A	N/A	N/A
Cholamandalam Investment and Finance Company Ltd.	56.86	56.98	43.43	43.63	36.32	36.44
Dabur India Ltd.	34.82	36.9	32.34	33.4	30.24	31.16
Divi's Laboratories Ltd.	58.1	33.63	50.92	42.24	39.2	42.13
DLF Ltd.	30.66	26.23	21.25	21.26	15.9	15.9
GAIL (India) Ltd.	142.45	175.71	90.78	99.1	130.7	204.97
Godrej Consumer Products Ltd.	34.55	34.64	31.99	31.69	30.46	30.46
Havells India Ltd.	29.28	29.93	25.96	26.89	22.16	22.88
Hindustan Aeronautics Ltd.	109.31	119.98	97.07	103.28	81	78.27
Hyundai Motor India Ltd.	83.33	54.17	62.91	53.67	64.55	14.19
ICICI Lombard General	36.59	37.04	34.26	34.73	33.91	31.28
Insurance Company Ltd.						
ICICI Prudential Life Insurance Company Ltd.	2.64	2.65	3.88	3.96	6.85	6.82

Indian Oil Corporation Ltd.	422.42	457.71	257.55	264.03	204.77	298.29
Indian Railway Finance Corporation Ltd.	112.27	31.33	91.31	32.31	70.06	45.02
Info Edge (India) Ltd.	11.96	11.96	8.97	8.97	7.86	7.86
Interglobe Aviation Ltd.	N/A	N/A	N/A	N/A	N/A	N/A
Jindal Steel Ltd.	177.26	227.64	146.11	236.3	46.49	125.1
JSW Energy Ltd.	12.37	12.37	9.58	9.58	6.82	6.82
Life Insurance Corporation of India	0	0	0	0	0	0
Lodha Developers Ltd.	9.37	20.17	12.26	21	4.63	5.48
LTIMindtree Ltd.	80.64	80.05	67.47	67.98	39.17	38.3
Pidilite Industries Ltd.	33.3	36.4	30.49	32.8	25.37	23.52
Power Finance Corporation Ltd.	215.39	99.37	178.58	72.24	131.05	76.18
REC Ltd.	242.16	247.31	202.25	210.35	167.22	167.62
Samvardhana Motherson International Ltd.	16.8	7.01	18.28	7.2	20.17	5.77
Shree Cement Ltd.	42.24	51.34	56.03	69.99	53.01	57.54
Siemens Ltd.	37.56	37.59	28.33	28.36	26.93	27.84
Swiggy Ltd.	N/A	N/A	N/A	N/A	N/A	N/A
Tata Power Company Ltd.	0	0	0	0	2.09	2.09
The Indian Hotels Company Ltd.	3.35	4.54	N/A	N/A	1.87	1.87
Torrent Pharmaceuticals Ltd.	30.25	40.96	26.5	17.58	22.84	17.08

TVS Motor Company Ltd.	26.39	30	18.61	19	16.91	17.01
United Spirits Ltd.	18.64	20.95	18.9	19.2	7.49	17.66
Varun Beverages Ltd.	30.81	30.81	15.85	15.85	8.5	8.5
Vedanta Ltd.	107	131	112	124.88	37.5	138.12
Zydus Lifesciences Ltd.	5.2	13.31	6.3	6.3	17	17

Source:- ACE Equity NXT database

Findings: From the above table, we can get an idea about the budgeted amount and the actual amount of CSR spent by the companies of our study. Some companies did not earn profits in certain years and hence they did not fulfill the 2% criteria of CSR in those years. The sector-wise analysis (government and non-government) is given in the subsequent tables.

Table 2: Table showing the budgeted CSR and actual amount spent on CSR of the government companies listed in NIFTY Next 50 for the three preceeding years.

	2024 (₹ in crores)		2023 (₹ in crores)		2022 (₹ in crores)	
NAME OF THE COMPANIES	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR
Bharat Petroleum Corporation Ltd.	315.68	158.19	237.59	128.67	183.74	137.78
GAIL (India) Ltd.	142.45	175.71	90.78	99.1	130.7	204.97
Hindustan Aeronautics Ltd.	109.31	119.98	97.07	103.28	81	78.27
Indian Oil Corporation Ltd.	422.42	457.71	257.55	264.03	204.77	298.29
Indian Railway Finance Corporation Ltd.	112.27	31.33	91.31	32.31	70.06	45.02

Life Insurance Corporation of India	0	0	0	0	0	0
Power Finance Corporation Ltd.	215.39	99.37	178.58	72.24	131.05	76.18
TOTAL	**1,317.52**	**1,042.29**	**952.88**	**699.63**	**801.32**	**840.51**

Source:- ACE Equity NXT database

Findings:- The Government sector companies has faired poorly in the years 2023 and 2024, failing to spend their entire budgeted amount of CSR. In the year 2024, the unspent amount was 20.89% of the budgeted amount of CSR whereas in the year 2023, the deficit was 26.58%. In 2022, the actual amount spent on CSR activities was more than that of the budgeted amount. In spite of having qualified the three criteria for engaging in CSR activities, the deficit for two consecutive years do not augur well for these companies. There should be an accountability of these companies to the public and the reason for not spending the entire budgeted amount should be mentioned in the CSR report so as to ensure transparency and fairness.

Table 3: Table showing the budgeted CSR and actual amount spent on CSR of the non- government companies listed in NIFTY Next 50 for the three preceeding years.

	2024 (₹ in crores)		2023 (₹ in crores)		2022 (₹ in crores)	
NAME OF THE COMPANIES	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR	BUDGETED CSR	ACTUAL CSR
ABB India Ltd.	21.96	26.23	15.46	10.88	9.88	5.89
Adani Energy Solutions Ltd.	0.09	0.56	N/A	N/A	0.26	0.26
Adani Green Energy Ltd.	0.45	0.46	2.49	2.49	2.76	2.78
Adani Power Ltd.	57.67	39.06	16.35	16.73	N/A	N/A
Ambuja Cements Ltd.	51.26	63.23	45.57	70.58	N/A	N/A
Avenue Supermarts Ltd.	47.04	42.57	37.23	31.11	31.29	29.13

Bajaj Holdings and Investment Ltd.	8.5	10.72	8.68	9.83	8.7	6.32
Bajaj Housing Finance Ltd.	21.31	21.21	12.68	13.32	7.67	7.67
Bosch Ltd.	22.47	23.39	17.05	20.25	21.58	22.47
Britannia Industries Ltd.	46.72	46.72	41.61	41.61	38.57	38.57
CG Power and Industrial Solutions Ltd.	9	9	N/A	N/A	N/A	N/A
Cholamandalam Investment and Finance Company Ltd.	56.86	56.98	43.43	43.63	36.32	36.44
Dabur India Ltd.	34.82	36.9	32.34	33.4	30.24	31.16
Divi's Laboratories Ltd.	58.1	33.63	50.92	42.24	39.2	42.13
DLF Ltd.	30.66	26.23	21.25	21.26	15.9	15.9
Godrej Consumer Products Ltd.	34.55	34.64	31.99	31.69	30.46	30.46
Havells India Ltd.	29.28	29.93	25.96	26.89	22.16	22.88
Hyundai Motor India Ltd.	83.33	54.17	62.91	53.67	64.55	14.19
ICICI Lombard General Insurance Company Ltd.	36.59	37.04	34.26	34.73	33.91	31.28
ICICI Prudential Life Insurance Company Ltd.	2.64	2.65	3.88	3.96	6.85	6.82
Info Edge (India) Ltd.	11.96	11.96	8.97	8.97	7.86	7.86
Interglobe Aviation Ltd.	N/A	N/A	N/A	N/A	N/A	N/A

Jindal Steel Ltd.	177.26	227.64	146.11	236.3	46.49	125.1
JSW Energy Ltd.	12.37	12.37	9.58	9.58	6.82	6.82
Lodha Developers Ltd.	9.37	20.17	12.26	21	4.63	5.48
LTIMindtree Ltd.	80.64	80.05	67.47	67.98	39.17	38.3
Pidilite Industries Ltd.	33.3	36.4	30.49	32.8	25.37	23.52
REC Ltd.	242.16	247.31	202.25	210.35	167.22	167.62
Samvardhana Motherson International Ltd.	16.8	7.01	18.28	7.2	20.17	5.77
Shree Cement Ltd.	42.24	51.34	56.03	69.99	53.01	57.54
Siemens Ltd.	37.56	37.59	28.33	28.36	26.93	27.84
Swiggy Ltd.	N/A	N/A	N/A	N/A	N/A	N/A
Tata Power Company Ltd.	0	0	0	0	2.09	2.09
The Indian Hotels Company Ltd.	3.35	4.54	N/A	N/A	1.87	1.87
Torrent Pharmaceuticals Ltd.	30.25	40.96	26.5	17.58	22.84	17.08
TVS Motor Company Ltd.	26.39	30	18.61	19	16.91	17.01
United Spirits Ltd.	18.64	20.95	18.9	19.2	7.49	17.66
Varun Beverages Ltd.	30.81	30.81	15.85	15.85	8.5	8.5
Vedanta Ltd.	107	131	112	124.88	37.5	138.12
Zydus Lifesciences Ltd.	5.2	13.31	6.3	6.3	17	17
TOTAL	**1538.6**	**1598.73**	**1281.99**	**1403.61**	**912.17**	**1029.53**

Source:- ACE Equity NXT database

Findings

From the above table, it is clear that the non-government companies has exceeded our expectations and performed exceptionally well in CSR activities. We can see that in the preceeding three financial years, the actual amount spent by these companies in CSR activities is much more than the budgeted amounts. These compliances are due to charitable purposes, legal compulsion and social obligations.

CSR activities of the companies

All the companies listed on this index has constituted CSR committees of their own which are by their Board of Directors respectively. All the companies spend their money on the areas which are stated as follows:-

- Vocational skill development programs.
- Partnerships to preserve & promote indigenous heritage, culture, arts and handicrafts.
- Disaster relief and rehabilitation programmes for the people who are affected time and again by various natural calamities.
- Income-generation and livelihood enhancement programs through job training.
- Community development programmes such as setting up of community health centers in rural areas, ensuring social and financial inclusion, establishing toilets, providing sanitary napkins for women, etc.

The committees have the following functions to perform:-

- To formulate and recommend to the Board, the Corporate Social Responsibility and sustainability (ESG) Policy and monitor them from time to time.
- To formulate and recommend to the Board, an Annual Action Plan for the Company and have an oversight on its implementation.
- To recommend the amount of expenditure to be incurred on CSR activities.
- To enable Board of Directors the oversight on sustainability (ESG) related policies, strategies and activities of the Company.
- To advise the management on potential business implications of sustainability/ ESG performance.

The amount spent in CSR are closely monitored and audited in an accountable and transparent manner so as to prevent any misappropriation of funds. The CSR committees periodically review the CSR project reports and they are presented annually to the Board of Directors.

Suggestions and recommendations

- During the study, it is found that the public sector banks and insurance companies which are listed in this index did not comply with the regulations. In spite of making profits in their last three financial years, they refrained from doing any CSR activity which totally violates the Companies Act. Every company are bound to give something back to the society. These companies should immediately be made answerable to their stakeholders for their non-compliance. The policymakers should

take stern action against them so that in future, no other company can do the same.

- Most of the CSR projects of the companies focused on the urban areas. They should focus more on developing the remote villages by undertaking various projects for increasing the standard of living of those people which are not always accessible by the government. The upliftment of the rural economy can only improve our overall growth.
- The government companies should clearly state the reasons for better disclosure their inability to spend their entire budgeted amounts of CSR. They should also strive for better accountability and spending entire amount of CSR from the next financial years.
- Most of the people see CSR as a legal responsibility done only for philanthropic activities. But this is not the case. CSR should be seen as a strategic tool for the companies through which one can competitive advantage over others. This aspect of CSR should be imparted to all the stakeholders, especially common people.

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JOB INSECURITY AND STRESS IN THE AGE OF ARTIFICIAL INTELLIGENCE: CAN RESILIENCE HELP?

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ABSTRACT

In the current competitive corporate environment, job insecurity and stress have emerged as significant concerns for employees. An examination of current research on resilience, job insecurity, and stress shows that there is limited investigation into how resilience affects the connection between job insecurity and stress. This research aims to examine how resilience influences the relationship between job insecurity and stress. Data was collected from 258 employees working in the Indian IT sector. The findings suggested moderating impact of resilience on the association between job insecurity and perceived stress. The study concludes by discussing the theoretical and practical significance of these results.

Keywords: Job Insecurity, Stress, Artificial Intelligence, Resilience

INTRODUCTION

Artificial intelligence has opened up new opportunities for efficiency, but it has simultaneously intensified concerns about job security for workers worldwide. According to a report by *The New York Times*, AI could impact up to 300 million full-time jobs (Kessler, 2023), while McKinsey highlights that 45% of jobs are susceptible to automation. In today's highly competitive corporate environment, job insecurity and related stress have become increasingly critical issues for the workforce. With the ever-changing world economy, organizations are encountering steep competition from the competitors and are hit by the weakening demand of products and services. Most of the organizations are bleeding and find their sustenance route through cost minimization. Particularly the service sector resorts to cost minimization through downsizing. In such a scenario, job insecurity prevails amongst people. As a result of the job insecurity working population becomes venerable to stress. Workplace stress results in high absenteeism, high labor turnover, poor timekeeping, low morale, poor motivation, increased ill-health, accidents, and adversely affects performance (World Health Organization [WHO] 2024,). It does not stop at these only. As stress steps into the environment of work, it further makes one vulnerable to get short-tempered, disturbed sleep, erratic concentration, stomach ailments, and headache. As stress further assumes chronic proportions, it leads the individual to conditions like insomnia, high blood pressure, anxiety, and significantly weakens the immunity. Serious health conditions like obesity, depression, and heart diseases too develop with stress. The problem aggravates when the person under the influence stress engages in unhealthy activities like being abusive, indulging in overeating or eating unhealthily, taking recourse to drugs,

alcohol, or smoking as means to deal with the problem (American Psychological Association [APA], 2020). Previous research hasn't paid sufficient attention to how resilience affects the link between job insecurity and stress during times of fast technological change. This study looks at whether resilience can help reduce the stress caused by job insecurity.

LITERATURE & HYPOTHESES

Role of Job Insecurity on Stress

Scholarly interest in job insecurity began over three decades ago with the influential publication by Greenhalgh and Rosenblatt (1984). In this foundational work, the authors aimed to consolidate existing research on the causes, consequences, and nature of job insecurity. Building on this foundation, Vander Elst and colleagues (2014) describe job insecurity as an unwanted possibility of losing one's current job in the future, along with the related fears or concerns about this potential job loss. This suggest that people experience job insecurity in their own personal way (Sverke et al., 2002), and it's something they don't choose (De Witte, 2005; Greenhalgh & Rosenblatt, 1984; Sverke et al., 2002). It affects both how they think and how they feel.A thorough review of the research on job insecurity reveals a general consensus among scholars that it is essentially a subjective experience. This subjectivity arises from how individuals perceive and interpret their actual work situation. Even similar objective circumstances can lead to varying levels of uncertainty among employees, depending on how they understand their environment (Klandermans & Vuuren, 1999; Sverke et al., 2002).

Also, it was found that employees who feel their job is not secure don't want to quit on their own. Instead, they're worried about being fired or losing the good benefits that come with the job (Sverke et al., 2002). It is pertinent to note here that those employees who are working on temporary basis or those who chose to work on temporary contractual arrangement are not affected by job insecurity. Employees engaged in contractual arrangement are not affected by job insecurity because they do not feel that there is any breach of contract with the employer in the event of losing the job or in anticipation of losing the job and its benefits. In summary, temporary workers typically do not expect job security. Therefore, those employed under contractual agreements are less impacted by feelings of job insecurity (Vander Elst et al., 2014). On the other hand, permanent employees see job security as a key promise from their employer in return for their loyalty. When they feel their job might be at risk, they believe this promise has been broken, which makes them feel more insecure about their job.

Feeing of insecurity about future possibility of job loss is the central component of job insecurity experience. Huang et al. (2012) have clearly and precisely distinguished between cognitive and emotional job insecurity. Huang et al. (2012) defined cognitive and affective job insecurity as "awareness of the possibility of job or benefit loss; affective job insecurity is the emotional experience of being worried or emotionally distressed about these potential losses" (p.752). In simple terms, cognitive job insecurity indicates an employee's thinking or awareness that there is probability of loosing the current job or its benefits whereas affective job insecurity reflect the worries and emotional reactions resulting out of the threats of probable chance of losing the job. De Witte (2005) argues that even though there is a subtle theoretical difference between cognitive job insecurity and affective job insecurity in the job insecurity experience, however, both the components are intertwined while employees experience job insecurity as a whole. De Witte (2005) argues that simply being aware of or considering the possibility of losing one's job leads to anxiety,

making employees emotionally sensitive to the negative effects of job insecurity.

De Witte (2005) divided the reasons for feeling unsure about a job into three groups: big-picture factors, personal background, and personality traits. Big-picture factors are things like the overall economy, how many people are unemployed in an area or country, and changes happening in a company. Individual background traits refer to demographic and job-related aspects such as an employee's age, tenure, and position within the company, these are considered objective factors. Personality traits, like how much control someone feels they have and how often they feel negative emotions, affect how they see job insecurity. This means feeling insecure about a job is more about how a person feels than the actual situation. Since these traits differ among people, they impact perceptions of job insecurity in several ways.

Researchers have also found some personal things that affect job insecurity. These include work values, how people explain events (attribution styles), the need for stability, and whether they feel in control of their lives (locus of control), perceived job significance, and feelings of powerlessness when facing potential job loss (Mauno et al., 2001; Elst et al., 2011). These factors act as intermediaries in shaping overall understandings of job insecurity. Essentially, job insecurity is an individual's perception of the chance of losing their job, which can vary greatly from one person to another (Shoss, 2017). It is subjective and not always tied to actual risk (Shoss, 2017). Stress arises when people feel they lack the resources to handle challenges (Lazarus & Folkman, 1984), and it depends on cognitive appraisal. Coping strategies and personality traits influence how stress is experienced (Costa & McCrae, 1990). When individuals struggle to cope with job insecurity, it can heighten stress, making effective coping crucial in managing its psychological impact.

Hypothesis 1. Individuals experiencing job insecurity will also experience stress.

Moderating role of Resilience.

Most research on resilience come from clinical psychology. The first study of resilience started in the 1970s. Researchers were surprised to see that some children who faced long-term stress did not have problems growing up (Garmezy, 1971, Werner & Smith 1982). These surprising results made researchers curious to learn what helps people stay strong mentally. Garmezy's 1971 study about children with parents who had schizophrenia is very important in resilience research. Masten and Reed (2002) studied teenagers who did well and stayed strong even when they faced immense problems. They say that people who are resilient can handle tough times and risks better. The idea of resilience as a personal strength has been extended. Researchers from different fields have looked at how resilience works at work. Studies from psychology show that resilience is important and useful in work settings. According to Luthans (2002a), resilience at work means being able to bounce back from hard times, conflicts, failures, or even from good things like progress and more responsibilities. Also, Fredrickson and Joiner (2002) found that resilience helps people grow emotionally in a positive way.

Luthans (2002a) also emphasizes that resilience encompasses the capacity to manage both challenges and positive developments. Scholars such as Fredrickson and Joiner (2002) and Richardson (2002) assert that resilience involves adaptive responses to both negative and positive experiences. Additionally, resilience has been shown to be a valid and measurable psychological construct, as supported by research from Block and Kremen (1996) and Wagnild and Young (1993).

The scientific study on the protective factors of resilience is a paradigm shift in resilience research (Jessor, 1993). Resilience protective

factor refers to those factors and circumstances that positively moderates the negative effects of risk and helps an individual to successfully adopt to the given situation (Masten, 1994). Werner (1993) categorized protective factors into within individual factors (outgoing, active, autonomous, positive self-concepts), in family factors (close bond emotionally stable parent), and in community factors (support from peers and elders). These factors in combinations help individuals to successfully adopt to challenging situations.

Risk factors also refers to "vulnerability factors" (Kirby & Fraser, 1997), Drug abuse, alcoholism (Sandau-Beckler et al., 2002), experiencing violence (Qouta et al., 2001), continuous exposer to stressful event and experiencing burnout (Baron et al., 1996; Smith & Carlson, 1997), unemployment, under education, and poor health (Collins,2001) are the major risk factors that make an individual susceptible to poor adaptation in challenging circumstances and inhibit people from displaying resilience. It's important to understand that just having risk factors doesn't always mean things will go wrong. In fact, dealing with risk factors can help people become stronger and more resistant to problems. Cowan and colleagues (1996) explain this by saying that the real issue isn't the risk itself, but how the risk leads to problems through certain processes. They compare this to getting small doses of a disease through vaccines, which helps build resistance to that disease. So, when risks are correctly identified and managed using the right resources, people can better handle tough situations. Resilience, a key psychological strength, enables individuals to adapt and recover from setbacks (Masten & Reed, 2002; Coutu, 2002). In today's volatile work environment, such adaptability is vital for success. As job insecurity is dynamic and can be addressed through interventions (Abildgaard et al., 2018), resilience may buffer its negative impact. The Conservation of Resources theory (Hobfoll, 1989) posits that mental strengths, like resilience, can help protect people from stress at work. Conceptual model (Figure 1).

Hypothesis 2. Resilience will weaken the connection between job insecurity and stress, especially for those individuals with high resilience.

METHODOLOGY

Sample and procedure

This study was conducted on a sample of 258 respondents belonging to three large information technology companies operating in eastern part of India. Currently Indian IT sector is facing unprecedented intense competitions. Indian IT companies are increasingly resorting to cost optimizations measures in shape of workforce downsizing measures. This study included 249 male and 9 female respondents. The age of respondents ranges from 26 to 49 years. Work experience of the respondents ranged from 5 to 18 years. Majority of respondents (74 %) had graduate degrees and rest 26 % of the respondents had post graduate degrees. To reduce common method bias, confidentiality was ensured, following Podsakoff et al. (2003).

MEASURES

Job insecurity was measured using a set of 4 questions from Vander Elst et al. (2014). The set of questions was reliable, showing a Cronbach's alpha of. 834.One example item from this scale is: "I feel insecure about the future of my job." Stress symptoms were evaluated using a stress symptom scale developed by Lovibond and Lovibond (1995). Seven items from this scale were selected, and responses were recorded. One example item from this scale is: "I found it difficult to relax." The scale showed a Cronbach's alpha of 0.837. Resilience was measured using the Wagnild and Young (1993)

scale. The scale showed a Cronbach's alpha of 0.848.

RESULTS AND DISCUSSION

The primary aim of this study was to examine the moderating role of resiliency on the relationship between job insecurity and stress. Study hypotheses were examined with the help of correlation, regression, and structural equation modeling (Joreskog & Sorbom, 1993). We posited in Hypothesis 1 that individuals experiencing job insecurity will also be experiencing stress. As evident in Table 1, job insecurity shared significant association with stress (r= .503, p < 0.01). It can be observed in Table 2 that job insecurity predicated stress with (β =.030, p<.01) path estimate. These results suggest that hypothesis 1 is supported. Further, it was proposed in Hypothesis 2 that resiliency would be negatively correlated to stress. As seen in Table 1 that resiliency shared a negative association with stress (r= -.204, p<0.01). Therefore, hypothesis 2 is also supported. We assumed in hypothesis 3 that resiliency would moderate the strength of the relationship between job insecurity and stress. As can be seen from the path estimates in Table 2, resiliency moderated the strength of the relationship between job insecurity and stress (β= -.023, p < 0.01). Further, as depicted in Figure 2, levels of resiliency moderated the strength of the relationship between job insecurity and stress. Given these findings hypothesis 3 is supported.

Tables1. Descriptive statistics and correlations.

Variables	Mean	SD	1	2	3	4	5	6	7	8
1. Respondent Age	35.48	6.488								
2. Education	3.2713	.47098	-.135*							
3. Gender	.03	.184	-.016	.025						
4. Work experience	10.80	8.259	.967**	-.136*	-.026					
5. Social desirability	.3140	.46500	.060	.000	.008	.057				
6. Job insecurity	.0194	.13812	.047	.038	-.027	.034	.026			
7. Stress	.0126	.10843	.064	.009	-.022	.098	-.002	.503**		
8. Resilience	4.7710	.55935	-.032	.037	.084	-.028	.011	-.148*	-.204**	

Note: *$p < .05$; **$p < .01$

Table 2. Moderating model path estimates

Predictor	Path	Outcome	Estimate	S.E.	C.R.	P
Job Insecurity	→	Stress	.030	.006	5.488	**
Resilience * Job insecurity	→	Stress	-.023	.002	-9.600	**

Note: **$p < .01$

Figure 1. Hypothesized model (Authors own source)

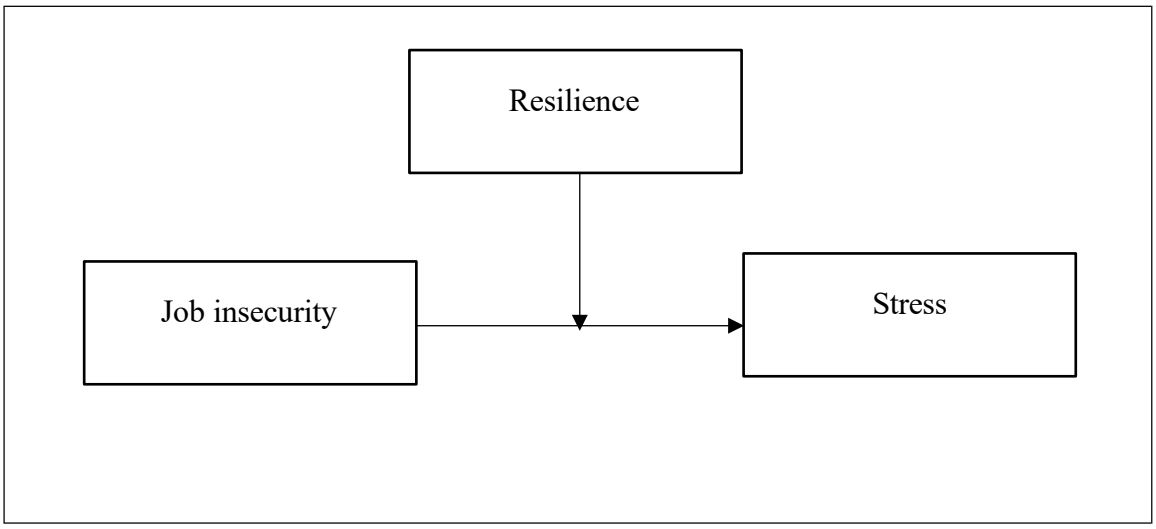
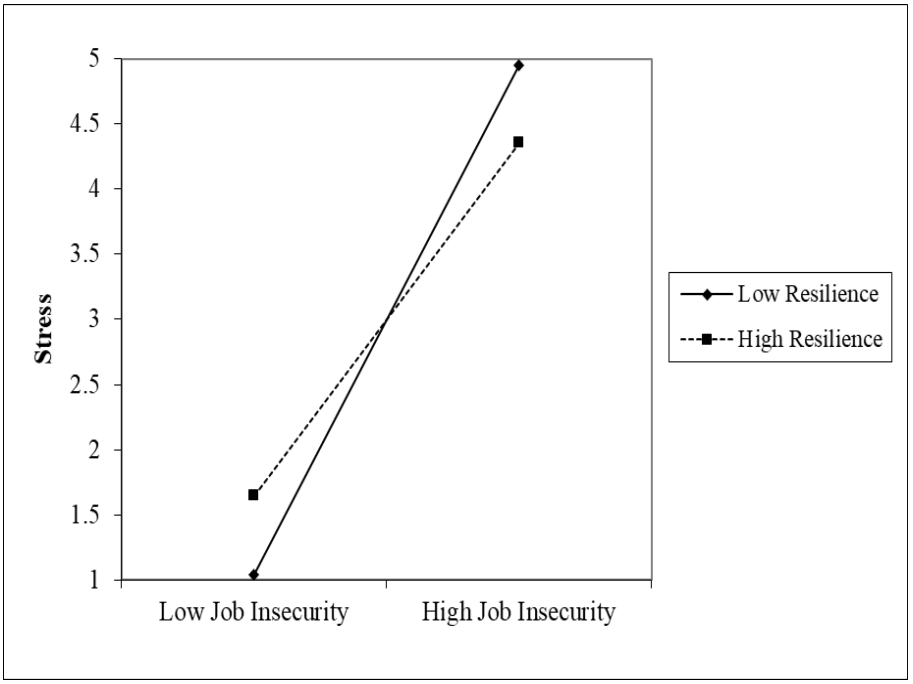


Figure 2. Moderating effect



This research shows that the resiliency, which was first studied in Western cultures, is also true in other cultures. The study found that resiliency helps people handle job insecurity and stress, even in non-Western settings. It suggests that being resilient can reduce how much stress and job insecurity perception. Helping workers become more resilient at work can lower their stress and improve their performance, job satisfaction, and willingness to help others in the organization.

Limitations and scope

This study was based on a sample of 258 participants working in the IT sector. Further, studies could be conducted with a larger sample involving respondents from service and manufacturing to demonstrate enhanced generality of findings. Furthermore, this study design was cross- sectional in nature. Therefore, absolute causality cannot be ascertained. Therefore, addition studies employing longitudinal and experimental designs may be conducted to evaluate the causal relationships of stress, job insecurity, and resilience.

Theoretical implications

Resilience can be developed through interventions (Luthans et al., 2017). As it helps reduce stress, HR professionals can implement resilience-building strategies to boost performance, well-being, job satisfaction, and retention. By checking how resilient employees are, how worried they feel about their jobs, and how stressed they are, these initiatives will help create a positive work environment. This can help keep employees healthy and reduce the negative feelings caused by job insecurity. The findings of this study suggest theoretical and managerial implications. Survey of resiliency literature depicts that resiliency can be increased through appropriate interventions (Luthans et al., 2017). Theoretically, drawing on the insights from this study in terms of the moderating influence of resiliency in diminishing the influence of job insecurity on stress, further experimental studies aiming at examining the impact of resiliency on stress can be attempted in future to establish causality.

Managerial Implications

In terms of managerial implications, as this study found that resiliency had a favorable influence on decreasing stress, human resource professions can use this understanding to implement resiliency interventions to reduce stress in workforce. Increase in resiliency is likely to motivate employees for higher performance and would eventually enhance workforce well- being. Moreover, enhancement in resiliency can help to enhance job satisfaction and also would help in retention of talented employees. As resiliency significantly decreases the detrimental influence of job insecurity on stress, in these lines, psychometric assessment of resiliency, job insecurity and stress can be conducted to assess the improvement areas needed to foster the overall employee well-being. Existing research on resiliency indicates that it positively impacts work outcomes, so human resource professionals can leverage this understanding to encourage employees to become resilient, and aid in supporting employees for long-term organizational growth.

CONCLUSION

Work-related stress and job insecurity are significant issues in the modern work environment. Our study shows that resilience can help reduce stress. These challenges are widespread in today's rapidly changing workplace, and their prevalence, along with the resulting impacts, pose serious challenges for today's organizations. Our research demonstrated that people's resilience, as a positive psychological resource, diminishes the influence

of job insecurity on stress perceptions in work settings. Our research findings, in particular, showed that individuals experiencing higher levels of resiliency experience less stress. Therefore, efforts towards nurturing and maintaining resilience in the workplace would assume great significance for management practitioners.

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GENDER EQUALITY IN RECRUITMENT FOR SUSTAINABLE EMPLOYMENT: A SYSTEMATIC REVIEW

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ABSTRACT

Getting equal opportunities in recruitment makes people feel welcomed and valued. It also helps them feel fairly represented, and this forms the base for sustainable employment. This study is a systematic review of 48 peer-reviewed papers on gender equality in recruitment for sustainable employment. The review uses the SPAR-4-SLR method to keep the process clear and reliable. Using the TCM (Theory, Context, Methodology) framework, the study develops a conceptual framework to illustrate how theories, contexts, and methods have been employed in previous research. This approach helps to find gaps in the research and suggest a future research agenda. The findings indicate that bias and stereotypes continue to influence recruitment practices. At the same time, policies, artificial intelligence tools, and representation can support diversity, but only to a limited extent. The study also gives practical suggestions for managers, HR professionals, and organizations to make recruitment more inclusive and supportive of gender equality and sustainable employment.

Keywords: Gender Equality, Recruitment, Sustainable Employment, Sustainability, Hiring, Reduced Inequality

INTRODUCTION

Gender equality in recruitment remains a persistent challenge despite ongoing efforts to promote diversity and inclusion in organizations. Field experiments demonstrate that discrimination in hiring continues to affect women and minority groups. For example, a classic study showed that job applicants with White-sounding names received 50 percent more callbacks for interviews than equally qualified applicants with African American–sounding names, highlighting the influence of implicit bias in recruitment (Bertrand & Mullainathan, 2004). Beyond racial cues, gender stereotypes also shape recruitment outcomes. Role Congruity Theory explains that prejudice arises when there is a mismatch between gender stereotypes and the perceived requirements of leadership or professional roles (Eagly & Karau, 2002). Women are often associated with communal traits such as warmth and nurturing, while leadership and many high-status jobs are associated with agentic traits such as assertiveness and dominance. This incongruity can result in women being judged as less suitable for stereotypically male-dominated roles. Recruitment practices themselves may inadvertently reinforce inequality. One pathway is through gendered wording in job advertisements. Gaucher, Friesen, and Kay (2011) found that job ads containing masculine-coded words (e.g., “ambitious,” “dominant”) reduced women’s sense of belonging and interest in applying, whereas feminine-coded words (e.g., “supportive,”

"interpersonal") did not have the same exclusionary effect on men. Similarly, a meta-analysis confirmed that gender stereotypes affect hiring decisions across contexts, with women more likely to face bias in male-typed roles (Koch, D'Mello, & Sackett, 2015). Recruitment systems that rely on traditional evaluation processes can also amplify bias. However, research shows that structured decision-making can mitigate disparities. Bohnet, van Geen, and Bazerman (2016) found that when candidates were evaluated jointly rather than separately, performance information outweighed gender stereotypes, reducing biased outcomes. This suggests that careful design of recruitment systems can play a role in promoting gender equality.

RESEARCH PROCESS

The SPAR-4-SLR framework is well-suited for this review because it provides a transparent and systematic process for carrying out a structured literature review. The topic of *gender equality in recruitment* is broad, involving multiple theories, methods, sectors, and countries. Using SPAR-4-SLR ensures that the review is rigorous, unbiased, and replicable, and it also helps move from a very large set of search results to a smaller, more focused group of high- quality studies that can answer the research question.

SPAR-4-SLR

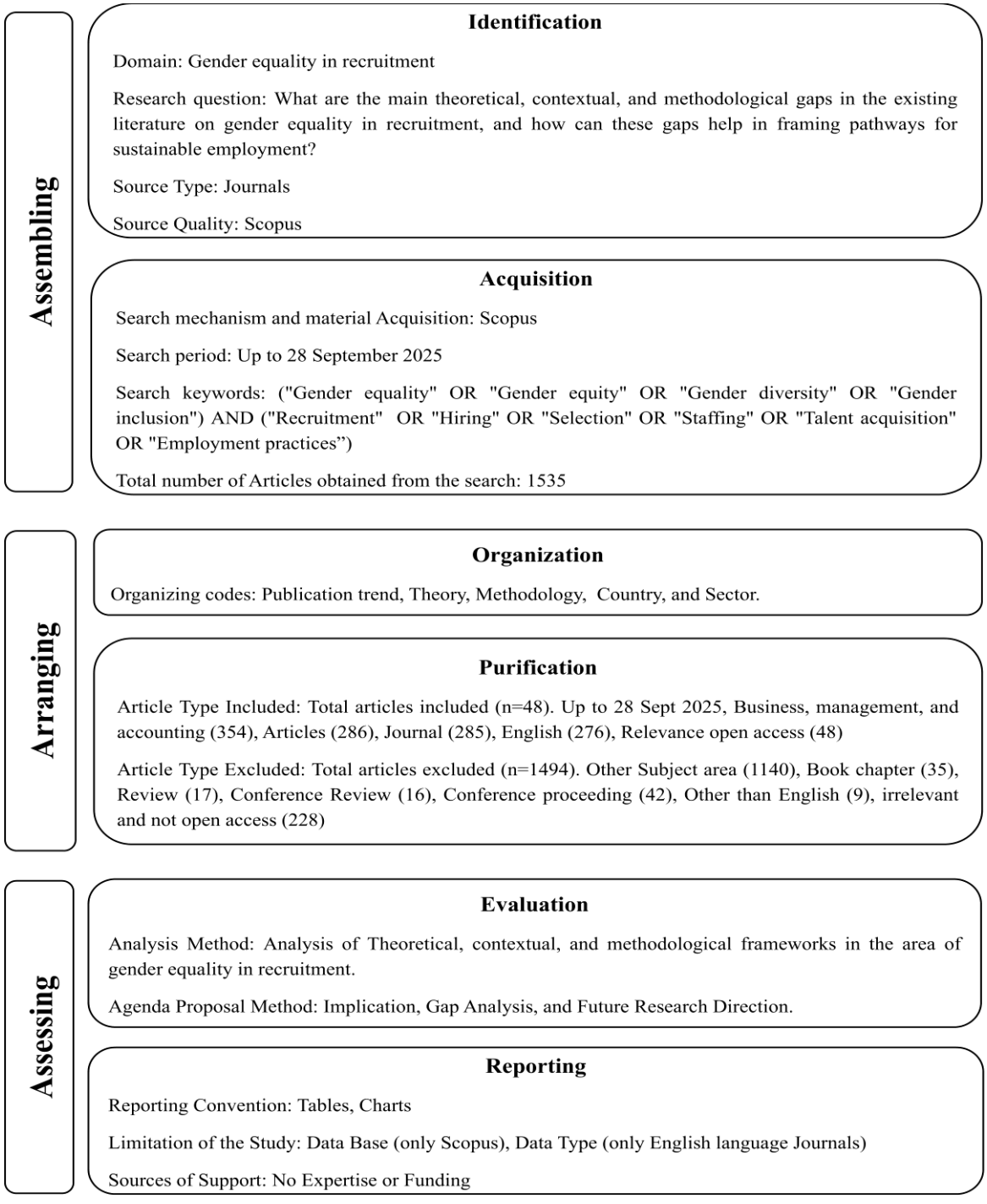
This study used the SPAR-4-SLr approach (see Figure 1). The first stage is assembling, which has two steps: identification and acquisition. Identification involves defining the research domain, formulating the research question, and deciding where to search. In this review, the focus is on gender equality in recruitment, with the key question being: *What are the main theoretical, contextual, and methodological gaps in the existing literature on gender equality in recruitment, and how can these gaps help in framing pathways for sustainable employment?*. Journals indexed in Scopus were chosen as the data source.

The acquisition step involves building and applying a search strategy. Keywords such as "gender equality," "gender diversity," "re

arranging, which includes organization and purification. Organization involves sorting the articles and creating a database with key fields such as author, year, journal, country, sector, methods, and theories. This step helps in mapping the literature before detailed screening. Purification is the filtering step where inclusion and exclusion criteria are applied. The review included only peer-reviewed journal articles written in English, related to business and management, relevant to recruitment and gender, and available in full text. Excluded items included book chapters, conference papers, non-English publications, and irrelevant studies. After applying these rules, the dataset was reduced to 48 articles.

The third stage is assessing, which has two steps: evaluation and reporting. Evaluation means carefully analyzing the final set of articles. Data were extracted on country, sector, theory or framework, methodology, data collection, software, analysis techniques, findings, limitations, and suggested future directions. A basic quality assessment was also done, checking whether studies had clear questions, adequate samples, and appropriate methods. Reporting involves presenting the results in a clear and structured way. The findings were summarized in tables and charts, showing patterns across countries, sectors, and methods. Gaps were highlighted, and research directions were suggested. The review also reported its limitations, including reliance on one database (Scopus), English-only articles, and the exclusion of gray literature.

Figure 1: Research Process



Findings

The trend of publications shows that equal opportunity in recruitment has been discussed for a long time. Research in this area has grown more steadily in recent years. A small rise in 2017 relates to the introduction of the United Nations Sustainable Development Goals (SDGs). These goals gave more attention to gender equality and decent work. After that, the topic became more visible among researchers. In the past five years, publications have increased more clearly. This reflects the progress women are making in achieving leadership and professional roles. It also shows that awareness of fairness in recruitment is becoming stronger every year.

Theoretical frameworks

The analysis shows that some theories are used many times to explain gender equality in recruitment. The most common are Role Congruity Theory (Eagly & Karau, 2002) and the Lack of Fit Model (Heilman, 1983). Both point out that stereotypes and a mismatch between gender roles and job roles create bias in hiring. Social Role Theory (Eagly & Wood, 2012) is also often used. It explains how cultural expectations about men and women shape recruitment decisions. Together, these theories form the base of much research. They highlight how gender stereotypes and role mismatch affect hiring. Another theory that appears often is Signaling Theory. It is used in areas like employer branding, impression management, and job ads. This theory explains how organizations send signals through recruitment practices, such as wording in ads or diversity policies. These signals influence how applicants see the opportunity and decide to apply. Related models like the Attraction Selection Attrition (ASA) model and Person–Organization Fit theory also appear. They explain how organizations and candidates match with each other. The review also found some theories that are used less often but are still important. The Stereotype Content Model (Fiske et al.) uses competence and warmth to explain recruiter perceptions. Homologous Reproduction (Kanter, 1977) is seen in studies of coaching and academic hiring. It shows how decision-makers often choose people who are like themselves. Representative Bureaucracy Theory and Symbolic Representation Theory also appear, but mostly in public sector research. A few studies used critical perspectives. Examples are Postcolonial Feminism, Intersectionality, and Foucauldian governmentality. These are not common in recruitment studies, but they add insights about how gender connects with race, religion, and power. Other recent work uses Algorithmic Fairness frameworks and Debiasing approaches. These focus on bias in AI recruitment tools and mark a new area of study. Some studies did not use a formal theory at all. They used ideas like the "business case for diversity" or just described workplace practices and outcomes. These papers give useful practical insights. But without a theory, it is harder to compare them with other studies

Contextual analysis

Contextual analysis explains the setting in which the study was conducted. It usually includes the country where the research took place and the sectors that were examined.

Country

The findings show that most research on gender equality in recruitment comes from a few countries (see Table 1), with the United States leading. Many studies from the U.S. focus on workplace diversity,

recruitment practices, and hiring experiments. The strong presence of U.S.-based research reflects the country's active debates on diversity, affirmative action, and equal employment policies. Germany, Sweden, and the United Kingdom also contribute heavily. Research from Germany often examines labor markets, recruitment policies, and organizational practices, especially in higher education and public administration. Swedish studies focus on gender equality in leadership, recruitment in creative industries, and academic hiring. In the U.K., the focus is often on equality policies, organizational frameworks, and case studies of recruitment. Together, these European countries provide a strong base of evidence, especially on institutional frameworks and policy-level analysis. Other European countries, such as Italy, the Netherlands, Spain, Switzerland, Norway, and Ireland, also appear in the review, though less frequently. These studies often explore specific industries, such as family businesses in Italy, public administration in the Netherlands, and academic recruitment in Switzerland and Ireland. While not as dominant as the U.S. or Germany, they add valuable perspectives from varied cultural and institutional contexts. Research from India also stands out. Several studies from Indian institutions highlight recruitment challenges faced by women, especially in the hospitality and technology sectors. These contributions are important because they bring perspectives from emerging economies where gender inequality in employment remains a major issue. A smaller number of studies come from Australia, Japan, Vietnam, and the United Arab Emirates. These works provide useful regional diversity. For instance, Japanese research focuses on employment structures and women's participation in the labor market, while UAE studies look at progress in education and employment toward gender equality goals.

Table 1 Countries covered

Country	Count
USA	13
Germany	7
Sweden	5
United Kingdom	5
India	3
Netherlands	3
Italy	2
Norway	2
Australia	1
Ireland	1
Japan	1
Romania	1
Spain	1
Switzerland	1
United Arab Emirates	1
Vietnam	1
Total	**48**

Sectors

The research on gender equality in recruitment covers a wide range of sectors (see Table 2). The most studied areas are technology, higher education, hospitality, and the public sector. These industries dominate because they are either male-dominated fields where women struggle to enter or public institutions where equality policies are closely examined. The technology and STEM sectors appear frequently. Studies here focus on startups, online tech training, IT companies, and technical fields like computing and engineering. These sectors are often male-dominated, and research highlights issues of gender bias, stereotypes, and efforts to create inclusive hiring practices. Closely related are works on online recruitment and AI-based hiring tools, which bring attention to how digital systems may either reduce or reinforce bias. The higher education and academic sector also receives strong attention. Research examines the recruitment of professors, academic fellowships, and leadership appointments in universities across different countries. These studies highlight how gender inequality persists even in knowledge-driven sectors and how policies like transparency, quotas, or evaluation frameworks can support women's representation. The hospitality and tourism industry is another major focus. Many studies analyze recruitment in hotels, tourism firms, and related services. This sector is important because it employs large numbers of women but continues to face challenges such as discrimination, stereotyping, and unequal career opportunities. Some works also compare hospitality with other service industries such as healthcare, banking, and retail. The public sector is widely studied as well, especially in Europe, the United States, and Asia. Research covers civil services, state bureaucracies, government agencies, and public recruitment advertisements. These studies often link to theories of representative bureaucracy and equality in public employment, examining how recruitment policies reflect broader social commitments to fairness. Beyond these dominant fields, several specialized sectors are studied less often but add important insights. For example, sports research looks at hiring practices in intercollegiate athletics and national governing bodies of sport. Media and creative industries provide perspectives on talent management and cultural barriers. Corporate governance and board selection studies explore how gender diversity is addressed in leadership and decision- making positions. Other sectors like construction, mechanical trades, retail, food, financial services, and multinational corporations also appear, though less frequently, showing that gender equality in recruitment is a concern across both traditional and modern industries

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Table 2: Sectors covered

Major Sector	Coverage
Education / Higher Education	Recruitment of professors, academic fellowships (Spain, Switzerland), senior leadership (Ireland, Sweden, Netherlands), and professorial appointments.
Public Administration / Civil Service / Government	Recruitment practices in Germany, Norway, Korea, the USA, SES, and Dutch universities, and transparency in academic recruitment.
Hospitality & Tourism	Recruitment in hotels, tourism industry managers, T&H workforce studies, comparisons with other service industries (retail, healthcare, banking).
Technology & STEM / IT Sector	Cybersecurity startups, IT/Tech firms, ITEC (IT, electronics, computing), STEM employment, LinkedIn/online resume job matching, tech training programs, Fortune 500 recruitment.
Corporate Governance / Boards	Gender diversity in board appointments, board recruitment experiments, governance in sports boards, and national governing bodies.
Sports Sector	NCAA intercollegiate women's sports (assistant coach hiring), national governing bodies of sport recruitment.
Media & Creative Industries	German media sector, digital game industry (Sweden), cultural/creative industries.
General Labor Market / Employment	Non-traditional employment (construction, engineering, trades), COVID-19 labor market impact in Central America, women's re-entry after career breaks, and career development programs.

Methodological frameworks

Most studies on gender equality in recruitment use quantitative methods, with statistical modeling and experiments being the most common. Techniques such as regression analysis (OLS, logistic, fixed effects), mediation analysis, ANOVA, and Structural Equation Modeling (SEM) appear frequently. These methods are often used with large datasets from surveys, experiments, or secondary sources. They allow researchers to test relationships between gender, recruitment outcomes, and organizational practices in a structured way. Experimental designs are especially common. Many studies use randomized online experiments, vignette-based experiments, eye-tracking, or field experiments in real organizations. This approach helps to measure bias and stereotypes in hiring decisions directly, often by controlling conditions such as candidate gender or job ad wording. Several studies also combine experiments with survey data, strengthening their results through replication.

Another widely used approach is survey research, often through online questionnaires distributed to employees, managers, or students. These surveys are

analyzed with techniques like factor analysis, CFA, path analysis, and regression models. They help to capture attitudes, perceptions, and experiences related to recruitment and gender equality. Secondary data analysis is also important. Large datasets from government reports, organizational records, job advertisements, or online platforms (such as LinkedIn or employer review sites) are analyzed with econometric methods. Computational text analysis, AI-based debiasing techniques, and big data models (e.g., LSTM neural networks, word embeddings) show how digital and algorithmic methods are becoming part of recruitment research. While quantitative methods dominate, the review also shows several qualitative studies. These rely on interviews, discourse analysis, case studies, and thematic coding. They explore contexts like the digital game industry, academic recruitment, or education, offering in-depth insights into how gender and power relations shape recruitment practices. Some qualitative works use critical discourse analysis or feminist perspectives to highlight structural inequalities. A smaller but valuable set of studies uses mixed methods. For example, some combine content analysis of job ads with interviews of recruiters, or survey results with qualitative case studies. These approaches provide a more holistic view by combining statistical evidence with contextual understanding. In terms of research design, the most common are experimental, cross-sectional, analytical, and comparative designs. Experiments dominate when bias and stereotypes are studied, while cross-sectional and analytical designs are used for large surveys or secondary datasets. Comparative and case study approaches appear in contexts such as higher education or public administration, especially when recruitment policies are compared across countries or organizations. Exploratory designs are less frequent but are used in qualitative research to open new questions. Longitudinal and diagnostic designs are rarely seen, showing a gap for future research that could track changes over time.

Discussion

The literature shows that gender bias in recruitment persists. Stereotypes, wording in job ads, evaluation practices, and new technologies all play a role. However, important gaps remain in what scholars study and how they study it. These gaps limit our ability to design policies and practices that lead to sustained, equal employment outcomes for women and other marginalised groups.

Theoretical gaps

Many studies show an over-reliance on a few frameworks such as Role Congruity, Lack of Fit, Signaling, and Person–Organization Fit. While these theories are valuable for explaining individual- and organizational-level bias, their dominance narrows the view of broader structural causes. At the same time, there is limited use of intersectional and critical perspectives, such as intersectionality, postcolonial feminism, or governmentality. As a result, research often fails to capture how gender interacts with race, class, religion, or migration status in shaping recruitment outcomes. Another gap is the underuse of macro and systems theories, including population dynamics, institutional theory, and political-economy perspectives. These approaches could provide a deeper

understanding of long-term systemic drivers of inequality and the impact of policy or market changes over time. Work on algorithmic fairness in recruitment is also still at an early stage. Although studies on AI and hiring algorithms are emerging, theoretical development that links socio-technical perspectives with recruitment practices remains underdeveloped.

Contextual gaps

Much of the research originates from the United States and parts of Europe, creating a strong Western bias. Evidence from Africa, Latin America, and large parts of Asia is limited, which restricts the global applicability of findings. Studies are also concentrated in a few sectors, particularly higher education, technology/STEM, hospitality, and the public sector. Other important areas, such as the informal economy, agriculture, and small enterprises, remain understudied. Furthermore, limited attention is given to differences across organizational size and type. Few studies systematically compare recruitment practices in multinational firms, SMEs, startups, and public agencies, even though contexts differ and require tailored interventions.

Methodological gaps

Methodologically, the literature shows several recurring gaps. A shortage of longitudinal studies is clear, as most research is cross-sectional or experimental, leaving the long-term effects of policies and interventions underexplored. There is also an underuse of mixed- methods approaches that combine rich qualitative depth with strong quantitative analysis. This limits understanding of the processes and meanings behind recruitment practices. In addition, field trials and real-world interventions are less common compared to lab and vignette studies. Few randomized controlled trials, organizational interventions, or action-research projects have been conducted to test scalable solutions in practice. Sampling also presents a limitation, with many studies relying on convenience samples such as students, online panels, or English-only texts, which reduces external validity. Finally, in studies involving AI, there is often insufficient measurement and transparency. Many machine-learning evaluations lack standard fairness metrics, clear audit processes, and external validation, making it difficult to fully assess the role of algorithms in recruitment.

Pathways for sustainable employment

Addressing these gaps can create stronger pathways for sustainable employment. Expanding beyond the dominant theories to include intersectional, macro, and socio-technical perspectives can help capture the structural, cultural, and technological forces that shape recruitment. This shift would allow researchers and policymakers to design interventions that tackle not only individual bias but also systemic inequality. Broadening the geographical and sectoral focus is also crucial. More research from Africa, Latin America, Asia, and understudied industries such as agriculture, informal work, and small enterprises would produce context-sensitive insights and ensure that policies are globally relevant. Similarly, comparing practices across different organizational types, from startups to public agencies, can reveal which interventions are scalable and which must be tailored. Methodologically, pathways forward include greater use of longitudinal designs to track lasting effects of diversity

initiatives, mixed-methods approaches to connect statistical evidence with lived experiences, and field trials or action research to test solutions in real organizational settings. Improvements in sampling diversity and the adoption of transparent standards in AI-based recruitment are also necessary to build fair and trustworthy systems. Taken together, these pathways highlight that sustainable employment depends not only on removing bias in recruitment but also on embedding inclusivity, accountability, and long-term monitoring across policies, organizations, and technologies.

Implications

The findings carry important implications for managers, HR professionals, and organizations that aim to make recruitment more inclusive and supportive of gender equality. First, organizations need to move beyond surface-level diversity statements and address structural barriers by embedding inclusive policies across all stages of recruitment. This can be achieved through standardized job descriptions, structured interviews, and transparent evaluation criteria that reduce the influence of bias and stereotypes. Second, HR professionals should adopt intersectional approaches, ensuring that recruitment policies consider not only gender but also

how it interacts with race, class, religion,

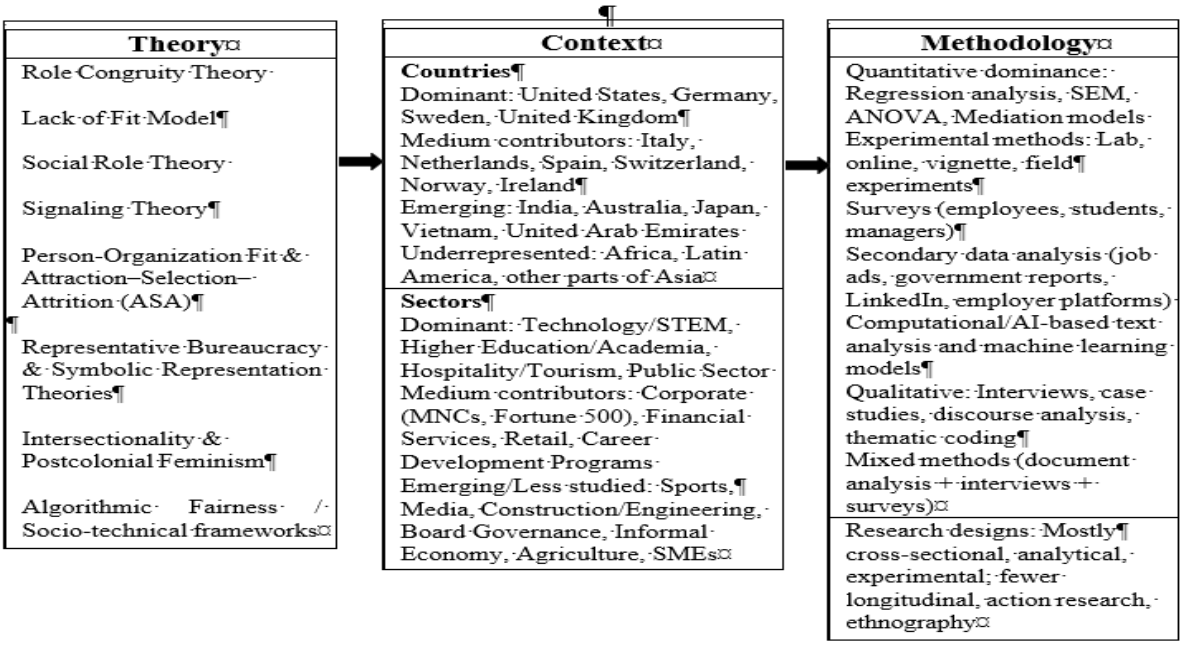
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disability, and other identities. Third, managers should embrace evidence-based practices, such as joint evaluation, blind review of applications where appropriate, and the consistent use of fairness audits in AI-driven recruitment systems. These steps will help create fairer hiring outcomes and build trust in recruitment processes. Fourth, organizations can support sustainable employment by combining recruitment reforms with supportive workplace policies, such as flexible work arrangements, mentorship programs, and leadership pathways for women and underrepresented groups. Finally, organizations should invest in long-term monitoring and evaluation of recruitment initiatives. Tracking outcomes over time will help to assess whether diversity measures lead to real and lasting change in representation and career progression. By integrating these practical steps, managers and HR professionals can ensure that recruitment not only provides equal access but also contributes to sustainable and inclusive employment systems.

Conceptual Framework

Based on the analysis, this study adapts the TCM framework and presents a conceptual framework for understanding gender equality in recruitment (see Figure 2). The framework is outlined below

Figure II: TCM Conceptual Framework



CONCLUSION

This study reviewed 48 peer-reviewed papers on gender equality in recruitment and analyzed them using the TCM (Theory, Context, Methodology) framework. The findings show that a few dominant theories, such as Role Congruity, Lack of Fit, Social Role Theory, and Signaling Theory, largely shape the field, while critical perspectives like intersectionality, postcolonial feminism, and algorithmic fairness remain underexplored. In terms of context, research is concentrated in Western countries and specific sectors such as higher education, technology, hospitality, and the public sector, while regions such as Africa, Latin America, and underrepresented sectors like agriculture, SMEs, and informal economies receive limited attention. Methodologically, most studies rely on quantitative and experimental approaches, while longitudinal, mixed-method, and real-world intervention studies are relatively scarce. By consolidating these insights, the study proposes a conceptual framework that highlights both dominant trends and underexplored areas, offering pathways for future research and practice to make recruitment more inclusive and supportive of gender equality in sustainable employment.

Limitations

Although this study provides a structured review and develops a conceptual framework, several limitations should be acknowledged. First, the review is based only on peer-reviewed journal articles, which may exclude valuable insights from grey literature, policy documents, and organizational case studies. Second, the reliance on English-language publications introduces the possibility of linguistic and regional bias, limiting the global scope. Third, while the TCM framework is useful for organizing and comparing studies, it may not capture every interdisciplinary perspective on gender and recruitment. Finally, since recruitment practices and technologies evolve quickly, particularly with the rise

of AI-based tools, some recent developments may not yet be fully represented in the reviewed studies.

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SUSTAINABLE TARGETED ADVERTISING AND ITS DISCONTENTS: AN EMPIRICAL INVESTIGATION

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ABSTRACT

Classical market segmentation strategies provided duality of considerations before companies. The striking feature of the duality was exclusivity, for example a marketer thought of choosing between mass marketing on niche marketing but not both of them altogether. This paradigm of market targeting shifted with the onset of digital platforms providing access to large masses of digital platforms users along with mechanisms to design and present personalized niche offerings. This metamorphoses of market segmentation and targeting apparently stands on a benign foundation of access to personal data and built in algorithms to provide targeted advertising in digital economy. However, a closer examination reveals that the sustainability of such marketing strategies is questioned by a large number of factors including the nature and extent of influence of targeted advertising in guiding purchase behaviour, intrusion in the privacy of consumers and ethical considerations among others. This research attempts to explain factors influencing sustainability of targeted advertising. It attempts to outline variables that pose a concern for sustainability of targeted advertising. The research further suggests ways to build sustainable digital advertising strategies through incorporating ethical and transparency related measures in the current digital advertising scenario.

Keywords: Sustainable Targeted Advertising, Digital Advertising, User confidence, Information disclosure, fiduciary obligation

INTRODUCTION

The advertising potential of social media and other digital platforms was realised relatively late when Facebook started showing brand messages in early years of last decade. The initial reaction to web-based platform advertising was rather passive from the side of advertisers. The rise of advanced algorithm systems created opportunities to tailor advertisements based on the specific needs of the consumers. This was certainly an improvement over traditional media advertising that relied on platform strength and viewership rather than consumer preferences. The earlier segmentation and

targeting methodologies had in built exclusivity and fusion of niche targeting and catering mass consumer bases together were not visualised. The emerging targeted advertising through digital media platforms has not only challenged the conventional segmentation and targeting theory but also revolutionised the advertising space. However, this is not without its obvious pitfalls arising in the area of concern for privacy and ethical apprehensions pertaining to treatment of data. The intrusion in to individuals' privacy is also emerging as a concern for the certain interest groups. This translates in to incursions in freedom of the individual consumers to choose and rationally create decision imperatives. These concerns require a rigorous body of research to assess the influence of these factors on ethical and legal sustainability of the targeted advertising.

Sustainable targeted advertising (STA) caters the efficiency of customised marketing practices with the principles of ecological aspirations, ethical Duties and responsibility. Traditional targeted advertising (TTA) emphasises on formulating messages to consumer segments based on demographics, particular behaviours, or preferences (TechTarget, 2025a). By adding sustainability, firms emphasize transparency, reduced advertising waste, and respect for consumer privacy, aligning marketing practices with broader social and environmental goals (TechTarget, 2025b). Prior Studies indicate that sustainable advertising strengthens brand trust, consumer loyalty, and purchase intention to some extent, particularly when firms demonstrate authentic environmental commitments rather than vague claims (Çelikkaya, 2024; Lim et al., 2021).It has been observed that Consumers increasingly expect brands to incorporate sustainability in both what they advertise and how they advertise, while regulatory frameworks discourage greenwashing (Adinugroho et al., 2025; Hegde et al., 2025).Thus, sustainable targeted advertising offers a pathway for businesses to achieve dual objectives: driving marketing performance and meeting stakeholder expectations for social and ecological responsibility.

LITERATURE REVIEW AND RESEARCH QUESTIONS

Targeted advertising involves presenting advertisements to customers based on personalised clues and data accessed through past records from a repository online which essentially involves selection of a platform that itself accumulates consumer traits and data (Anand & Shachar, 2009). The proliferation of internet technologies and ease of access to digital platforms through mobile phones has enormously expanded the opportunities for delivering personalised advertisements and offerings to huge mass segments (Haddadi, 2011). A complex network of data collection, aggregation, processing and commercial exchange of data takes place involving a range of intermediaries and technologies to deliver personalized advertisements to consumers (Ullah, 2020). The emergence of artificial intelligence technologies has provided greater tools to sharpen the targeted advertising by utilizing object recognition technologies apart from learning from past purchase data (Lee, 2019). Social media

platforms like Facebook have also contributed to the accentuation of targeted advertising by designing discriminative groups to attract advertisers and enhance their revenue at the cost of user privacy (Speicher, 2018). Collection of personally identifiable information like date of birth, phone numbers, locations, check in to different locations by social media platforms and other service providers have aggravated the privacy risk for users stemming from targeted advertising without acquiring active and informed consent (Venkatadri, Lucherini, Sapiezynski, & Mislove, 2019). Targeted advertising also has the ability to interfere in the utility assessment by consumers and affect fair value exchange (Shin & Yu, 2020). User groups share apprehensions about targeted advertising being intrusive and embarrassing (Zhang, 2010). User's share their personal data to connect and enjoy interactive networks in social media space; however, these details are being used for targeted advertising in contrast to user expectation (Balkin, 2020). The information boundary theory postulates these targeted and personalized advertisements as intrusive in individual privacy (Groot, 2022). Advertisers vouch for added sales through targeted advertising while consumers have often negative perception of the advance targeting techniques (Truong & Simmons, 2010). Intrusiveness of targeted advertising is likely to evokes emotional, behavioural and cognitive response from the consumer groups (Riedel, Weeks, & Beatson, 2018). Magnitude of intrusiveness such as greater access to browsing history and information pertaining to previous transactions are proportionate to negative consumer perceptions about advertisers (Doorn & Hoekstra, 2013). Utilizing consumer locations has added even higher level of targeting which results in greater consumer discomfort about intrusion in privacy (Paul E. Ketelaar, 2018). Targeted advertising utilizing demographic data and behavioural patterns of the user pose ethical concerns for the user groups (Plane, Redmiles, & L, 2017). Temptations of gains from targeted advertising may drive advertisers to ignore ethical concerns more than ever before (Drumwright & Murphy, 2009). Personal identifiers and demographics-based targeting affect the user groups in multiple ways and ethical implications of the same range from brand image to perceptions about reasonability of the product being offered (Allen, 2022). The new technologies utilizing biometric data for delivering targeted advertising has raised the concern for privacy ethics amongst consumer groups (Ramsoomair & Pandey, 2020).In certain sensitive cases such as pregnancy and other disease conditions, the targeted advertising may bring shame to the subject user and have ethical repercussions by creating a negative user perception (Golpayegani, 2021).A range of facets of advertising are against the normative ethics being observed in business (Ma, 2019).

CONCEPTUAL FRAMEWORK

The proponent of information boundary theory (IBT) (Stanton, 2002) proposes that people tend arrive at a decision about what to disclose about themselves (boundary opening) and what to keep confidential (boundary closure) based upon the confidence in the intention of the receiver

of the information to keep the same as safe and confidential. This also suggests that there may develop a tendency to protect information from disclosure due to concerns of privacy protection amongst people using a certain digital media platform (Stanton & Stam, 2003). Moreover, the decision to make disclosure (boundary opening) and privacy protection does not occur by itself but depends on the level of knowledge available with respect to the fairness of the data handlers(bounded rationality).Herein, it is also pertinent to mention that observance of fiduciary responsibilities by data handlers(digital media platforms) to keep the user data safe and secure and use it only in trust of the user may have a bearing on the easing of limitations on decision making about boundary opening and closure**.** Based on this conceptual exploration, the study caters testing of two set of Hypotheses as:

Set of Hypotheses

H1: A platform's willingness to disclose personal information is not positively correlated with user confidence in its commitment to confidentiality.

H2: Information disclosure increases as platforms perceived fiduciary obligation does not lower privacy concerns.

Research Method

A descriptive design based on cross section data point has been adopted. A sample size of 437 based on survey data has been utilised to explain the sustainable targeted advertising and consumer discontents. Responses have been collected through a structured questionnaire which is redesigned based on replication of already tested scale. Scale Reliability (Cronbach alpha 0.76) and validity measures have been ensured.

Data Analysis and Interpretation

Correlation between willingness to disclose & confidence in confidentiality

Table: 1 Test of Correlation

Statistic	**Value**
Spearman correlation	0.079
p-value	0.438

Source: Analysis output through excels.

As per data analysis, there is a very weak and statistically insignificant positive correlation ($\rho = 0.079$, $p = 0.438$) between *willingness to disclose personal information* and *user confidence in a platform's confidentiality.* This means that researcher is fail to reject the hypothesis. It means *that increased confidence in platform confidentiality* does not reliably translate to *greater willingness to disclose.*

Regression to predict the Effects of fiduciary obligation & privacy concern on disclosure.

Table:2 Regression Output

Variable	Coef.	Std.Err.	t	P>|t|	95% confidence interval Lower bound (0.025)	95% confidence interval Upper Boud (0.975)
Intercept	2.124	0.78	2.72	0.008	0.574	3.673
Fiduciary	0.176	0.291	0.6	0.547	-0.401	0.753
Privacy	- 0.056	0.216	- 0.26	0.795	-0.484	0.372
Interaction	0.024	0.072	0.33	0.74	-0.118	0.166

Source: Analysis Output

Regression model predicts that neither perceived fiduciary obligation nor privacy concern nor their interaction significantly affects the willingness to disclose personal information (all $p > 0.05$). This suggests that even if users regard platforms as having a fiduciary duty, higher privacy concern does not meaningfully lower the tendency to share information on such platforms as described under the study.

FINDINGS AND DISCUSSION

After analysis of the collected data, Spearman correlation between *users' willingness to disclose personal information* and *their confidence in a platform's confidentiality* was very weak and not statistically significant ($\rho = 0.079$, $p = 0.438$). This suggests that a user's trust in a platform's confidentiality commitment does not meaningfully influence whether they are willing to share their personal information. In contrast, expectations that trust in confidentiality would motivate users to be more open while sharing their personal information, the data reveals that no such relationship between these two factors in this context exist. Users may base their disclosure decisions on other considerations, such as necessity, convenience, or perceived benefits, rather than mainly on their level of confidence in data protection. This finding implies that simply increasing assurances about confidentiality may not be sufficient to encourage users to share more information in the context of such encounters. The regression analysis indicated that neither the platform's perceived fiduciary obligation, privacy concerns, nor their interaction significantly predicted willingness to disclose personal information. This finding suggests that the belief that a platform is obliged to act in the user's best interest (fiduciary obligation) does not significantly affect disclosure behaviours, even when privacy concerns are factored in. Users seem to weigh multiple factors when deciding to disclose information, and legal or ethical assurances alone are not the dominant

influences. This explores the complexity of user attitudes toward privacy and suggests that organizations may need to address a broader perspective of motivations and concerns such as control, benefits offered, prior negative experiences, or social norms while encouraging others to information sharing on such platforms.

Managerial Implications

Study offers insight that dependence solely on assurances of confidentiality or ethical responsibility is unlikely to increase user data disclosure. Managers should implement multidimensional approaches that also explore value and convenience to users. Understanding and target the different factors influencing disclosure, such as perceived benefits, ease of use, personalization, and social influence, rather than focusing exclusively on privacy assurances. There should be clear communication on how user data will be used for tangible benefits (e.g., improved services), as transparency alone may not sufficiently factors as users need to see direct value of any such exposure. Branding and marketing professionals can offer personalized experiences or incentives for data sharing, as these may be stronger motivators than formal guarantees of confidentiality. Companies can educate users about data usage practices and real-world benefits, addressing misconceptions and reducing undue privacy concerns through regular, honest engagement.

CONCLUSIONS

Present work offers an empirical analysis that, neither users' confidence in a platform's confidentiality nor their perception of its fiduciary duty significantly influences their willingness to disclose personal information. The study revels no statistically meaningful correlation or predictive relationship between these variables and information disclosure. This suggests that assurances around data protection and ethical responsibility alone are insufficient to motivate users to share personal data on different social media platforms. Therefore, platforms of social media or any websites seeking to encourage greater disclosure should consider broader strategies that caters additional user concerns, motivations, and decision factors beyond simple trust in privacy commitments or perceived fiduciary obligations to a great extent. Findings have greater impact on policy makers and internet companies which can create best balance by understanding such underlying dimensions of discontents in the context of sustainable targeted advertising.

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GREEN MARKETING AS A CATALYST FOR SUSTAINABLE CHANGE

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ABSTRACT

Given that human demands are limitless, and resources are scarce, it is very important for marketers to make effective and waste-free use and production of resources. This need arose during the last few years when corporate bodies realised the importance of eco-friendly products and how beneficial it would be in terms of sustainable marketing. This phenomenon has gained popularity in modern marketing and is termed as Green Marketing. Companies are now more oriented towards products that are manufactured and distributed in accordance with climate and environmental safety standards. This paper aims at understanding how businesses are pursuing green concepts for environmentally conscious consumers— those who care about the environment and let it affect their purchasing decisions. It further attempts to understand the type and extent of marketing strategies adopted under the umbrella of green. It also critically analyzes the potential and challenges of green marketing and discusses the most recent developments in the Indian context related to green marketing. The study concludes that green marketing has and will continue to gain popularity among consumers and businesses when used in a holistic manner.

Keywords- *Sustainable Development, Green Marketing, Marketing Strategies, Eco friendly Marketing, Perceived Value, Green Washing*

INTRODUCTION

The need for sustainable development has increased on a massive scale in the last decade with companies focusing more on environmentally friendly products and services. Brundtland report (WCED 1987) explained sustainable development as an approach that meets the needs of the present without compromising the requirements of future generations. The first introduction on sustainability was coined by Sheth and Parvatiyar (1995) which focused on environmental oriented products and service. This was further tweaked and explained as a marketing process for products which meets three primary criteria (i) customer needs (ii) organizational goals and (iii) compatibility of processes with the eco-systems. Sustainability is now becoming a matter of concern for investors too, with 78% of global investors saying that they place more emphasis on ESG

(Environmental, Social & Governance) now, than they did five years ago. 65% of global investors believe that ESG will become a standard practice over the next five years.

To cater to the ESG, companies are adopting the practices of Green Marketing. As per the standards of the American Marketing Association, Green marketing refers to the marketing of the products that are environmentally safe. When the traditional marketing process undergoes massive transformation in terms of product modification, process and production change, advertisements changes and many more different ranges of activities, considering the factors of carbon footprints, then it is referred to as green marketing. According to Pride and Ferrell (1993) Green marketing, is also alternatively known as environmental marketing and sustainable marketing, which refers to an organization's efforts at designing, promoting, pricing, and distributing products that will not harm the environment.

Why Green Marketing

Green Marketing is necessary because there is an increasing worldwide concern in terms of climate protection and environmental preservation. Individuals who are genuinely concerned about climatic conditions are curious and cautious both about safe and ecofriendly products. Considering this, green marketing has surfaced, speaking of expanding the market for environmentally friendly and socially conscious goods and services. As a result, consumers worldwide have become more concerned with protection of the environment and they themselves want to leave a clean earth for their future generations. Environmentalists' numerous research shows that people are worried about the environment, with consumers and producers both inclined towards environmentally friendly products. Thus, in today's era Green Marketing is inevitable. India urban consumers who are literate are becoming increasingly conscious of the benefits of green products. For the majority, though, it is still a novel idea. The customer must receive education and informed on the dangers to the environment. The new green movements will require a great deal of time and work to spread among the public. Indian customers are aware of the benefits of utilizing natural and herbal beauty products because of their legacy in ayurveda. Indian consumers are exposed to natural food consumption and other healthy living practices like yoga. Customers are already aware of these factors and are likely to embrace environmentally friendly items.

According to a new survey by consulting firm Bain & Company, 20% of consumers in India are environment conscious while 52% in urban India expects to increase spending on planet friendly brands. Progressive companies see this as an opportunity and have the upper hand over those companies that have not taken up green marketing yet. Through a poll conducted in February 2022 on sustainable consumerism in India, Rakuten Insight realized that 69 percent of customers were willing to pay more for goods that were made with environmental considerations. However, 31% of respondents said they would not be able to pay extra (Statistica, 2023).

Green Marketing Practices across the world

Companies in the current era do realize the need to go green. The motivation,

however, could vary including societal pressure, changing customer preferences, government binding or self-consciousness. There were more than 200 new companies across the globe that vowed on September 20, 2023, to reach carbon net-zero emissions by the year 2040, including Twitter, Salesforce, and Procter & Gamble. Microsoft, Starbucks, and Nike are just a few of the hundreds of businesses that have already pledged to meet the 2°C objectives by 2030 and align with the Paris COP21 climate agreement. There are few who are also striving for net-zero carbon footprints (Alexis Benveniste, CNN Business report, 2021).

However, it needs to be clearly understood that only when done correctly, green marketing may be an effective marketing technique. According to business research insight report 2023, the global Green Marketing Market is expected to grow from 49250.7 million in 2021 to USD 60811.48 million by 2027, at a CAGR of 3.58%.

Change in consumer preference and consciousness to lessen the environmental effect is also emerging as a driving factor for companies to go green. 48% of consumers in the United States have displayed a change in their consumption habits. A whopping 73% of millennials are willing to pay more for sustainable items, as opposed to the 66% of worldwide customers who are willing to pay for sustainable brands (Consumers International Report,2025).

Companies are even altering their marketing approach by boosting their sustainable marketing expenses to stand out in the net-zero discussion area and keep sustainability as a market differentiation. According to a recent poll conducted by Environmental Leader, 82% of businesses intend to increase their green marketing spending.

One recent example of green marketing is the announcement by IKEA that they will begin selling renewable energy from solar and wind sources to individuals and families soon. The news was taken with lots of positivity from green consumers around the world. Similarly, Patagonia is a prime example of a brand that encourages green marketing without falling into the trap of attempting to convince clients that every part of their business is sustainable

There are a few retail brands which do communicate with customers about the materials they use for packaging and delivery. However, an integrated use of green strategies is yet to be achieved. Concerns like ozone depletion and global warming are critical to human health and survival. Everyone wants to live a good life, regardless of wealth. Both the business class and I would be in excellent health and vitality. The primary goal of every corporate firm is to make both economic and financial profit. However, the damage that global capitalism has done to the environment is just now becoming apparent. The business class is developing corporate citizenship in this sense. Therefore, the business class's use of green marketing is still based on the self-serving historical perspective of long-term sustainability in company, customer satisfaction, and obtaining the necessary licenses from the relevant authorities. Asian nations are realizing how important green marketing is to the developed world, but there is still a significant disconnect between their comprehension and execution.

Greening Of the Organization

Greening Champion

An organization can only be genuinely green if it embraces the motto and completely incorporates green efforts into all facets of operations. This change, though, usually doesn't happen overnight. Rather, the execution of the program is led by a single person or group of people. They are referred to as "green champions." Previous studies indicate that an organization's members are essential to its performance and its green initiatives. Therefore, before embarking on a green transformation, businesses should do well to determine who the most logical advocate is. Research possibilities exist since there is a dearth of information on strategies for boosting organizational buy-in to new environmental policies.

Green Processes

The J. of the Acad. Mark. Sci. procedures and practices that the company uses are linked to another part of guiding the business toward a green orientation (Kassinis and Soteriou 2003; Montabon et al. 2007). In keeping with this, the literature has addressed two primary subjects in great detail. Specifically, prior study has concentrated on how waste might be decreased to get better environmental performance (when considered non-green activities). Environmental management systems (EMS) are the subject of the other major body of process literature, with a focus on EMS certification.

Green Alliance

Managers are looking for partners based on green efforts as environmental management techniques receive more attention (Kumar and Mandelet, 2006). Companies looking to step up their green initiatives could find it helpful to collaborate with other businesses through informal partnerships or alliances. Research on partnerships is prevalent in cause-related marketing (e.g., Lichtenstein et al. 2004; Ellen et al. 2006), and it indicates that selecting the appropriate partner is critical to the success of both businesses.Social alliances haven't gotten the same attention as strategic partnerships, which are nevertheless widely used in business. A social alliance is defined as a long-term, mutually beneficial cooperation for both businesses, rather than just cause-related marketing, between a corporation and a non-profit (Berger et al. 2006). According to Berger et al. (2006), social partnerships are long-term investments connected to expanding or changing a business. They offer a fantastic chance for companies looking to step up their green initiatives.

Green Consumer

Implementation of Green Marketing in India

More than 25% of Indian customers say they prefer environmentally friendly items, while about 28% say they are concerned about their health. Green marketers may thus target a variety of sizable and varied consumer niches.

Examples of green marketing include the water-saving Surf Excel detergent (marketed with the slogan "do bucket paani roz bachana") and the energy-efficient LG consumer durables. We also have green buildings, which use less energy, water, and building materials and have better design, construction, operation, maintenance, and waste disposal practices, all of which have a positive influence on human health and the environment. In India, the Confederation of Indian Industry.The

Confederation of Indian Industry (CII) - Godrej Green Business Centre is leading the green construction movement in India, which has acquired a lot of momentum in the previous few years. India's green building footprint has grown from 20,000 square feet in 2003 to over 25 million square feet now.

Businesses that create innovative and enhanced goods and services with consideration for the environment open up new markets, boost their profitability over time, and get a competitive edge over those that don't care about the environment. Many businesses desire to be among the first to adopt green practices because they will soon need to do so. Green marketing offers several benefits that companies want to take advantage of, including: It guarantees consistent, long-term growth in addition to profitability. Even though the initial cost is higher, in the long run it saves money. It assists businesses in marketing their goods and services with consideration for the environment. It also helps them get access to new markets and gain a competitive edge. The majority of workers also experience a sense of pride and accountability in being employed by an environmentally conscious organization. Encouraging environmental sustainability in product design and manufacture may lead to big corporate growth, innovation, and brand equity potential. The lack of public agreement on what defines "green" and the lack of standards provide several difficulties for green marketers. Essentially, when it comes to a product or firm making green marketing claims, there is no standard for "how good is good enough". The need for more agreement among customers, marketers, activists, regulators, and powerful individuals has hindered the expansion of environmentally friendly products as consumers are frequently dubious of claims made by firms and businesses alike. A further difficulty that new and old green marketers may have as green messaging and goods proliferate is misunderstanding in the marketplace.

LITERATURE REVIEW

Green marketing strategy encourages firms to use environmental inputs to create new, better goods and services, which helps them expand into new markets and earn more money while also giving them a competitive edge over those firms that do not care about the environment. The concept of green marketing encompasses concepts of green at all stages of value creation. These products are more desirable than ever before. But the concern about green products has ceased to be the same as the previous theories, as consumers are not just looking for traditional tangible products. Businesses overestimate the green attributes of traditional products, leading to consumer refusal or even a negative reaction. Most of the markets, however, have failed to implement the concept in an integrated manner and are left with strategizing at only one or few areas of marketing which has led to a gap between perceived value and actual value of the product.

Empirical findings also indicated that marketers of green products have stated the gap between pro- environmental attitudes and green purchasing behavior (Fazin et al 2020; Ferraz et al 2017). In a recent study (Kardos et al 2019; Bhaskaran 2006), it was found that consumers have a lack of trust towards the plethora of eco-labeling on products.

According to a report (Volkswagen’s

Emissions & Vos L), use of false communication of green by Volkswagen in 2015, led not only to losses of €7 billion in profits but also to a decrease in investments and reputational losses (the value of the company's shares decreased by 25%). The chain reaction to this scandal provoked a decline in consumer confidence in the brand "Made in Germany", as well as the investment attractiveness of the car market. In 2015, the value of the shares of all automobile companies decreased by 3–14% (Toyota—by 3.24%, BMW—88%, Honda—13.73%, Ford—12.42%, General Motors—4.32%, Mercedes—6.51%, Fiat—5.97%). Such practices of green marketing myopia is termed as green washing, and has a detrimental impact not only on the brand but also on the trust of consumers regarding green products (timesofindia.indiatimes.com). Many other organizations were found to use the green washing concepts in the past including BMW in automobile industry (theguardian.com), which advertised a zero-carbon electric car that had gasoline engines; Tarte Cosmetics and The Body Shop in cosmetics industry. This kind of greenwashing tactics, is leading to denial of consumer conviction and increased in dissonance (Szilagyi et.al, 2022).

Few of the most applied green practices used by companies in the present scenario is green advertising, eco-labels and focus on continuous improvements, associated with sustainability, which increases the perceived value of the product and positively impacts consumer purchasing decisions (Yoon et al, 2017). A business that wants to launch a green marketing campaign must start with a green design. This is mainly because of the inputs, manufacturing procedures, distribution, methods of use and disposal, etc. that are made during the design phase (Garg,2015). Though a few organizations are also focusing on adopting practices related to the production and distribution process of green products, unlike the previous cases, they are not easily perceived by the consumers. This leads to a gap in perception regarding the value of the green product (Touboulic, 2015). According to a recent study conducted by the European Commission, green claims like "green" or "friendly to nature" are commonly practiced by more than 80% of e-commerce stores, websites, and advertisements that were searched. Of these, 35% were explicit (logos and labels), 21% were vague or general environmental claims, and 55.45% were implicit (images, design, and color suggesting environmental benefits) (European Commission report 2022).

Many studies show that green marketing can improve a company's performance (Hasan & Ali, 2015), customer satisfaction (Tripathi, 2014), competitive advantage (T. B. Chen & Chai, 2010; Prakash, 2002), and has many other advantages. In a study conducted by Govender and Govender (Govender & Govender, 2016) on consumers regarding goods that are more environmentally friendly, it shows that consumers do tend to choose to buy goods that are more environmentally friendly. Green marketing thus becomes part of the strategy of the business to satisfy client, investor, regulatory, and organizational requirements (Dangelico & Vocalelli, 2017). Companies now focus on a green marketing mix that includes product, price, place and promotion (Kotler and Amstrong, 2014). These four Green Ps

helps the organization to analyze the relationship between consumer perception and their reaction towards sustainable brands (Davari and Strutton, 2014)

RESEARCH METHODOLOGY

This paper used a literature review approach to gather relevant information and critically analyse various facets of green marketing for creating sustainable businesses. The literature review involved, analyzing and synthesizing existing studies, theories, and empirical evidence to develop a comprehensive understanding of the subject matter. An extensive literature review was conducted using popular databases such as Web of Science, Scopus, Google Scholar, EBSCO host, etc. where research papers from reputed journals were considered for review from the year 2017-2025 and included seminal work. Several blogs, articles, and survey reports from authentic sources were reviewed to strengthen the discussion. The keywords used for the search included sustainable development, green marketing, perceived value, marketing strategies and ecofriendly marketing.

Green marketing strategies

Sharma, A. P. (2021) through his research paper based on systematic literature review gave a framework of green marketing strategies. He proposed a green purchase model which included aspects of Green Marketing Mix, Green consumption process and factors affecting Green Purchase. Considering the holistic green approach, organizations must formulate strategies for offering sustainable products by utilizing sustainable resources. A responsible supply chain and trash management system that is conscious of emissions is also the need of the hour. Further on implementing electronic marketing practices and green alliance would further expand the green horizon for the organizations. A comprehensive approach must also incorporate green marketing objectives into business plans (Lendel, V.and Soviar, J;2015). Ginsberg and Bloom claim that by varying the extent of green practices, a business can adopt four ecological marketing strategies.

Lean green strategy - when a company tries to be socially responsible but does not prioritize educating the public about these efforts. The focus is on lowering expenses and raising productivity through environmental initiatives, creating a low-cost competitive edge. The lean-green approach is developed to address the three pillars of sustainability - economic, environmental and social unlike lean manufacturing.

Defensive green marketing strategy - when a business fends off competitors or a crisis by promoting environmental activities. Such activities are irregular and transient, despite the fact that they are sustainable and promising. This is because the organization does not intend going green to set as a differentiating factor with competitors.

Shared green strategy - refers to an organization's long-term investment in ecologically friendly operations that demand substantial non-financial and financial resources. The corporation views green marketing as a chance to develop cutting-edge technology and products that satisfy consumer demands and provide it a competitive edge.

Extreme green strategies - are completely included into the life cycle of a product and business activity. The business

frequently uses specialized stores and distribution networks to service niche markets who are conscious of green aspects (Esmaeili, A et al., 2017).

Green Alliance - Businesses now engage in consumer -environment solidarity and are also involved in the green marketing environment. Companies can join a green alliance by committing to donate to certain charity or activist organizations that are working to protect the environment in some capacity

Green Pricing - The fundamental idea behind green pricing is the price ranges that customers are ready to pay for environmentally friendly goods and services. Customers love ecofriendly goods and services, and buying recycled paper, unbleached coffee filters, and renewed energy services may increase the market for eco-friendly prices. Consumers will frequently pay more for environmentally friendly products (Ahammad, 2012).

RESULTS

The paper clearly states that across the world, the concept of Green Marketing has gained momentum, and many companies are successfully applying the Green Marketing strategies to their products and services. Though acceptability towards green products consumption has substantially risen globally including India. Lack of consumer awareness, high priced products, issues of green protection, pricing and product promotion are also some of the challenges faced by the companies. Consumers today are also aware of such marketing gimmicks and as a result are facing difficulty in developing trust regarding the perceived value of green products. Several deceptive marketing practices used under the umbrella of green like green washing, green squashing, and green sheen. This can be overcome only by adopting the holistic green marketing approach.

DISCUSSION

Green products are ones that are produced using environmentally friendly technologies and pose no threat to the environment. Major climatic issues like depletion of Ozone layer and Global warming are of much concern and there is constant requirement of monitoring to prevent any climatic hazard. From the point of an organization, financial gain and economic profit are key aspects of growth but with due course of time organizations have realized there is a necessity of building a greener environment. Green marketing offers business bottom line incentives and top line growth possibilities. While modification of business or production processes may involve start-up costs, it will save money in the long term. Companies that develop new and improved products and services with environmental impacts in mind give themselves access to new markets, substantially increase profits, and enjoy competitive advantages over those marketing non environmentally responsible alternatives. Business is adopting more sustainable practices and moral approaches to delivering their goods and services. In report of Deolitte's 2021 'Rethink.Reshape. Rewire' study, 50% respondents have considered climate change as a risky factor that can impact business growth and, in that survey, it was further explored that 31% consumers have perceived to switch to renewable products and prefer to do business with those companies who produce renewable products.

CONCLUSION

The moment is ideal to choose' Green Marketing' internationally right now. If all nations adopt stringent policies, there will be significant changes in the business sector worldwide and it is the need of the hour to produce sustainable products. From a commercial standpoint, a skilled marketer is one who not only persuades customers but also actively includes them in promotion of their goods. Green Marketing includes an environmental and social component; therefore, it should not be seen as just another marketing strategy. Instead, it needs to be pushed with much more zeal. It is crucial that green marketing become the rule rather than the exception or merely a trend given the grave threat posed by climate change.

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GEN AI: UNVEILING THE BLACK BOX

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DOI: https://doi.org/10.64558/bllp/706684vaabgd

ABSTRACT

Generative Artificial Intelligence (GenAI) is the promising contemporary topic in the field of marketing research. This study tries to summarize the applications of GenAI in marketing and its adjacent domains while taking in consideration-attitude/perceptions of concerned stakeholders and the significant challenges posed by GenAI. This study used a systematic literature review of 27 Scopus papers by classifying the articles into four themes - (1) GenAI in advertising, (2) GenAI in innovation, (3) GenAI in services, and (4) Applications/Adoption of GenAI. This study proposes to present a solid understanding of Gen AI's strategic adoption, providing guidance for the marketers, managers, and policymakers navigating this dynamic technological phenomenon.

Keywords: GenAI, Generative Artificial Intelligence, Marketing, Literature review, Academic Research, Advertisement, Service, Innovation, ChatGPT, Data Privacy.

INTRODUCTION

A type of artificial intelligence that can produce a variety of unique content is known as generative artificial intelligence (GAI). It is called "generative" AI because it can produce particular types of output, such as text, audio, images, and video, based on supervised or unsupervised training. It is capable of independently learning and executing a wide range of tasks and ideas (and is currently only hypothetical) (Stening, 2023). Platforms like ChatGPT, Bing AI, Bard, DALL-E 2, and many more are well-known GAI tools in the present era. With the introduction of ChatGPT in November 2022 and the subsequent release of additional large language model (LLM)-based generative AI (GAI) products from Google and Microsoft, interest in artificial intelligence (AI) has skyrocketed. This has led to substantial discussions about the effects of AI in academia and the general public. (Ooi et al., 2025). Google recently announced in May 2023 that their AI language model, PaLM 2, will be integrated with more than 25 products, including Google Maps and Gmail. This announcement articulates a vision of the eventual ubiquity of LLM-based tools, which will "become an unremarkable part of day-to-day life." Additionally, the company revealed that it's own LLM—Bard—will soon enable users to use text- and image-based prompts, demonstrating the quick development of GAI technology (Heikkila, 2023). Alongside model development, the AI-generated content (AIGC) produced by

natural language generation algorithms continues to improve in terms of coherence, consistency, and grammar (Cao et al., 2023).

Businesses are adopting GenAI, developing new skills, and rethinking their strategies to ensure survival and growth in this dynamic environment (Bahoo et al., 2023). Businesses' capacity for innovation has been greatly increased by integrating AI technologies, which has led to notable changes in business models and marketing strategies as well as changes in corporate strategies, operational efficiency, and competitive advantage (Bahoo et al., 2023). Especially in marketing, GenAI is highly used to design advertisements, ideate new product ideas, and generate personalized videos and other content. In addition to that, it is also used in generating marketing communications to different stakeholders. (Hill, 2024).

Studies have begun to examine the implications for organizations and institutions from this revolutionary technology, even though the research in the academic discourse on GAI's simple impact is still in its early stages. While outlining the implications of increased adoption, a number of researchers have also drawn attention to GAI's current shortcomings, including an excessive dependence on a single "source of truth." incomplete, erroneous, or inconsistent results; a lack of explainability and transparency; and inherent bias in the data and algorithms used (Dwivedi et al., 2024).

The rapid integration of GenAI into marketing practices marks a critical moment to investigate its influence on the marketing domain. This comprehensive study attempts to summarize wonderful insights from 27 promising research papers on Gen AI (Generative Artificial Intelligence), highlighting its multifaceted applications and sweeping impact across marketing and adjacent domains in the 21st century, where individuals and corporations are showing a greater enthusiasm in adopting Gen AI. (W Hu, 2023). This study unveils how GenAI boosts organizational capabilities in advertisement, academics, generating quality content for promotion, enhancing customer engagement, triggering innovational ecosystems, leveraging value co-creation, and skill development/reskilling using Systematic Literature Review (SLR). Apart from that, it also shed light on the attitude and perception of GenAI among customers and employees, also including significant challenges related to GenAI like ethical governance, perceived authenticity, IPR, responsible use, and regulatory compliance. By showcasing multidisciplinary viewpoints, it presents a solid understanding of Gen AI’s strategic adoption, providing guidance for the marketers, managers, and policymakers navigating this dynamic technological phenomenon.

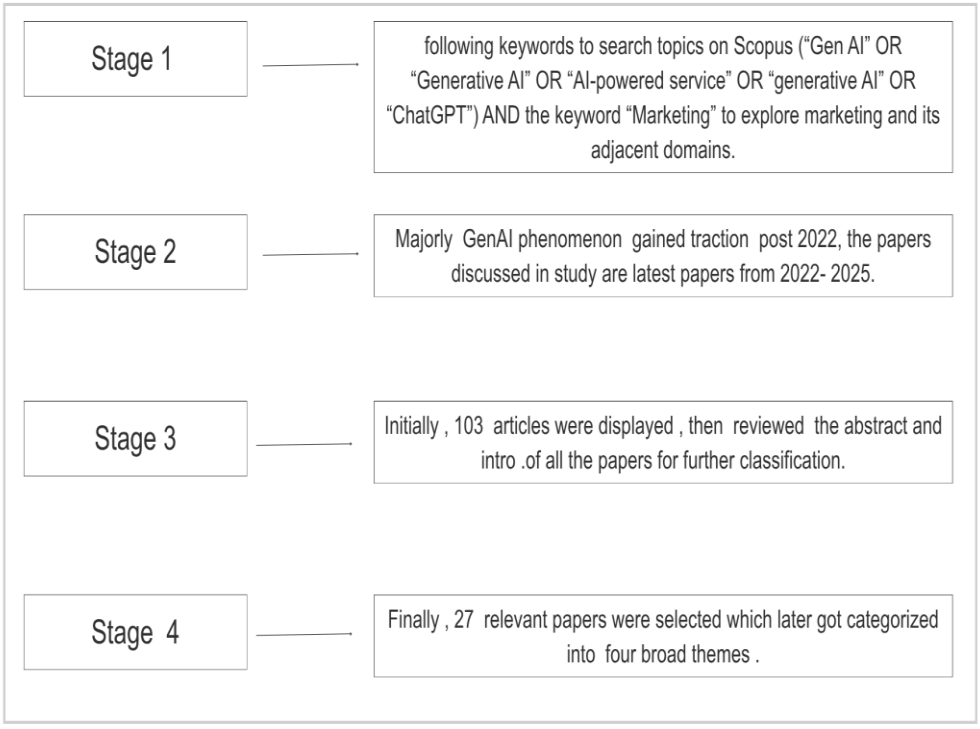
METHODOLOGY

In order to consolidate the wide spectrum of GenAI research, the systematic literature review (SLR) process suggested by Brereton et al. (2007) had been followed. It was tried to consolidate a wide spectrum of

GenAI research among the best journals listed in Scopus between 2022 and 2025. For undertaking the review, Scopus was used as the preferred search engine, as it is highly reliable and widely adopted by academia. The following keywords were used to search topics ("Gen AI" OR "Generative AI" OR "AI-powered service" OR "generative AI" OR "ChatGPT") AND the keyword "Marketing" to explore marketing and its adjacent domains. This initial search displays a total of 103 articles. Mainly, the papers found were between 2022 and 2025. At a later stage, the abstract and introduction section of each article were read out to finalize 27 articles that seemed relevant to this study of marketing and adjacent domains. Diverse industrial contexts like pharmaceuticals, tourism, sports marketing, academics, digital marketing, peer-to-peer platforms, etc. had been collectively covered by these articles, which enriches the scope and value of this study.

These relevant articles were also further classified into four broad themes for better understanding—(1) GenAI in advertising, (2) GenAI in innovation, (3) GenAI in services, and (4) Applications/Adoption of GenAI. For an unbiased, comprehensive, and consistent synthesis of evidence, enhancing the overall research credibility, SLR is used.

Figure 1: Planning of the systematic literature review



REVIEW AND FINDINGS

GenAI in advertising

GenAI is rapidly transforming the advertising industry like never before. Marketing giants like Coca-Cola and Cadbury are using GenAI in their advertisements. Ma and Sun (2020) assert that AI has been and will continue to play a significant role in transforming the marketing industry. The AI marketing landscape is predicted to reach previously unprecedented heights with the advent of GAI, which can produce new content like chat responses, synthetic data, or deepfakes. GAI is disrupting digital search and advertising, social media interaction, and other modern marketing strategies. Large tech corporations have begun utilizing GAI's power in their advertising and other marketing products. Meta revealed earlier this year that it was first inviting a small number of advertisers to test out its proprietary GAI capabilities. At the same time, its main rival, Google, is starting a more widespread deployment of GAI features in its advertising business. (Ooi et al., 2025)

Bijalwani (2025) presents a thorough analysis of how OpenAI's Sora (a Gen AI platform for video creation) is reconfiguring routine jobs in the marketing and advertising domain. They also highlighted the threats, such as job loss and skill redundancy due to GenAI. Talking about perceptions of AI-generated content among audiences, Kirk and Givi (2025) find out that the AI-written emotional communications reduce positive word of mouth (PWOM) and customer loyalty due to the perceived inauthenticity of messages. It also identifies factors or conditions that mitigate or reverse this effect, offering important insights through seven preregistered experiments. While continuing the trend of exploring Gen AI content, Hartmann J. et al. (2025) contributes to marketing literature by demonstrating that state-of-the-art generative AI may produce high-quality, effective marketing images that can outsmart the humans while reducing production costs. It encourages marketers to integrate AI mindfully to optimize creative and commercial outcomes.

This line is extended by Madathil J.C. (2025), whose paper looks at the impact of Gen AI in video ads by classifying them into two types: human-AI collaborative ads and other fully AI-generated character ads without any human presence. The study contributes to marketing literature by applying the Elaboration Likelihood Model to Gen AI ads, showcasing that perceived creativity and AI anxiety act as mediators between types of Gen AI ads and consumer attitudes. It underscores the importance of human participation in AI-assisted ads to boost perceived creativity, reduce anxiety, and improve brand morality. The findings offer insights guiding the balance of innovation with consumer comfort, whereas Seo I. et al. (2025) highlights the evolving role of AI-generated content (AIGC) in the tourism industry, marking differences

from traditional videos. It redefines understanding of authenticity and trust in the AIGC context, also offering critical insights for enhancing video quality and destination appeal, as perceived realism and transparency have a crucial role to play. To set guidelines for the AI-generated advertising, Sean Sands et al. (2024) mention about six guiding principles that can help in responsible GenAI advertising : transparency; respect for privacy and intellectual property; avoidance of bias; ensuring human oversight; establishing clear procedures; and being responsible for AI-driven outcomes.

Table 1. Summarizing articles under the advertising theme

Article	**Methodology**	**Contributions**
Bijalwani et al., 2025	Literature review Blogs	Threats and Opportunities in jobs Levels of automation in job roles.
Kirk and Givi (2025)	Seven preregistered experiments done online Moderation and Mediation Analysis	Investigating consumer responses to AI vs. human-generated marketing communications. Well document the AI authorship effect.
Hartmann J. et al. (2025)	3 part research design involving synthetic images, controlled comparison and real-world campaign testing	Gen AI can produce high-quality images compared to human artists. Guidelines to integrate GenAI thoughtfully in creative outcomes.

adathil J.C. (2025)	Multi-method approach Sentiment analysis of ads and comments. Experimental survey designs	Perceived creativity and AI anxiety mediate the Gen AI video–consumer attitude relation. Insights for designing effective GenAI videos.
Sean Sands et al. (2024)	Systematic Literature Review	Contribute six guiding principles for responsible AI-powered advertising.

GenAI in Innovation

GenAI possesses a unique feature of having high awareness of context and generating customized responses according to it, which boosts its capacity to enhance the innovation process. It has proven its worth in the retail and consumer goods industries through customized marketing and innovative product design, resulting in unique and captivating consumer experiences (Cillo and Rubera, 2024). Additionally, GenAI is transforming innovation management by improving information processing and lowering the risks and expenses associated with conventional innovation processes (Haefner et al., 2021). GenAI has been widely used in marketing across a variety of industries due to its quick ability to produce innovative content (Agrawal et al., 2022).

Cillo and Rubera (2025) build a decent foundation for comprehending the transformative role of GenAI, especially with different innovation components/steps, i.e., developing, testing, communicating, and engaging. It also explores how GenAI can ignite innovative activities within the organizations, while also looking for the consequences of GenAI on two marketing capabilities: market assets and firm value.

Bringing the discussion to complementors (third parties that build interfaces on top of GenAI) platforms—Vincent Heimburg et al. (2025) discusses a fundamental shift from previous digital technologies, stressing the unique challenges of GenAI platforms in respect of complementors. Unlike traditional APIs, these complementors jointly create value within these ecosystems. The authors identify two major hurdles: the open-endedness and inscrutability of GenAI models. To address these, the paper also presents four practical mechanisms, like system instructions, context data, curation of user inputs, and output revision suggestions, as unique solutions for both standalone and embedded complementors.

Ooi K.B. et al. (2025) highlights GAI within Industry 4.0 and acknowledges its capabilities to boost customer engagement, decision-making, creativity, and automation. However, it also points out major concerns like ethical issues, data privacy, false information, skill gaps, and adoption issues. On the other hand, Pagani M and Wind Y (2025) explore the transformative impact of GenAI on marketing creativity and creative processes in business contexts. It gives a solid framework exhibiting how AI can inspire agile creative methods and boost out-of-the-box thinking in marketing, going towards a truly collaborative creativity.

While taking the discourse to the innovation in academic processes fuelled by GenAI, R. Rohan et al. (2023) try to address a crucial concern: can these GenAI tools be capable enough in research tasks like theory building and testing ? The article focuses on the challenge of measuring some latent constructs in IS while validating the theory-testing capabilities of ChatGPT. Whereas Scott-Kennel et al. (2025) examines whether GenAI chatbots like ChatGPT, Gemini, Perplexity, and Claude really act as genuine collaborators, constructivist tools, or potential cheats in academic research within marketing. It checks the validity of the idea to integrate GenAI at various stages of the research process—such as literature review, research gap identification, theory alignment, and methodological design—all through a constructivist lens.

Table 2. Summarizing articles under Innovation theme

Article	**Methodology**	**Contributions**
Cillo and Rubera (2025)	Rigorous technical review In-depth qualitative Research process	Investigate consequences of GenAI on firm marketing capabilities (market assets, firm value)

Vincent Heimburg et al. (2025)	Embedded case study design 44 semi-structured interviews	Present practical mechanisms like system instructions, context data, curation of user inputs, and output revision for both kinds of complementors.
R Rohan et al (2023)	Two structured experiments Tested a complex extended model while including TAM theory	Investigating ChatGPT utility in IS for understanding latent constructs and theory testing.
Ooi K.B et al. (2025)	Used a qualitative and multidisciplinary method with an expert-based viewpoint approach.	Presents cross-disciplinary perspectives on how GAI is impacting org. processes.
Pagani and Wind (2025)	Mixed-method approach Qualitative interviews followed by quantitative analysis.	Actionable insights for leveraging AI in creative strategy. Moving beyond automation to collaborative activity.
Scott-Kennel et al. (2025)	Adopted a PAR approach comprising iterative engagements. Use CLT theory to frame the analysis.	Systematically dissecting GenAI in marketing academic research.

GenAI in services

Generative artificial intelligence (GenAI) is one of the few disruptive technologies that has the potential to drastically and quickly affect the service operations. Although they can be used to supplement functions and improve work and enable service providers to perform their jobs more effectively. With a better grasp of GenAI's potential and constraints, service operations can profit from it. (Ooi et al., 2025) GenAI has a lot of immense potential to enhance services by facilitating hyper-personalization, automating routine tasks, improving customer interactions, etc. It is widely used for bringing efficiency and better service delivery in various industries. GenAI automates certain customer service interactions, staff management, and other mid-level tasks. Strategically, GenAI can assist managers in managing knowledge and synthesizing data to produce recommendations based on logic. (Korzynski and others, 2023).

Westerbeek H. (2025) looks at how GenAI is fundamentally reshaping sports industry marketing by enabling hyper-personalized fan engagement, real-time content creation, and data-driven strategies. By referring to GenAI as a transformative but ethically complex force, it frames guiding principles to foster responsible innovation while maintaining the integrity of the sports industry in this new age.

Another stream of literature talks about content creators and sponsored content. Arsel Z. et al. (2025) term sponsored content as an epistemic market object that drives marketing functions but is hardly understood in its entirety by creators, brands, and intermediaries. It showcases how valuation and coproduction ambiguities generate power asymmetries and incomplete knowledge work, which in turn fundamentally reshape market actor relationships in digital marketing ecosystems. It also offers actionable recommendations for balancing stakeholder interests to foster collaboration and trust. Pushing the discussion to the hospitality and tourism industry, Dogru T. et al. (2025) examines the role of GenAI in the above-mentioned sector, exploring its potential across different business functions—this paper uniquely integrates expert perspectives to highlight both the promising innovations and pitfalls of GenAI, giving the opportunity to harness GenAI responsibly in the hospitality and tourism industry.

On similar lines, J. Yu and T. Meng (2025) explore the role of GenAI in tourism marketing, especially in destination imagery creation, personalization, and increasing consumer engagement across different stages of the tourist journey. This article contributes a conceptual framework linking to the technical capabilities of image GenAI within tourism marketing paradigms, along with indicating cautions about ethical challenges like authenticity, cultural misrepresentation, and privacy. Apart from that, Anil Bilglihan et al. (2025) covers the wide array of GAI’s applications and challenges, especially in the hospitality and tourism industry, calling on future researchers to propose a dedicated conceptual model, while this paper’s key

contribution is a well-structured framework that clarifies how GAI's diverse intelligences enhance marketing processes and outcomes while dealing with critical issues.

In addition to that, shaping the students to be ready for evolving Gen AI-shaped job markets, Grewal D. et al. (2025) stresses the urgency for educators and policymakers to update academic curricula and teaching methods to prepare students for a future job market where AI-related skills are demanded by employers. This study also provides a critical roadmap for transforming marketing pedagogy, instructing educators to integrate AI, analytics, and technology-enabled pedagogy while mentioning the challenges across all topics.

Table 3. Summarizing articles under Services theme

Article	**Methodology**	**Contributions**
Westerbeek H. (2025)	Narrative Literature review method Articles between 2022-2025	Conceptual integration of sports – consumer behaviour. Guiding principles for enabling responsible innovation.
Arsel et al. (2025)	Large-scale qualitative study Analyzed third-party platform reviews and comments.	Presents recommendations for balancing the interests and flattening hierarchical partnerships.
Dogru et al. (2025)	Inductive collaborative approach using the REFLECT model.	Integrates different expert perspectives highlighting innovations and pitfalls of GenAI
Yu and Meng (2025)	Used comprehensive literature review Theoretical Synthesis approach	Developed a conceptual framework linking the technical capabilities of image GenAI with tourism marketing.

Grewal D. et al. (2025)	Comprehensive review of marketing education paradigms. Analyzing themes and trends.	Provides a roadmap for transforming marketing education—connecting educational connections with industry needs.
Anil Bilglihan et al. (2025)	Analyzing prior theoretical frameworks for key GenAI functions.	A well-structured framework for how GAI enhances marketing processes and outcomes.

Applications/Adoption of GenAI.

The wide range of human-oriented tasks, such as software coding, image creation, music production, and content creation for multiple applications, are expected to be drastically disrupted by the widespread adoption of GAI (Dwivedi et al., 2023). ChatGPT became the fastest-growing app by registering over 100 million users within a couple of months of its launch. Corporate houses are quite enthusiastic about using GenAI in different functions to gain cost efficiency and better services. Research has shown that GAI technology is likely to disrupt the creative industries, including music, film, and art, as well as the healthcare sector, including supply chain management, manufacturing design, gaming development, medical diagnosis, and finance (Jo, 2023).

A study by Grewal D. et al. (2025) unveils amazing insights into how GenAI is set to transform the marketing discipline. It contributes to literature with a practical four-quadrant framework that helps organizations choose GenAI tools based on two critical factors: the level of input customization and the degree of human augmentation required before deploying the GenAI output.

On the other hand, talking about GenAI concerns, Reed C. et al. (2025) highlights the risk of algorithmic bias (gender, racial, and cultural distortion) increasing. This study brings an analytical framework for detecting and managing bias in AI-driven digital marketing, covering both traditional AI and GenAI applications. It also introduces a concrete checklist for practitioners and researchers, showing how biases can arise across all stages of the customer journey.

Moving ahead, Faruk M. et al. (2025) explains how GenAI tools like ChatGPT are reshaping digital business. Developing economies like Bangladesh are increasingly using GenAI tools for content creation, automation, and strategic

improvements. The paper summarizes a wide review of ChatGPT's usefulness across different sectors, revealing that content creation, SEO optimization, and product description are the major drivers for ChatGPT usage, while lead generation has a negative relation. Other variables like email marketing, social media management, customer relationships, and marketing research were not very significant in GenAI usage.

GenAI-enabled learning is discussed by Narang U. et al. (2025)—as it calls for updating the curriculum to better equip the graduates with relevant GenAI skills. GenAI promises to enhance learning through personalized teaching, collaborative problem-solving, and efficient data analysis but also points out some significant risks, such as overreliance on GenAI tools, diminished student autonomy, ethical concerns (like privacy and plagiarism), and inequities in access. This paper attempts to develop a comprehensive framework for GAI's optimum use by conceptualizing its roles as tutor, teammate, and tool within marketing subjects.

Unveiling the role of GenAI tools in the pharmaceuticals industry, which has stringent regulations and distinct communication challenges, Vitellaro F. et al. (2025) proposes a conceptual framework extending the UTAUT2 technology adoption model by integrating a new psychological factor—fear of obsolescence. It also showcases that while GenAI enhances operational efficiency and creativity in marketing communication, human creativity and oversight remain irreplaceable. while Fan N. et al. (2025) examines the increasing influence of AI-generated content (AIGC) in peer-to-peer accommodation markets, especially Airbnb, where listing descriptions have a critical role in consumer decision-making. This paper contributes to literature by enhancing signaling theory by displaying how nuanced linguistic signals in GenAI descriptions affect consumer visibility and bookings.

In addition to the above articles, Chan H. et al. (2025) provided a structured classification of existing literature and pragmatic insights related to industry applications. It finds out the critical research gaps and presents a proposal to guide future studies on GenAI's role in enhancing marketing performance along with mitigating the inherent risks. This article attempts to bridge the gap between academic research and industrial practice while keeping concerns and limitations in mind.

With a different geographical context, Huang X. et al. (2025) explores Chinese millennials' purchase intentions toward clothing apps featuring AI-generated patterns from premium fashion brands, combining the Theory of Planned Behavior (TPB) and Customer Perceived Value (CPV). This study indicates that perceived brand design effort and price value significantly increase purchase intention, but perceived variety does not, challenging some established assumptions about variety in the AI-driven fashion industry.

Talking of dual responses about Gen AI in education from students, Pavone G. (2025)

highlights that some students find AI empowering for their learning, while some also have legitimate concerns regarding dependence, academic legitimacy, and the anxiety of automation, particularly when individual psychological traits like self-esteem and academic anxiety come into the picture. This study provides educators guidance on building more inclusive and supportive environments for AI integration and stresses the importance of customized learning approaches in an AI-driven era.

Table 4. Summarizing articles under the Applications/Adaptation theme

Article	**Methodology**	**Contributions**
Grewal D. et al. (2025)	Multi-pronged qualitative and empirical approach.	Ideates a four-quadrant framework based on two critical factors: degree of input customization and level of human augmentation.
Reed C. et al. (2025)	Systematic Literature Review (PRISMA flow) An inductive, qualitative case study	Proposes an analytical framework for detecting and managing bias in AI driven digital marketing.
Faruk M. et al. (2025)	Mixed –method approach, qualitative literature review and quantitative survey implementing regression and ANNOVA.	Finding that Content Creation, SEO Optimization, and Product Description are the main drivers for ChatGPT usage, while Lead Generation even has a negative effect.

Narang U. et al. (2025)	Multi method approach on role theory and community of inquiry theory.	A comprehensive framework for GAI role in education as a tutor, teammate and tool within marketing courses.
Vitellaro F. et al. (2025)	Exploratory qualitative methodology in-depth interviews. Gioia method using NVivo software.	Proposes a conceptual framework extending UTAUT2 model by including a factor – fear of obsolescence.
Fan N. et al. (2025)	Experiments based on Prediction – Interpretation – Inference machine learning framework	Enriches signaling theory by explaining the impact of nuanced linguistic signals on AI generated descriptions.
Chan H. et al. (2025)	Systematic Literature Review from databases like Web of Science and Scopus	Offering a structured classification of existing literature and practical insights into industry applications.

Huang X. et al. (2025)	Quantitative approach with purposive sampling SEM for hypothesis testing.	Actionable insights for premium brands on communicating human–AI collaboration in design.
Pavone G. (2025)	Mixed Methods Approach	Provides educators with guidance on creating more inclusive and psychologically supportive environments for AI integration

CONCLUSION -

Generative Artificial Intelligence (GenAI) is the promising contemporary topic in the field of marketing research. Along with that, it has been predicted by scholars to be a disruptive technology tool in various components of marketing (Hau, 2025). Inspired by the relevance of GenAI in marketing and its adjacent domains while taking consideration of the attitudes/perceptions of concerned stakeholders and the significant challenges posed by GenAI, we come up with this paper. This study is one of the first attempts to comprehensively consolidate a wide spectrum of Gen AI research among the best journals listed in Scopus between 2022 and 2025 with a Systematic Literature Review (SLR) methodology, bringing together the theoretical constructs with practical insights across diverse industrial contexts. Then, based on the collected papers, we have classified the articles into four themes - (1) GenAI in advertising, (2) GenAI in innovation, (3) GenAI in services, and (4) Applications/Adoption of GenAI. Prevalent use of GenAI in marketing activities and decision-making is promising for corporate houses and consumers too, yet it is still at the infant stage of a mass adoption process. This study is poised to contribute to the marketing domain in a unique way by providing a nuanced view of GenAI for the concerned stakeholders like marketing managers, academicians, innovators, and policymakers to best harness the potential benefits of GenAI along with taking care of the concerns posed by it. It adds value to the existing

literature by collating different dimensions of recent GenAI research to chart a roadmap for better and more informed decision-making.

Future Research Direction and Limitations—

Fast-paced integration of GenAI and marketing has led the firms to be more creative, agile, and customer-centric. It had been a matter of fact that from algorithm-based personalization to generative content-based systems, marketing has come a long way in terms of AI usage for creativity, collaboration, and as a strategic agent. Yet publications that surged from 2022 to 2025 have substantial knowledge gaps in terms of theory and methodology.

Future research should focus more on longitudinal studies for tracing how GenAI reshapes innovations, customer relationships, and marketing performance**.** Moreover, future studies should focus on human-AI collaborations in advertising, creating content, and creatively co-creating value with marketers. In addition to that, focus should also be towards more comparative studies, as marketing is a diverse domain; comparative studies would better help enhance Gen AI and marketers' value co-creation.

Further diffusion of AI in small and medium enterprises (SMEs) and in emerging markets like India needs considerable attention. Researchers should also focus on developing clear metrics to measure GenAI's contribution to marketing outcomes while focusing on strengthening ethical grounds regarding transparency, privacy, and accountability issues. Major areas that need more exploration include AI literacy enhancement to increase GenAI adoption and governance and regulatory compliance issues in emerging markets.

Finally, this study recognizes its limitations, as it draws a small sample size of 27 articles from only one database between the time frame of 2022 and 2025. Studies including other important databases and for a longer timeframe would bring in more insights for the marketing domain.

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DOES THE COVID-19 HEALTH EMERGENCY IMPACT THE INTEGRATION OF PRECIOUS METALS AND THE INDIAN EQUITY INDEX? A TIME-VARYING APPROACH TO CONNECTEDNESS AND SPILLOVER.

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DOI: https://doi.org/10.64558/bllp/926140nfzysf

INTRODUCTION

In this current globalised and interconnected world, the fundamentals of the one financial asset may have an impact on the other financial assets. The correlations among the financial assets and its dynamics evolves in time, which has grabbed the attentions of the researchers or fund managers to understand the dynamics, at different time frame. From the ground breaking work of (Markowitz, 1952) Modern Portfolio Theory, it can be understand that negatively correlated assets helps in reducing the overall portfolio risk. This has led to creation of several Market portfolios, however, remained unanswered the systematic risk in this context. During the Global Financial Crisis, none of the insights has able to mitigate the exposure of the portfolios, and Crash impacted all the portfolios. From this instance, the concept of the connectedness and contagion came into existence. The investigations in this domain has increased in the number on Connectedness issues across the different assets in different markets. This venture in exploring the connectedness in one assets or market with another assets or market is the main interest of the researchers of the domain, so that they can hedge the portfolios, or reduce the systematic risk of a portfolio with another asset.

In this quest, several papers investigated the connectedness at the different market level, inquiring about the market integration and connectedness among the asset's systematic and return and volatility spillover such as (Al Hajj et al., 2024; Ali et al., 2024; Antonakakis et al., 2020; Chang, Chang, & Lee, 2023, 2023; Chang, Chang, Ling, et al., 2023, 2023; Das et al., 2025; Dhingra et al., 2025; El Khoury et al., 2024; Gazi et al., 2024; Gökgöz et al., 2025; Guru et al., 2023; Kumar & Gupta, 2025; Mishra et al., 2024; Panazan et al., 2024; Panda et al., 2023; Younis et al., 2023). Where it has been observed that market connectedness increases during crisis periods such as (Das et al., 2025). In which, Russia and Brazil were the net transmitters of the volatility to the system, while India, China, and South Africa are the net volatility receivers in the system. One study has explored the geopolitical risk and the stock market volatility in the SAARC region. The study concludes that their strong connection between India and Bangladesh stock market, while the connection between geopolitical concerns and Sri Lankan stocks was the strongest and increased in intensity after 2019 (Panazan et al., 2024).

Similarly, several others authors considered the Financial assets connectedness as their area of interest (Babar et al., 2024a, 2024b; Belhassine & Karamti, 2021; Hanif et al., 2024; Mensi et al., 2021, 2025; Mohamed Dahir et al., 2020; Ramesh et al., 2024; Rehman et al., 2023, 2023, 2024; Siddiqui & Roy, 2021; Singh et al., 2024; Sundararajan & Balasubramanian, 2025; Wan et al., 2024; Ye & Geng, 2021). In which, (Chang, Chang, & Lee, 2023) used quantile connectedness approach to investigate the relationships of oil shocks and the BRICS stock market, and Russia and South Africa plays the net transmitting roles, while the Brent oil, India, and Shanghai are net recipients for most time. The connectedness has strengthened when facing the market crisis such as the global financial crisis, European debt crisis,

and Covid-19 periods.

In this market connectedness area, another strand of the studies focuses on the Oil shocks on the markets (Chang, Chang, Ling, et al., 2023; Guru et al., 2023; Hanif et al., 2024; Mensi et al., 2025; Ramesh et al., 2024; Rehman et al., 2023, 2024; Tiwari et al., 2025), and few others on the commodities such as golds, agricultural commodities, energy commodities and commodity futures except the Oil (Babar et al., 2024a, 2024b; Mensi et al., 2021; Younis et al., 2023; Zeng et al., 2023), some are on the ESG stocks indexes (Singh et al., 2024; Wan et al., 2024), and very few are on the health stock indexes such as (Chatziantoniou et al., 2022; Smolo et al., 2022; Ye & Geng, 2021).

From the literature of the Connectedness, we found that most of the studies concludes that during the crisis period, the connectedness of the financial assets increased which due to increased fears, and panic which is precondition to the contagion concept. However, from the portfolio diversification perspective, this connectedness of the assets increases the systemic risk of the invested assets during the crisis period across the globe. The less connected stocks can be used for hedging against target portfolio. Additionally, from the literature it has been observed that very few studies have focused onthe Commodities and the Equity market combined, therefore, this aims to add to the connectedness literature insights from the Commodities (e.g., Gold, and Silver) and Equity (Nifty 50 Index). In this study, we aim to investigate the inter-relationships of the Gold, Silver, US dollar index, Nifty50 index and Indian VIX Index in the covid 19 context. Our study has been targeted to know that which assets were the transmitters of shock to the system and how this relationship has impacted during the covid 19 periods? How the connectedness of the financial assets has evolved in the covid 19 periods?

The empirical results from our study unveils that Precious Metals such as Gold and Silver emerged as significant transmitters of the uncertainty of the system during the covid-19 crisis period. The systemic inter-assets connectedness has remained high even after the post-covid periods. Finally, Indian VIX and US Dollar Index was the net receivers of the systematic risks. However, the US dollar index's role of net receiver has heightened during the during the covid-19 period. The findings highlight the importance of dynamic risk assessment, particularly in times of market stress. Investors and policymakers must account for the fact that inter-market linkages intensify during systemic shocks and may not fully dissipate in the aftermath.

DATA AND METHODOLOGY

Data Collection

This study has considered the Gold, Silver (precious metals) as commodities of interest for assets diversification, with Nifty 50 index. In which, to capture the dependence on the US dollar index of the above commodities and Indian VIX to capture the volatility dynamics in between the different assets class. Daily price data has been collected from the Yahoo Finance website using the tickers of the R studio. Then closing prices were transformed to logged returns used for final study for the period starting from 01-07-2016 to 30-06-2025. We divided our sample into three different periods, for capturing the effects of the Covid-19 as major health crisis in this relationship. First, we have started with 01-07-2016 to 29-01-2020, and called pre- covid period. Second period starts from the day when WHO declared COVID-19 as a public health emergency (i.e., 30-01-2020) to end with 31-05-2020, as WHO declared COVID-19 as a Global pandemic on 11th March 2020. Thirdly, post-covid period, period starting from 01-06-2020 to 30-06- 2025.

METHODOLOGY

This study employs the Time-Varying Parameter Vector Autoregression (TVP-VAR) based Connectedness Approach, as developed by (Antonakakis et al., 2020), to examine the dynamic interrelationships among five key financial variables: Gold, Silver, US Dollar Index, Nifty 50, and the India VIX. Our methodology portion, builds on the foundational spillover index framework proposed by (Diebold & Yilmaz, 2012; Diebold & Yılmaz, 2014) while incorporating time-varying dynamics to better capture structural changes and crisis-induced volatility.

The TVP-VAR Mode

Let y_t be an $N \times 1$ vector of variables. We specify a TVP-VAR(p) as:

$$y_t = \Phi_{t,1} y_{t-1} + \Phi_{t,2} y_{t-2} + \cdots + \Phi_{t,p} y_{t-p} + \varepsilon_t, \qquad \varepsilon_t \sim N(0, \Sigma_t) \quad \ldots\ldots \; Eq.(1)$$

or more compactly:

$$y_t = \Phi_t Z_{t-1} + \varepsilon_t \quad \ldots\ldots \; Eq.(2)$$

Where:

$Z_{t-1} = (y'_{t-1}, y'_{t-2}, \ldots, y'_{t-p})'$ is an $Np \times 1$ lag vector,

Φ_t is an $N \times (Np)$ time-varying coefficient matrix,

Σ_t is the time-varying covariance matrix of the residuals.

This model allows the coefficients Φ_t, Σ_t to evolve over time and assumed to be follows the law of motions.

From TVP-VAR to Generalized FEVD

To compute connectedness measures, the TVP-VAR model is converted at each time t into its moving average (MA) representation:

$$y_t = \sum_{h=0}^{\infty} A_{h,t} \varepsilon_{t-h} \quad \ldots\ldots \; Eq.(3)$$

Where $A_{0,t} = I$, and $A_{h,t}$ are derived recursively from the Φ_t. Then the Generalized Forecast Error Variance Decomposition (GFEVD) at Horizon H is computed:

$$\Theta^{(H),g}_{ij,t} = \frac{\sigma_{ii,t}^{-1} \sum_{h=0}^{H-1} (e_i' A_{h,t} \Sigma_t e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_{h,t} \Sigma_t A_{h,t}' e_i)} \quad \ldots\ldots \; Eq.(4)$$

Here:

$\sigma_{jj,t}^{-1}$ is the j^{th} diagonal elements of Σ_t.

e_i is a selection vector with 1 at position i and 0 elsewhere.

The numerator captures the influence of shocks in variable j on variable i; the denominator is the total forecast error variance of i.

Because of non-orthogonal shocks, the row sums $\Theta^{(H),g}_{ij,t}$ need not be unity.

We normalize the decomposition row-wise:

$$\tilde{\Theta}^{(H),g}_{ij,t} = \frac{\Theta^{(H),g}_{ij,t}}{\sum_{j=1}^{N} \Theta^{(H),g}_{ij,t}} \quad \ldots\ldots \; Eq.(5)$$

So that,

$$\sum_{j=1}^{N} \tilde{\Theta}_{ij,t}^{(H)} = 1 \ldots \ldots Eq.(6)$$

and summing over all i, j gives N.

Connectedness Measures

From the normalized GFEVD matrix $\tilde{\Theta}_t^{(H)} = [\tilde{\Theta}_{ij,t}^{(H)}]$, one derives the standard connectedness metrics.

Directional "TO" (Contribution to others):

$$C_{j\rightarrow\cdot,t}^{(H)} = \sum_{i=1}^{N} \tilde{\Theta}_{ij,t}^{(H)} \underline{\underline{=}} \, i \neq j$$

Directional "FROM" (Contribution from others):

$$C_{\cdot\leftarrow i,t}^{(H)} = \sum_{i=1}^{N} \tilde{\Theta}_{ij,t}^{(H)} \underline{\underline{=}} \, i \neq j$$

Net Connectedness:

$$NET_{i,t}^{(H)} = C_{\cdot\leftarrow i,t}^{(H)} - C_{j\rightarrow\cdot,}^{(H)}$$

Total Connected Index (TCI):

$$TCI^{(H)} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} \tilde{\Theta}_{ij,t}^{(H)}}{N} \underline{\underline{=}} \times 100$$

Net Pairwise Directional Connectedness:

For every pair (i, j):

$$NPDC_{ij,t}^{(H)} = \tilde{\Theta}_{ji,t}^{(H)} - \tilde{\Theta}_{ij}^{(H)}$$

This shows whether $i \rightarrow j$ dominated or $j \rightarrow i$ dominated at time t.

NETWORK CONNECTEDNESS:

The network connectedness comes from the NPDC measures, Network connectedness refers to the graphical representation of pairwise directional spillovers between variables in the connectedness framework. It's a network where:

- Nodes represent variables (e.g., Gold, Silver, Dollar Index, etc.),
- Edges (arrows) represent spillovers from one variable to another,
- Edge thickness reflects the strength of the directional connectedness

EMPIRICAL RESULTS:

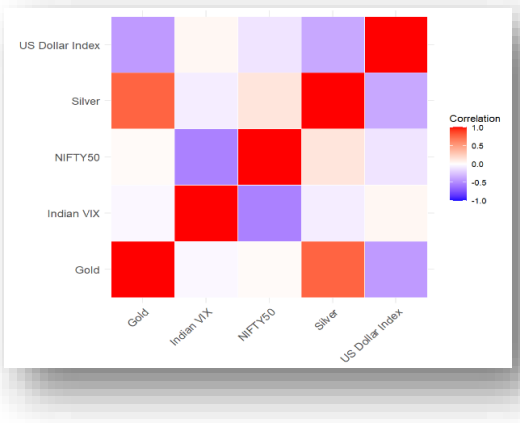
Preliminary results:

The descriptive statistics given *Table 1*. The correlations heatmap into the *Figure 1*, shows the strength of the Correlations between the Precious metals with Equity variables. *Table 1*, the highest average value has been observed in the Nifty 50 Index, followed by Gold, silver, US Dollar Index and the Indian VIX with a negative mean value with highest variations (i.e., S.D). All the variables except the Indian VIX is negatively skewed, whereas Nifty 50 index has Highest Kurtosis values. The ADF test shows that series are stationary at levels. The values are only log changes. To get the percentage changes of each variable, we need multiply the 100 with each value. In the *Figure 1*, the correlation heatmap which ranks positively correlation (i.e., +1) coloured as Red whereas negatively correlation (i.e., –1) coloured as Blue. Where Gold and Silver returns exhibit a strong positive correlation (0.77), Gold and USD Index are negatively correlated (–0.43), while Silver and USD Index also share a negative relationship (–0.38). Additionally, NIFTY50 returns have a strong negative correlation with Indian VIX (–0.54), NIFTY50's correlations with Gold (0.03) and Silver (0.14) are close to zero, indicating minimal linear association. This suggests Gold and Silver can function as hedges or diversifiers in equity portfolios, especially during stress periods when correlations may turn negative.

Table 1: The Descriptive Statistics

Variable	Mean	Std Dev	Min	Max	Skewness	Kurtosis	ADF p-value
Gold	4.00E-04	0.0097	-0.0511	0.0578	-0.2172	6.8044	0.01
Silver	3.00E-04	0.0188	-0.1239	0.0888	-0.5247	8.4186	0.01
US Dollar Index	8.48E-06	0.0043	-0.0308	0.0197	-0.2107	5.5359	0.01
Nifty 50	5.00E-04	0.0107	-0.139	0.084	-1.4884	25.0333	0.01
Indian VIX	-1.00E-04	0.0531	-0.3531	0.5046	0.9041	12.2261	0.01

Figure 1: The correlation heatmap



Connectedness Results:
Static connectedness

By employing the (Antonakakis et al., 2020) methodology, we first presented the spillover Table of the Variables in *Table 2*. Where upper portion of *Table 2* shows the spillover for the pre-covid period, the middle portion, reveals the during the covid period. And lastly, the lower portion, shows that post- covid period, Connectedness.

Table 2 (UPPER) Spillover the pre-COVID period

Variable	Gold	Silver	US Dollar Index	Nifty 50 Index	Indian VIX	FROM
Gold	51.2	32.83	14.03	0.91	1.03	48.8
Silver	33.63	53.17	10.54	1.66	1.01	46.83
US Dollar Index	17.91	12.95	67.2	1.12	0.82	32.8
Nifty 50 Index	1	2.27	1.29	69.84	25.6	30.16
Indian VIX	0.8	0.97	0.77	26.32	71.13	28.87
TO	53.34	49.02	26.64	30.01	28.46	187.47
Inc.Own	104.54	102.19	93.84	99.84	99.59	cTCI/TCI
NET	4.54	2.19	-6.16	-0.16	-0.41	46.87/37.49

Table 2 (MIDDLE) Spillover during the COVID-19 period

Variable	Gold	Silver	US Dollar Index	Nifty 50 Index	Indian VIX	FROM
Gold	47.75	34.32	8.75	5.65	3.53	52.25
Silver	34.4	47.59	5.3	4.74	7.98	52.41
US Dollar Index	11.98	10.49	62.67	7.83	7.03	37.33
Nifty 50 Index	7.52	10.39	2.64	58.1	21.35	41.9
Indian VIX	5.1	8.53	3.73	23.02	59.62	40.38
TO	59	63.73	20.42	41.24	39.88	224.27
Inc.Own	106.75	111.32	83.09	99.34	99.5	cTCI/TCI
NET	6.75	11.32	-16.91	-0.66	-0.5	56.07/44.85

Table 2 (LOWER) Spillover the post-COVID period

Variable	Gold	Silver	US Dollar Index	Nifty 50 Index	Indian VIX	FROM
Gold	53.53	33.1	11.51	0.9	0.96	46.47
Silver	32.91	54.06	10.43	1.5	1.11	45.94
US Dollar Index	14.29	13.14	67.73	2.85	1.99	32.27
Nifty 50 Index	1.33	2.14	2.91	69.04	24.58	30.96
Indian VIX	1.04	1.32	1.56	26.02	70.06	29.94
TO	49.56	49.7	26.41	31.26	28.65	185.58
Inc.Own	103.09	103.76	94.14	100.31	98.7	cTCI/TCI
NET	3.09	3.76	-5.86	0.31	-1.3	46.39/37.12

The Table 2, has estimated the spillover effects and inter-connectedness of the investible assets. In this section, we will see that whether US Dollar Index and Indian VIX Index, indeed makes an influence in the relationships of the Commodities with Equity market. This section also unveils the transmitters/ receivers of the spillover in the system, additionally, revealing the net transmitters of the spillover in the system. In which, Table 2 (Upper), presents the spillover of the pre covid periods, where the corrected total connectedness index is 46.87%. It means that nearly 47% of the variance of the system due to the cross variables shocks. In this period, Gold is the largest transmitters of among the others in the system (53.34), next is the Silver (49.02) followed by the Nifty 50 Index (30.01), Indian VIX Index (28.46) and US Dollar Index (26.64). While the largest receiver of the spillover is the Gold (48.8) which is 26% of the overall spillover received. Followed by the Silver (46.83) [24.97%], US Dollar Index (32.8) [17.49%], Nifty 50 Index (30.16) [16.08%] and Indian VIX Index (28.87) [15.39%].

In the Pairwise spillovers, the largest spillover happened between Gold and Silver, where spillover from Gold to Silver (32.83), and the Silver to Gold (33.83). Similarly, Between Nifty 50 Index and India VIX Index spillover from Nifty 50 Index to India VIX Index (25.6) and the India VIX Index to Nifty 50 Index (26.32). However, the US Dollar Index's largest pairwise spillover was to Gold (17.91). In the whole system, the Gold and Silver acts as the net transmitters of the spillover, whereas, US Dollar, Nifty 50 and India VIX Indexes acts as net receiver of the spillover where US Dollar is the highest spillover receiver in the system then the India VIX and followed by Nifty 50 Index.

Table 2 (Middle), shows the spillover during the covid periods, in which, the corrected total connectedness index of the whole system has increased to 56.07% which is nearly 19.5% increase in the connectedness of the total system. In this period, Silver is the largest transmitters of among the others in the system (52.41), next is the Gold (52.25) followed by the Nifty 50 Index (41.9), Indian VIX Index (40.38) and US Dollar Index (37.33). While the largest receiver of the spillover is the Silver (63.73) which is 28.4% of the overall spillover received. Followed by the Gold (59) [26.3%], , Nifty 50 Index (41.24) [18.39%], Indian VIX Index (39.88) [17.78%] and US Dollar Index (20.42) [9.1%].

In the pairwise spillover, the largest spillover happened between Gold and Silver, where spillover from Gold to Silver (34.32), and the Silver to Gold (34.4). Similarly, Between Nifty 50 Index and India VIX Index spillover from Nifty 50 Index to India VIX Index (21.35) and the India VIX Index to Nifty 50 Index (23.02). However, the US Dollar Index's largest pairwise spillover was to Gold (11.98). In the whole system, the Gold (6.75) and Silver (11.32) acts as the net transmitters of the spillover, whereas, US Dollar (–16.91), Nifty 50 (–0.66) and India VIX (–0.5) Indexes acts as net receiver of the spillover where US Dollar is the highest spillover receiver in the system then the Nifty 50 Index and followed by India VIX.

Table 2 (Lower), unveils the spillover post covid period. The corrected total connectedness index (cTCI) of the (Antonakakis et al., 2020) shows that the spillover of the post covid periods, in which, the corrected total connectedness index of the whole system has decreased to 46.39%. In this period, Gold is the largest transmitters of among the others in the system (46.47), next is the Silver (45.94) followed by the US Dollar Index (32.27), Nifty 50 Index (30.96) and

Indian VIX Index (29.94) . While the largest receiver of the spillover is the Silver (49.7) which is 26.78% of the overall spillover received, which is marginally higher than the Gold (49.56) [26.7%], followed by Nifty 50 Index (31.26) [16.84%], Indian VIX Index (28.65) [15.43%] and US Dollar Index (26.41) [14.23%].

In the pairwise spillover, the largest spillover happened between Gold and Silver, where spillover from Gold to Silver (33.1), and the Silver to Gold (32.91). Similarly, Between Nifty 50 Index and India VIX Index spillover from Nifty 50 Index to India VIX Index (24.58) and the India VIX Index to Nifty 50 Index (26.02). However, the US Dollar Index's largest pairwise spillover was to Gold (14.29). In the whole system, the Gold (3.09), Silver (3.76) and Nifty 50 (0.31) acts as the net transmitters of the spillover, whereas, US Dollar (–5.86) and India VIX (–1.3) Indexes acts as net receiver of the spillover where US Dollar is the highest spillover receiver in the system followed by India VIX.

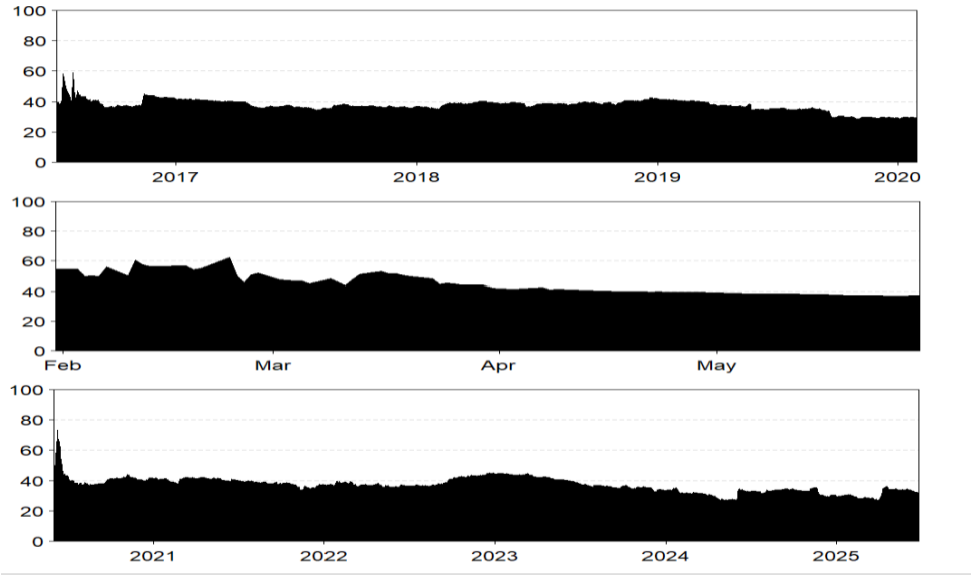
From the static connectedness analysis, it can be seen that the covid-19 health pandemic has increased the systematic risk from 46.87% to 56.07% people investing in this system. However, the linkages of the spillover unveil that specifically, during the covid periods, the shocks of the Precious Metals and the dollar sentiment have increasingly impacted the spillover to the Nifty 50 Index and India VIX Index. And in the post-covid periods these changes went back to the normal status quo. On the other hand, the shocks of the Indian VIX Index reveals that significantly increased spillover from the Indian VIX to the Gold, Silver and US Dollar Index, while decreased spillover to the Nifty 50 Index (from 26.32 to 23.02 and again went back to normal 26.02). On that this similar front, the shocks of the Nifty 50 Index have the increasingly high spillover to the Gold, Silver and US Dollar Index during the Covid

periods, while decreasing spillover during this period to the Indian VIX Index (from 25.6 to 21.35 again came back to normal 24.58 post covid).

Dynamic Connectedness

The time-varying nature of the connectedness measures has been observed by the (Ferrer et al., 2018), thus the understanding the dynamic connectedness and whether the connectedness has remained same as revealed by the static models, is utmost important in the study of the Connectedness of the Asset literature. We explore the time-varying spillover by using rolling windows of 200 days for pre-covid and post-covid periods. However, this rolling window needed to be changed for the during the covid periods, as during the covid period, our sample was 77 trading days, we respect to this, we used 30 days as the rolling windows. While keeping all the settings same, proceeded with the analysis and completed our dynamic connectedness analysis. Our results were robust with very little changes of the rolling windows and forecast horizons. The *Figure 2*, reveals the Total Connectedness Index for all the three periods, we considered in our study, in which, *Figure 2 (Upper)*, show the pre-covid period connectedness of the system, *Figure 2.*

Figure 2: The Time-Varying Connectedness of the System



(Middle), show the connectedness of the system during the covid periods, and lastly, *Figure 2 (Lower),* show the connectedness of the system of post covid periods. At closer look at the *Figure 2* reveals that total connectedness has drastically has increased during the covid period, signalling the higher systematic risk during this period. And the effects of the covid-19 pandemic have annulled at very beginning of the post covid periods. This has happened may be due to the fact that initial phases of the covid-19, has impacted the Indian stock market and other stock market drastically due to the stringent lockdown imposed, led to less economic activity which has impacted the valuations of the companies in the Indian and other stock market around the globe, leading to the finding a safe heaven like investments which was always a last resorts for the investors in the time of the crisis. But soon after when the fear and panic vanish from the perception of the investors, the total connectedness measure stabilised (See Figure 2 (Middle), the periods starting April 2020). There after post covid periods have seen a sudden pick in the initial periods, however, it drastically, changed its connectedness thereafter, and peaking around the January 2023, indicating the changing the sentiments in the markets.

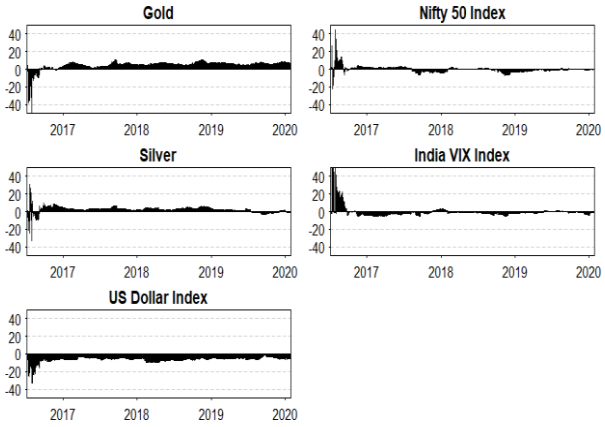


Figure 3 (a): Net spillover of the Assets in the pre-covid periods.

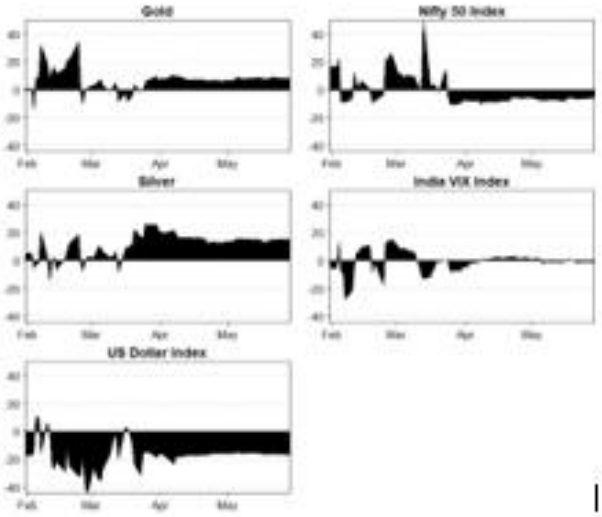


Figure 3 (b): Net spillover of the Assets during the covid periods.

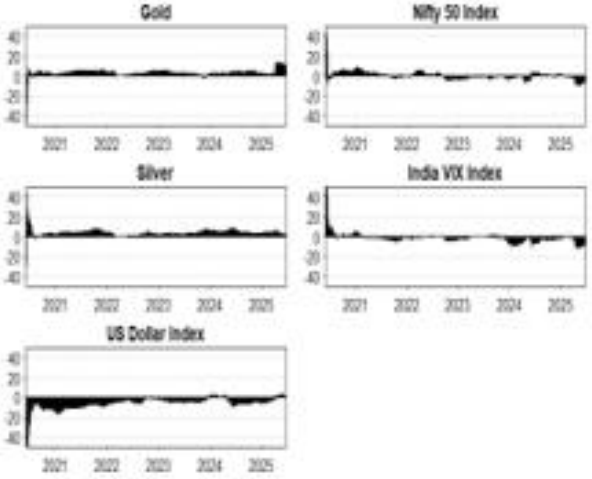
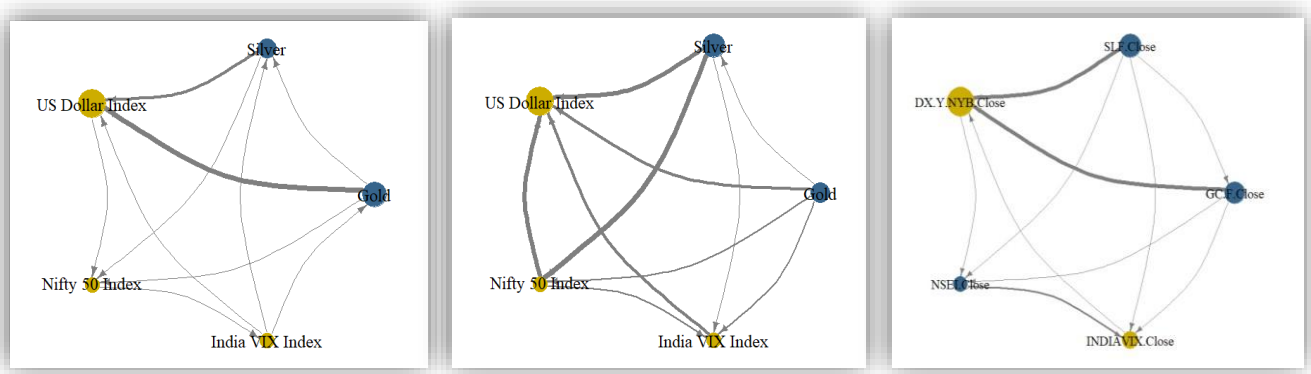


Figure 3 (c): Net spillover of the Assets in the post-covid periods.

Figure 4



From the definition of the *Section 2.5*, we can infer that the net dynamic spillover unleashes that whether the assets' role in the system as transmitters of the shock or the receiver of the shock. And how this role is changing over time. The *Figure 3* reveals the transmitters and the receiver of the shock in the whole periods. The *Figure 3 (a)* has unveiled the spillovers of the system for the pre-covid periods. *Figure 3 (b)* has shown the effects on the Financial Assets observed in between. The post-covid period, the transmitters' role regained back to the normal. During the covid periods, when WHO declared Covid-19 as Health crisis, investors were in panic mode and reached to the safe heaven like Gold, but when the shock has eroded from the market, the valuable stocks at discounted price was available, which sparked the reversal in the role during covid periods. In case of Silver, the notorious behavior has been observed initially showing few days with transmitter and few days with receiver of the shock. But after December 2016, the Silver mostly contributed to the transmission of the shocks in the system but from the starting of 2020, it again went to the roller coaster ride. During the whole covid-19 period, the Silver has contributed mostly to the Transmission of shocks to the system. While, only with few weeks it has got the receiver of the shocks from the system. Nifty 50 Index is the most notorious of all, it first received the shock and then became a transmitter of the shock, this roller coaster was evident during the whole period of study, however, during the Covid periods, has intensified in magnitude and frequency as well. On the other hand, the US Dollar Index was net receiver of the shock during the whole study period. However, during covid- 19 periods, it has intensified in magnitude. In addition, in the mid of February 2020, it has changed a little showing the impact of Covid-19 heath crisis. Finally, Indian VIX Index was transmitters of the shocks for first few months, then it remained the net receiver of the shock in the system, except the starting of 2018. During the Covid-19 periods, it has become the notorious one by changing its role from receiver to the transmitter. But soon after the covid-19 period, it again becomes mostly the receiver of the shock, except for the first six months of the post-covid periods. Showing delay in dying out of the effects of the Covid-19 Health Crisis.

during the covid periods. The *Figure 3 (c)* has revealed the effects in the post-covid periods.
In the study period, Gold has been a net receiver of shock for first one month and so, but the effect has changed dramatically starting from December 2016. Now, the role of Gold was a transmitter more or less. During the covid-19 periods, Gold's transmission has intensified, however, few reversals has been

Network Connectedness

The Network Connectedness diagram show the pairwise connectedness between the Gold, silver, US Dollar Index, Nifty 50 Index, and Indian VIX Index. The Figure 5 (a): Net Pairwise spillover of the whole system for pre-covid period. The nodes show the different investible assets class and the US Dollar Index and Indian VIX Index. The Figure 5 (b): Net Pairwise spillover of the whole system during the covid period. And similarly, Figure 5 (c): Net Pairwise spillover of the whole system for the post-covid period.

The Network Diagrams reveals that connectedness between the US Dollar index and Silver, and Gold which unveils that the connection between the US Dollar Index and Silver was relatively higher compared (From Silver to US Dollar Index) to Nifty 50 Index or India VIX Index but it started to gain strength from the during covid periods and it remained stronger thereafter. On that similar line, if we see the relationship between the US Dollar Index and Gold, the connectedness was stronger than the Silver in the pre-covid periods (Gold to US Dollar Index), it has weakened during the covid periods, but again came back stronger post-covid periods. During the covid period, the Connectedness strength between Nifty 50 index & US Dollar Index has strengthen strongly while direction of the spillover changed from US Dollar Index to Nifty 50 Index (Pre-covid periods) to the Nifty 50 Index to US dollar Index (During the covid periods), while came back to normal post the covid periods. The relationship between the Nifty 50 Index and Silver & Gold spillover was unidirectional from Silver & Gold to Nifty 50 Index however, strength was higher during the covid periods for the both of the commodities. The Connectedness between the Nifty 50 Index and Indian VIX index has strengthen during the covid periods compared pre-covid periods. And the strength has grown stronger post-covid periods. The dynamics of the US Dollar Index and Indian VIX index spillover was also unidirectional, but the

strength of the connectedness has increased during the covid periods compared to the normal time. On the other hand, Indian VIX Index and Gold had a spillover from Indian VIX Index to Gold (Pre-covid periods) which has changed drastically after covid periods spillover from Gold to Indian VIX Index. In this, the connectedness between this has also strengthen during the covid periods, but came back to normal post-covid pandemic. The spillover between the Indian VIX Index and Silver was from Indian VIX Index to Silver in the pre-covid periods, it has changed the course, during the covid periods to Silver to Indian VIX Index and remained the spillover in that same way. The relationships between the gold and silver spillover were from Gold to Silver till the covid periods, which has changed post covid periods. This discussion has reiterated the relationships of the assets of the interest, and find some interesting insights at the backdrop of the major health crisis (Covid-19 Pandemic). These insights not only helpful for budding portfolio managers also helpful for the policymakers for allocating strategic resources of the country in these resources.

CONCLUSION

The study of the financial assets and its potential hedging opportunities are in the interest to the researchers and the policy makers. In this study, we mainly focused on the issue of the connectedness of the financial assets, where firstly we have included the static connectedness as well as dynamic connectedness. The results show that the financial assets under investigation was less connected in the pre-covid periods, however, the connectedness has increased significantly during the covid-19 periods. The network diagrams also documents that the contagion between the financial assets has increased significantly during the post covid periods compared to pre and post covid periods. Pointing out that crisis not only alter the direction of the spillover of the financial assets, but redefine the roles in the domestic market with global precious metals by increasing the integration among them. In addition, the *Figure 3 (b)* has reveals that during the Covid-19 periods (Specifically for first 45-50 days), Nifty

50 Index's systematic risk can be minimised by the US Dollar Index, but starting from

April 2020, Commodities such as Gold, Silver can be used as a hedging instrument for the reduction of the systematic risk of the market. The findings reveal significant shifts in net transmitters and receivers of shocks, highlighting heightened systemic risk during the pandemic and structural changes in financial relationships post-crisis. These insights contribute to the broader discourse on market interdependence and risk contagion during periods of financial turbulence.

FUTURE SCOPE OF THE STUDY

This study has added to the literature the significant changes of the role of the transmitters and receivers of the precious metals and Indian Equity Market. Additionally, it has documented the increase of systematic risk during the Covid-19 as Health Crisis, of the financial assets of interest. Our study has shown that evolution of the Connectedness of the Financial Assets in the pre-covid, during the covid- 19 and post-covid periods, which unveils that during the Covid-19 Heath emergency the Nifty 50 Index has become more integrated to the Commodities such as Gold, Silver and US Dollar Index. However, it is not possible to cover every aspect of the into one study, therefore, future researchers should focus on the frequency domain of the analysis, additionally, future studies may consider the DCC-GARCH TVP-VAR or etc. models which has incorporated the dynamic correlations into the study. The Hedging efficiency of the Financial Assets can also be calculated for future studies.

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ENERGY TRANSITION AND ECONOMIC GROWTH: EVIDENCE FROM SOUTH ASIA, SUB-SAHARAN AFRICA, AND OECD ECONOMIES

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ABSTRACT:

This study examines the relationship between energy transition and economic growth across three regional blocs—South Asia, Sub-Saharan Africa (SSA), and OECD economies—between 2000 and 2022. Using a balanced panel dataset of 57 countries, the analysis incorporates multiple dimensions of energy transition, including renewable energy adoption, energy efficiency, fossil fuel dependence, and electricity access, while accounting for the moderating roles of institutional quality and human capital. Employing fixed-effects and dynamic panel estimations with robust standard errors, the results reveal that renewable energy consumption significantly enhances economic growth, whereas fossil fuel dependence and higher energy intensity constrain it. Institutional quality and human capital positively influence growth, though their direct moderating effects on renewables are weaker, suggesting lagged impacts. Regional analyses highlight strong renewable-led growth in South Asia, limited effects in SSA due to infrastructural and governance barriers, and innovation-driven growth in OECD countries. The findings substantiate endogenous growth and institutional economics theories, emphasizing that technological progress, efficiency improvements, and institutional capacity are central to sustainable growth. Policy recommendations underscore the need for region- specific strategies integrating renewable infrastructure, governance reform, and human capital investment to achieve long-term green growth and resilience.

Keywords: Energy transition, renewable energy, institutional quality, human capital, economic growth, panel analysis, cross-regional comparison.

INTRODUCTION

The global economy is completely transforming the ways of living as the different countries are trying to fulfill the dual aims of maintaining economic growth and taking care of the Earth's nature. The transformation is marked by the energy transition where the world is moving away from fossil fuels to renewables and to the efficient energy sources. This transition is not only a change in technology but also a more comprehensive economic and institutional change towards sustainability.

Economic growth has, more or less, always been linked with the consumption of fossil fuels. Starting from the Industrial Revolution, the three most important fossil fuels, namely coal, oil, and gas, have led to industrialization, thereby supplying energy for factories, transport, and agriculture (Stern, 2004). The resulting resources did cause a significant increase in the GDP of nations, but at the same time, they also led to

the emission of greenhouse gases, the degradation of ecosystems, and the acceleration of climate change (Shahbaz et al., 2019). In recent decades, environmental concerns have been growing and the progress made in the clean technology field has led the policymakers to adopt energy systems that can provide the necessary support for growth and at the same time prevent heavy ecological damage. Henceforth, the global energy transition is a very important step to have the economy grow without harming the environment (Bildirici & Bakirtas, 2014).

The energy transition is regarded as beneficial universally; the discussions regarding its impacts on the economy, however, continue. The proponents of the renewable energy sector highlight the issues that the sector can turn into a good way for technology innovations, raising the efficiency in all applications and sectors, and creating a lot of new jobs (Apergis & Payne, 2010; Bhattacharya et al., 2016). On the other hand, the critics point out the fact that the transition may bring along short-term costs, especially in the economies that are still developing, due to costly investments needed, problems related to the reliability of the power supply, and poor infrastructure (Ozturk, 2017; Dogan et al., 2021).

This research intends to pull apart the knots by looking at the different ways in which the energy transition motivates economic growth in three geographically and economically distinct regions: South Asia, Sub-Saharan Africa (SSA), and the Organisation for Economic Co- operation and Development (OECD). The research explores through various lenses the energy transition to a cleaner energy mix - making it harder to distinguish which pathway actually leads to economic growth. Therefore, the study yields a more comprehensive picture of how the different stages of development affect the result of the energy transition on economic growth.

BACKGROUND AND RATIONALE

The position of energy is two-fold; it is always needed for production and is also a source of innovation and productivity. The Solow-Swan growth model (Solow, 1956; Swan, 1956) and similar models treated energy as an exogenous input that was largely used in capital and labor productivity. On the contrary, endogenous growth theory (Romer, 1990; Aghion & Howitt, 1992) considers new technology and human talents at the center of the economic development

process over time. In this context, investment in renewables, energy efficiency, and clean technologies is regarded as a type of “green innovation” that not only increases productivity but also leads to knowledge spillovers and creates new markets.

The Environmental Kuznets Curve (EKC) hypothesis is another aspect of the debate, suggesting a non-linear relationship between income and environmental quality (Grossman & Krueger, 1995). In the early stages of development economic growth tends to drive the environment to worse conditions; however, once the income level goes beyond a certain limit, cleaner technologies and stricter regulation are factors leading to better environmental conditions. This means the pros and cons of the energy transition differ with the income level: developed countries might reap the benefits of growth while the undeveloped ones might face the drawback of being in transition.

Heterogeneity is evidenced by actual data. In the OECD countries, the adoption of renewable energy has been correlated with an increase in productivity and a decrease in

carbon intensity (Marques & Fuinhas, 2012; Pablo-Romero & Sánchez-Braza, 2017). These economies have a well-developed infrastructure, sound institutions, and supportive policies such as carbon pricing and subsidies that ease the transition. However, in the less developed regions, the main obstacles are inadequate financing,

RESEARCH PROBLEM

The main research question that this study revolves around is: What is the impact of the energy transition on economic growth in countries with different levels of development?

Green growth theories support the view that the use of renewable energy and improving energy efficiency lead to sustainable growth, but empirical findings are still inconsistent. For the countries in the development phase, the adoption of non-carbon energy sources might lead to the use of limited resources otherwise meant for industrialization. On the other hand, in developed countries, capital invested in clean energy could act as a new source of innovation and economic growth (Sadorsky, 2009; Payne, 2010).

One of the shortcomings of the current body of research is that it is rather limited. The results are often based on studies that are either geographically very narrow (single country) or a sample that is not very diverse. Additionally, the measurement of the energy transition is often very narrow, as it is mainly limited to the percentage of renewables involved, while other dimensions such as energy efficiency, fossil fuel dependence, and electricity access are disregarded. A thorough knowledge of the situation calls for the amalgamation of these different dimensions within one analytical framework that also considers the moderating effects of governance and human capital.

Thus, the current study is significant as it applies a multi-dimensional, cross-regional approach and looks into the economic consequences of energy transition in three different blocs: South Asia, Sub-Saharan Africa, and the OECD.

SIGNIFICANCE OF THE STUDY

This research brings forth a number of significant contributions to the academic literature and the policy debates of the day.
To begin with, the author has put forward a cross-regional analysis of the world's economies, which are at different stages of development. The comparative study of South Asia, Sub- Saharan Africa, and OECD countries aims to determine whether the regions' differences in institutional strength and policy maturity are the main drivers of the different renewable energy growth impacts.

In the second instance, the research suggests that the transition to renewable energy is not simply a matter of replacing one source with another, but rather it is a multi-dimensional process involving renewable energy adoption, energy efficiency, fossil fuel dependence, and electricity access. The application of this broad framework allows moving beyond the classical models that consider only one variable at a time, thus fostering a more realistic apprehension of structural and institutional dynamics.

Third, the author has identified institutional quality (comprising governance effectiveness, rule of law, regulatory quality, and corruption control) and human capital (measured by education spending and life expectancy) as the main mediators through which the transition to renewable energy can take place. This way, it is acknowledged that the winning transitions are those that are not only driven by technology but also by good

governance and social capacity, thus reflecting the tenets of institutional economics (North, 1990; Acemoglu & Robinson, 2012) once again.

The fourth and final contribution consists of the application of advanced econometric techniques to the panel data, such as the ones that deal with fixed effects and the like, in order to get rid of the country's heterogeneity as well as the endogeneity that might occur in the process. The analysis also adopts standardization, outlier management, and robust standard errors to ensure the reliability and validity of the results.

RESEARCH OBJECTIVES

The study is according to five connected objectives:

- To analyze the influence of renewable energy adoption and energy efficiency on the economic growth from the perspective of South Asia, Sub-Saharan Africa, and OECD countries.
- To determine the influence of fossil fuel dependency and carbon emissions on economic performance.
- To find out if the quality of institutions and human capital can amplify or attenuate the impact of energy transition on growth.
- To examine the regional disparities in the effects of energy transition with consideration of development levels, technological maturity, and governance as factors.
- To suggest policy recommendations that are specific for each region and at the same time sustainable for the environment and in line with the long-term economic growth strategies.

REVIEW OF LITERATURE

Over the last half a century, the interplay of energy demand and economic growth has been analyzed in detail in development and environmental economics. The problem has matured into viewing energy use and production primarily through the application of very intricate models which consider factors like technology, sustainability, and institutional quality among other things. This section discusses the academic progress from initial theoretical contributions to current research on energy transition—accompanied by the discussion of major controversies, empirical results, and voids that characterize this line of inquiry.

THE EARLY THEORETICAL AND EMPIRICAL FOUNDATIONS (1950S–1990S)

The first growth models did not recognize energy as an independent factor in production. In classical economic frameworks such as the Solow–Swan model (Solow, 1956; Swan, 1956) for instance, the growth of the economy was fanned by factors like capital accumulation, labor, and exogenously determined technological progress. In a way, energy was implicitly contained within the total factor productivity, implying that growth could go on indefinitely with increased technological wizardry.

Nevertheless, the 1970s oil crises steered the economists to reconsider their position. The economists of that time started to analyze the interaction of energy consumption and output very closely. Kraft and Kraft (1978) were able to provide the very first empirical evidence of such causation in their case of the United States whereby they found

that growth Granger- caused energy demand. Consequently, a flood of studies questioning the direction of causality followed the four hypotheses that were put forward:

- The growth hypothesis that claims energy consumption is the driving force behind economic growth;
- The conservation hypothesis that proposes the opposite;
- The feedback hypothesis that mentions bidirectional causality; and
- The neutrality hypothesis that asserts no relationship at all exists (Yu & Choi, 1985; Erol & Yu, 1987).

Most of the initial researches were bivariate and concentrated on the developed world, giving rise to ambiguous findings. Later on, Stern (1993, 2000) brought the field to a higher level by introducing multivariate models with cointegration methods which took into consideration the contributions of capital, labor, and technology, thereby proving that energy and output are jointly determined. His research was a turning point in the method of applying dynamic modeling to the energy-growth nexus.

Emergence of the Environmental Perspective (1990s–2005)

In the 1990s, environmental worries changed the dialogue around economic growth. The Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1995) first proposed that the deterioration of the environment is directly proportional to the rise in income but gradually reverses as societies move towards cleaner technologies. The idea of decoupling which means that economic growth takes place alongside the improvement of the environment, was thus, initiated.

Theoretical and methodological progress made in the evaluation of the energy–environment– growth triad. **Ang (2007)** reported in the case of France that there is a long-run bidirectional causality between energy consumption, carbon emissions, and GDP, thus supporting the feedback hypothesis. **Soytas and Sari (2003)** also stated that energy consumption has a considerable influence on income in developing countries, at the same time, warning that the adoption of energy conservation measures could lead to a slowdown in growth.

While this period saw the introduction of renewable energy into academic discussions, limited data was a major factor restricting empirical research. Still, early debates **(Cleveland et al., 2000)** conceded that the switching over to renewable energy sources was a key condition for the coexistence of economic and ecological stability, thus providing a foundation for further studies.

Transition to Renewable Energy and Panel Data Applications (2006–2015)

The global ascent of renewable energy technologies, climate agreements (such as the Kyoto Protocol, 1997; Paris Agreement, 2015), and the access to extended time-series data during the mid-2000s, were the factors that changed the scene. The econometrics also advanced, and simultaneous with the researchers' use of panel data methods that took into account heterogeneity and dynamic adjustment processes across countries, the econometric techniques got evolved.

Sadorsky (2009) was one of the pioneers in employing panel cointegration

techniques to study the interactions between renewable energy consumption and income in emerging economies. According to his findings, GDP and renewable energy had a bidirectional relationship, which means that investments in clean energy can lead to growth and environmental improvement at the same time. Much the same, **Apergis and Payne (2010)** analyzed the situation in OECD countries and confirmed the existence of a long-run equilibrium between the use of renewable energy and economic growth, thus supporting the feedback hypothesis in advanced economies.

Sadorsky (2011) applied the same methodology to G7 countries and found that while renewable energy contributes positively to the output, non-renewable energy sources still have the upper hand in the short run. Likewise, **Menegaki (2011)** carried out a study on 27 European countries and found neutrality — meaning that renewable energy policies did not have a significant impact on GDP, because of high costs and early-stage technology adoption, as was the case. It is really the mixed results that brought to the fore the context-dependent aspect of the energy–growth relationship.

In the case of underdeveloped areas, **Ozturk and Acaravci (2013)** observed one-way causation from energy to GDP for low-income countries, which implies that such countries are heavily dependent on energy availability. **Odhiambo (2014)**, focusing on Sub-Saharan Africa, demonstrated that energy dependence and CO_2 emissions exert negative effects on growth, highlighting the challenges of transitioning to renewables in energy-deficient contexts. **Bhattacharya et al. (2016)** advanced this literature by analyzing the top 38 renewable energy-consuming countries from 1991–2012, concluding that renewable energy consumption promotes economic growth in both developed and developing economies, though more strongly in the former.

Integration of Institutional and Technological Factors (2016–2020)

Towards the end of the 2010s, the research community started to point out the importance of the quality of the institutions, the level of innovation, and the governance as the intermediaries in the relationship between energy and growth. Referring to the institutional economics approach **(North, 1990)**, authors claimed that the success of the renewable energy policy mainly depends on the governance and regulatory framework in place.

Bildirici and Bakirtas (2014) focused their study on rapidly developing countries and disclosed that institutional criteria and the ability to innovate determine the share of renewable energy in economic performance. Similarly, **Marques and Fuinhas (2012)** argued that the existence of government support mechanisms and R&D investment are the two main factors influencing the conversion of renewable deployment into productivity gains.

Al-Mulali et al. (2016) took the debate further by adding trade liberalization, urbanization, and financial growth into the European countries' renewable–growth–environment model. The author's results showed that renewable energy is a pollution mitigator, but its impact on GDP is reliant on the presence of complementary economic and institutional factors.

Pablo-Romero and Sánchez-Braza (2017) did a cross-country comparison between the rich and the poor ones, highlighting that renewables in the case of high-income economies are the more significant contributors to growth owing to better innovation systems and market integration, while in the case of developing countries with infrastructural deficits the effect is just the opposite and weaker. Conversely, **Shahbaz et al. (2019)** with the help of the global panel of 157 countries from 1990 to 2014 confirmed that renewable energy not only contributes to growth but also plays a major role in reducing the carbon footprint, thereby giving support to the "green growth" hypothesis.

Contemporary Studies and Regional Divergence (2020–Present)

Recent years have seen intensified interest in the energy transition, focusing on regional disparities and structural heterogeneity. **Dogan et al. (2021)** found that renewable energy enhances growth in high-income economies but shows weaker effects in middle-income ones, highlighting the role of institutions and innovation capacity.

In Africa, **Adebayo and Kirikkaleli (2021)** and **Appiah (2022)** affirmed that renewable energy can only encourage growth if supported by good governance and skilled labor. In Asia, **Khan et al. (2022)** and **Rahman and Vu (2023)** found that the combination of renewable energy and digitalization is a factor of the sustainable growth of which R&D investment and institutional quality are important support pillars. In the case of the developed countries, **Mele and Lisi (2023)** as well as **Li and Zhang (2024)** acknowledged that renewable technology uptake contributes to productivity gains, and the impacts are more pronounced in the countries with carbon pricing and consistent regulatory environments.

Synthesis and Research Gap

The evolution of the literature reveals a few consistent themes and unresolved issues:

- The causality direction between energy transition and growth remains debated, May depend on country's income level and methods used
- Although beneficial, the empirical evidence on renewable energy suggests that significant contextual considerations such as governance, technology and human capital are determinants
- Most of the studies are context specific or use global samples as homogeneous comparisons and overlook potential cross-region differences that would allow structural asymmetries to be detected
- Only a few studies implemented a multi-dimensional concept of energy transition that encompasses renewable energy, energy efficiency, reduced fossil fuels use, and access to electricity
- Finally, while the effect of institutional quality is becoming more recognized in the field, the interactive effects of institutional quality together with energy transition remain under-studied

To address these issues, a comprehensive cross-region panel analysis is undertaken (2000- 2022). The analysis includes renewable energy consumption, energy efficiency, fossil fuel dependence together with institutional quality across South Asia, Sub-Saharan Africa, and

OECD economies.

Hypotheses

Based on the underlying theory and previous studies, the researchers put forward the following hypotheses:

- H1: It is hypothesized that the use of renewable energy will have a cumulative and significant effect on the economic growth of all regions.
- H2: Energy efficiency in the form of lower energy consumption will lead to the growth of the economy.
- H3: Fossil fuels will be a barrier to the growth of the economy.
- H4: Energy transition will have a more significant impact on growth in the countries/regions with better institutional quality.
- H5: The role of human capital in the economic growth resulting from renewable energy will be positive and strong.
- H6: The regional differences in development, technology, and institutions are responsible for the variation in effects' size and direction.

Subsequently, the hypotheses were subjected to fixed-effects and dynamic panel models testing, thereby allowing the reception of insights from both the cross-sectional and time-series perspectives.

METHODOLOGY

The method section specifies the data sources, definitions of variables, and econometric techniques applied to the assessment of the relation between energy transition and economic growth in South Asia, Sub-Saharan Africa, and OECD countries during the period from 2000 to 2022.

Data Sources and Sample Selection

The World Bank's World Development Indicators (WDI), IMF macroeconomic databases, and Worldwide Governance Indicators (WGI) are the key sources of information for the analysis and energy statistics from the Global Energy Observatory and Our World in Data are included. The total number of countries in the dataset is 57 with the following arrangement:

South Asia: India, Bangladesh, Pakistan, Sri Lanka, Nepal, Bhutan

Sub-Saharan Africa: 24 representative countries including Nigeria, Kenya, Ghana, South Africa, and Ethiopia

OECD: 27 advanced economies such as the United States, Japan, Germany, the United Kingdom, and France

The final balanced panel covers the period 2000–2022. Data were merged, cleaned, and converted into panel-long format using **Python** and **Stata**, ensuring consistency and comparability across indicators.

VARIABLE DEFINITIONS

- **Dependent Variable:**
  - **Economic Growth (GDPG):** Annual percentage growth rate of GDP (constant 2015 US$) — the measure of economic performance.
- **Independent Variables (Energy Transition Indicators):**
  - **Renewable Energy Share (RENEW):** % of renewables in total final energy consumption.
  - **Energy Intensity (EINT):** Energy

use per unit of GDP (MJ per $2017 PPP GDP), inverse measure of efficiency.

- **Fossil Fuel Consumption (FOSSIL):** % of fossil fuels in total energy consumption.
- **Electricity Access (ELEC):** % of population with access to electricity.

- **Moderating Variables:**

- **Institutional Quality (INST):** Composite index combining four WGI indicators — government effectiveness, regulatory quality, rule of law, and control of corruption (−2.5 to +2.5 scale).
- **Human Capital (HC):** Represented by education expenditure (% of government spending) and life expectancy (years).

- **Control Variables:**

- **CO_2 Emissions (CO2):** Metric tons per capita.
- **Internet Use (INT):** % of population using the internet (proxy for technological diffusion).
- **Population Density (POP):** People per km^2 of land area.

Variables were standardized and transformed where necessary; missing data were interpolated linearly, and skewed distributions (e.g., energy intensity) were log-transformed.

Results and Analysis

The current section shares the empirical evidence regarding the energy transition economic growth influence in South Asia, Sub-Saharan Africa (SSA), and OECD economies during the period of 2000 to 2022. The data was analyzed through different models starting from baseline estimation, followed by regional regressions, interaction models, dynamic specifications, and robustness checks. Robust standard errors or cluster-robust standard errors were used in all the models. Also, the coefficients were interpreted as elasticities or semi-elasticities.

Descriptive Overview

The global average GDP growth rate from 2000 to 2022 was about 3.4% each year. The most rapid growth was in South Asia (average 5.8%) and moderate in Sub-Saharan Africa (3.9%), although OECD economies still had a stable but lower average of 2.1% growth.

Renewable energy consumption was almost one-quarter of the total global energy consumption (around 23%), however, the consumption was not uniform across the globe with the different regions consuming different proportions, i.e. approximately 45% in SSA (where hydro and biomass are the main sources), 27% in South Asia, and 15% in the OECD countries. The energy intensity experienced a significant drop from 6.8 MJ/$GDP in 2000 to 4.9 MJ/$GDP in 2022, which is due to the efficiency gain in the sector.

On a −2.5 to +2.5 scale, the institutional quality rounded up to zero (average) but the OECD countries were scored +1.1, while South Asia and SSA were scored −0.4 and −0.6 respectively. The pairwise correlations demonstrated the predicted trends: the share of renewable energy has a direct correlation with GDP growth ($r \approx 0.29$), while the opposite is true for fossil fuel dependence and CO_2 emissions ($r \approx$

−0.31 and −0.34, respectively). The quality of institutions and spending on education were positively correlated with renewable energy adoption ($r \approx 0.42$), which implies that good governance and skilled human resources transition the energy. Baseline Regression Results

The **Fixed Effects (FE)** model with time dummies explained about 22% of within-country variations in GDP growth ($R^2 = 0.223$). The results were as follows:
All variables were statistically significant at the 5% level, except education expenditure ($p \approx 0.11$). These results confirm **H1**, **H2**, and **H3**: renewable energy boosts growth, while inefficiency and fossil dependence reduce it.

Regional Results

To capture developmental heterogeneity, region-specific regressions were estimated:

These findings confirm **H6**, showing that the energy–growth nexus differs markedly by development stage. In South Asia, renewable expansion has strong pro-growth effects, while in SSA, structural and institutional bottlenecks dampen outcomes. OECD economies experience modest yet positive innovation-led gains.

Interaction Effects: Institutional Quality and Human Capital

The inclusion of interaction terms revealed how governance and human capital shape the renewable–growth link:

These results only **partially support H4 and H5**, suggesting that while institutions and education enhance overall growth, their immediate moderating influence on renewables is limited—possibly due to lag effects.

Dynamic Panel Results

To capture persistence, a dynamic model with lagged GDP growth and renewable energy was estimated:

Table 1

Variable	Coefficient	Sign	Interpretation
Renewable Energy Share (RENEW)	+0.0136	Positive	A 1% increase in renewables raises GDP growth by 0.0136 points.
Energy Intensity (EINT)	−0.0214	Negative	Higher inefficiency lowers growth.
Fossil Fuel Consumption (FOSSIL)	−0.0092	Negative	Fossil dependence constrains growth.
Electricity Access (ELEC)	+0.0171	Positive	Electrification supports growth, especially in SSA and South Asia.
CO_2 Emissions (CO2)	−0.0156	Negative	Environmental degradation curtails long-term output.
Institutional Quality (INST)	+0.0248	Positive	Good governance enhances productivity and investment.
Education Expenditure (EDU)	+0.0075	Positive	Human capital contributes to growth but less strongly.

Table 2

Region	Renewable Energy Coefficient	Significance	Interpretation
South Asia	+0.3881	$p < 0.05$	Renewables drive growth through industrial expansion.
Sub-Saharan Africa	−0.0023	Not significant	Weak effect due to infrastructure and policy constraints.
OECD	+0.0191	$p < 0.05$	Renewables sustain moderate, innovation-led growth.

Table 3

Variable	Coefficient	Interpretation
RENEW	−0.0227	The direct within-country effect weakens once interactions are introduced.
RENEW × INST	−0.0173	Strong institutions may initially impose compliance costs but improve long-run sustainability.
RENEW × EDU	−0.0048	Education's moderating effect is small and delayed.

Table 4

Variable	Coefficient	Significance	Interpretation
Lagged GDP Growth	+0.2917	$p < 0.01$	Strong persistence: past growth predicts current growth.
Lagged Renewable Energy	+0.1638	$p < 0.05$	Renewables have delayed but lasting positive effects.
Energy Intensity	−0.0204	$p < 0.05$	Efficiency remains critical.
Fossil Dependence	−0.0087	$p < 0.10$	Gradual decline consistent with decarbonization trends.

These findings align with **endogenous growth theory**—renewable energy investments yield dynamic, long-term productivity effects.

Robustness Checks

Three robustness specifications were tested: standardized (z-scores), outlier-trimmed, and cluster-robust models. Across all, the renewable–growth relationship remained **positive and statistically significant**, confirming model stability.

Additional diagnostics showed no major violations of assumptions:

- **VIF:** between 1.8 and 4.2 (no multicollinearity).
- **Durbin–Watson ≈ 2.1:** minimal serial correlation.
- **Breusch–Pagan test (p = 0.078):** mild heteroskedasticity addressed with robust SEs.
- **Residual normality and Cook's D:** no influential outliers.

Discussion

Energy Transition and Growth

The outcomes confirm that renewable energy is a factor in long-term economic growth, which is in line with the endogenous growth theory (Romer, 1990; Aghion & Howitt, 1992). The remarkable renewable coefficient, mainly in South Asia ($\beta = 0.388$), points to the fact that clean energy investment leads to the development of new technologies, the growth of industries, and the creation of new jobs. The delayed positive impact is also indicative of the gradual benefits that new technologies bring to the renewable projects since the latter are time-consuming and the former happen through technological learning.

The negative coefficient on energy intensity validates that unprofitable energy use erodes productivity while dependence on fossil fuels limits diversification—thus confirming the energy efficiency–growth and decarbonization–growth hypotheses.

Institutional and Human Capital Dynamics

The quality of institutions had a very strong positive effect on the growth of the economy and a very weak interaction with renewable energy, which implies that good governance in the economy at large produces broadly, but the moderating benefits on renewables might take a while to materialize. This result is in line with the findings of Al-Mulali et al. (2016) and Dogan et al. (2021), who mentioned that institutional reform necessitates compliance costs at first before allowing the efficiency gains to take place.

In the same way, the influence of human capital was direct and positive but limited. This is in consistency with the view that education and health are key to the absorption of technology and its diffusion, but the benefits from such investments are often realized slowly.

Regional Divergence

The analysis highlights stark regional contrasts:

- **South Asia** benefits most from renewable expansion, as clean energy complements rapid industrialization.
- **Sub-Saharan Africa** shows limited impact due to underdeveloped infrastructure, financing gaps, and dependence on biomass.
- **OECD economies** exhibit steady, innovation-driven growth supported by mature governance and advanced technologies.

This heterogeneity mirrors the **Environmental Kuznets Curve**, where the benefits of decoupling emerge only once economies reach sufficient institutional and technological maturity.

Policy Implications For South Asia

- **Expand renewable infrastructure** through targeted fiscal incentives and public– private partnerships.
- **Improve efficiency** via energy audits, industrial retrofitting, and demand-side management.
- **Enhance governance** to ensure stable regulatory frameworks and attract foreign investment.
- **Invest in human capital**, particularly in technical and vocational education for green sectors.

For Sub-Saharan Africa

- **Modernize energy infrastructure**, emphasizing grid reliability and storage systems.
- **Bridge energy poverty** through decentralized off-grid and mini-grid renewable projects.
- **Build institutional capacity** for transparent, accountable energy governance.
- **Promote regional cooperation** via cross-border electricity trade and shared resource management.

For OECD Economies

- **Sustain innovation leadership** in hydrogen, carbon capture, and storage technologies.
- **Advance decarbonization** through circular economy initiatives and sectoral emission targets.
- **Support developing regions** through technology transfer, climate finance, and knowledge-sharing.

Cross-Regional Recommendations

- Strengthen institutional frameworks to ensure policy stability.
- Develop **green finance instruments** such as green bonds and carbon markets.
- Integrate energy transition with **education, R&D, and industrial policy** to foster inclusive, innovation-led growth.
- Establish **regional monitoring systems** for tracking renewable adoption and efficiency performance.

CONCLUSION

This investigation illustrates very convincingly and with much data that the worldwide energy change is a factor that the economy growth can rely upon but the effect depends on different the development stage and institutional capacity. Switching to renewable energy, working with more efficient technologies, and lessening the use of fossil fuels together increase the stable growth outlooks.

The findings affirm four hypotheses (H1, H2, H3, and H6) and partly support H4 and H5 highlighting that although the renewables are the main drivers of growth their outcome is conditioned by the presence of good governance and the investment in human capital. The use of dynamic models indicates that renewable energy is a source of benefits over a long term period because the effects are continuous and delayed.

On a theoretical level, the results reconcile the concepts of endogenous growth theory, the Environmental Kuznets Curve, and institutional economics, providing a common understanding of how technology, policy, and governance interact in the process of sustainable growth.

In the end, this paper gives a very clear message:

The energy transition should not be considered just an eco-friendly step but rather an economic move for making the economy more resilient, innovative, and inclusive.

To frontline this, countries need to unbind growth from carbon which would mean strengthening institutions and keeping human capital up as these are the pillars of a sustainable worldwide economy.

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MARKETING STRATEGIES TOWARDS SUSTAINABLE SERVICE: A NORTH - SOUTH COMPARISON OF INDIAN SHOPPING MALLS

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ABSTRACT

Shopping malls play a very crucial role in the retail industry of India. Over the last few years, a number of shopping malls have developed across the country. Not only shopping malls, but also e-commerce platforms have quickly expanded. This has led to massive competition amongst the stakeholders; the less strong parties are wiped out of the market. In this light, the literatures have been referred to and it is found that majority of the studies have focussed on a specific location to identify the factors impacting the service quality of the malls, but there is hardly any research which has conducted a region wise comparative analysis among the shopping malls. The present study is conducted to develop an in-depth understanding of the shopping malls of northern and southern India. Primary data relevant to the study is obtained from the shopping malls based out of the two regions mentioned above. The dataset is pre- processed and subjected to statistical analysis. It is found that the service quality dimensions impacting the mindset of the consumers from northern parts of India are efficiency of employees, promptness of employees and security of the transactions. In case of southern India, mall navigation and purchase experience, integrity of services and personalized care offered by the malls to the visitors play a significant role. By going further into the depths of the study, it is learnt that, in case of northern India, efficiency of employees show low performance. However, for southern India, there is no major area of concern. Net Promoter Score for north is satisfactory, however, majority of the south visitors seem to discourage their acquaintances from visiting malls. This findings from this study may act as guiding light for the mall managers. A happy customer keeps returning to the shopping mall; thus helping the mall to achieve its bottom line.

Keywords: Efficiency of employees, Service quality dimension, service quality perception, shopping malls

INTRODUCTION

India is one of the rapidly growing countries in terms of retail. Retail industry in India has undergone massive evolution over time. Several retail formats have developed, one such format being the shopping mall. A shopping mall is a collection of well-organized retail establishments contained within a single architectural building. Malls have developed into multipurpose leisure areas that combine retail with entertainment, amusement, and social interactions in addition to offering a variety of goods under one roof. Movie theatres, gaming areas, food courts, cafés, salons, banks, and other convenience-based businesses are now found in the majority of malls. In other words, consumers see malls as appealing central locations where they may shop, eat, socialize, and spend time with loved ones rather than just as locations to buy goods.

Malls have become an integral part of urban consumers' daily routines in the setting of modern lifestyle. Weekend mall excursions have become a common cultural practice for many homes, particularly in Tier-1 and metropolitan areas. A certain aspirational value is also projected by malls. They show how Indian customers' expectations for comfort, convenience, ambience, hygiene, safety, and choice are evolving. High-street shopping frequently lacks the "feel good" atmosphere that is created by the regulated environment, air conditioning, cleanliness, and visual merchandising. Sometimes, people visit shopping malls, just to overcome the boredom of the daily routine; they visit malls just for window shopping and enjoying the ambience and return home with a full heart. Over the past few years shopping malls have developed in every nook and corner of the country. Initially a massive change in the overall shopping behaviour was observed, but slowly, it led massive level of competition amongst the malls, making it extremely difficult for them to sustain in the fierce scenario. Along with shopping malls, India also witnessed massive growth in e commerce platforms. The e-commerce platforms offered goods and services to the consumers at the comfort of their homes. They also provided attractive promotional strategies like massive discounts, quick delivery, easier return and refund processes, etc. Therefore the shopping malls, not only faced competition amongst themselves but also from the e-commerce platforms. This led to declining sales, thus reducing the top line and bottom line and ultimately difficulty in survival.

These situations have made things really difficult for the shopping malls; it is observed that many shopping malls fail to achieve optimum tenant mix and proper visitor oriented designs. However, the malls which are outperforming others have presented themselves as experience centres rather than simply a collection of shops at one place. They have concentrated their efforts on long term sustainability, rather than simply concentrating on short term sales. This study aims to understand the service gaps and identify the loopholes existing in the shopping malls of northern and southern India. A happy customer will keep coming back to mall and also motivate his acquaintances to visit. This helps to improve the top line and bottom line of the malls.

LITERATURE REVIEW

Shopping mall culture has come into prominence in the last few years and India has witnessed a massive growth in the number of malls. It is found that shopping malls have become an integral part of human lives. The success of a business depends on understanding the needs of the customers and in depth understanding of their buying pattern. When the concept of shopping malls was very novel, Bloch P. et. al. (1994) performed a study for learning about consumer activity in the malls. They considered the shopping malls which were categorised as "super-regionals". It was revealed that tenant mix played a pivotal role in attracting consumers. In due course of time, Mohan M. et. al. (2015) explored a different facet of shopping malls and figured out that malls attract middle and upper classes and the catchment area attracts highly educated and young crowd. A significant difference existed in the shopping behaviour of high, medium and low spenders across all product categories and a high degree of positive correlation was found to exist between incomes of the respondent and money spent at the mall and low positive correlation between time and money spent at the mall. Mittal A. et. al. (2015) said that differences in the purchasing behaviour of shoppers existed among geographical markets (due to difference in cultures, income, demographics etc.) but at a shopping centre level, consumers cared for more tangible benefits such as merchandise, brands, variety, social infrastructure (milieu) and convenience. Moreover, Kumar A. (2017) said that location of the mall, comfort in shopping, status portrayed in shopping, knowledge about the goods/ service, parity of price and convenience of operational hours were the main attitude factors impacting the shopping behaviour of mall visitors. The visitors considered overall attractiveness of the mall, amenities and atmospherics, personnel, ease of shopping and convenience factors while selecting the shopping centres. Diany A. A. et. al. (2025) said that shopping mall service quality led to impulse buying of the consumers in the shopping malls. They also identified the emotions related to shopping as a key player in terms of moderating the buying decision. In the recent times, in order to understand the shift in the mall visitors' buying behaviour and the shopping motivations, Belwal R. et. al. (2025) figured out that apart from personal motivations, utilitarian values played a very important role. They found that the main categories of customers in the shopping malls were Practical Value Seekers, Discerning Shoppers, Selective Online Shoppers, Social Brand Seekers and Instant Gratifiers. Practical value seekers, discerning shoppers and social brand seekers preferred to purchase from the modern retail formats. Instant gratifiers showed high level of impulsive shopping behaviour as compared to others. Zalke A. (2025) said that mainly the factors related to marketing mix and promotions impacted the satisfaction levels. Salsabila A. et. al. (2025) conducted a service quality study on shopping malls and found that service quality as well as brand image impacted the satisfaction level of the customer. Better satisfaction level led to better perception of the visitors about the malls. The success of a shopping mall not only depends on understanding the needs of the consumers and their buying

behaviour; it is necessary to understand the post purchase behaviour and their evaluation of service quality of the malls. It is learnt that one of the popular analytical methods used in measuring service quality is Importance – Performance Analysis (OZTURK S. et. al., 2023). Baquero A. (2022) suggested that another very contemporary yardstick used in the service organizations is the Net Promoter Score. The researcher found that reaching high Net Promoter Score is synonymous with achieving high numbers.

These researches focused on understanding the mindset of the consumers, but hardly any study was conducted to compare the service quality of shopping malls based in northern and southern India.

OBJECTIVES OF THE STUDY

- To identify the main factors impacting service quality perception of shopping malls in Northern vis-à-vis Southern India and determine their impact
- To determine the service gaps of the malls located in the two regions under consideration
- To determine the Net Promoter Scores of the malls of northern vs. southern India
- To provide suggestions for improvement, wherever necessary.

RESEARCH METHODOLOGY

The goal of the current study is to investigate how the patrons in shopping centres in India's northern and southern areas view the quality of the services provided. The goal is to determine whether perceptions of these two wide geographic zones differ noticeably and to comprehend the underlying factors that influence consumers' assessments of mall service quality. A systematic questionnaire based on the Retail Service Quality Scale (RSQS) has been used to gather primary data for this aim. Although the RSQS is a widely recognized tool for assessing retail service quality, the constructs used in this study have been carefully modified to fit the operational environment, context, and features of Indian shopping malls, which have a very unique mix of retail, leisure, and entertainment.

Primary data was gathered from the popular shopping malls of both north as well as south India. A total of 216 replies that were deemed legitimate and useful, were collected and incorporated into the study. Both SPSS and R statistical tools were used to analyse the data, enabling cross-validation and more reliable statistical procedure management.

To accomplish the goals of the study, a variety of statistical techniques have been used. To find the underlying factor structure and ascertain if the modified RSQS items group meaningfully within the Indian mall setting, exploratory factor analysis (EFA) has been carried out. In order to determine which service quality factors, have the greatest influence on perception, regression analysis has been used. Prioritizing managerial interventions has also been done through Importance-Performance Analysis. Furthermore, the Net Promoter Score (NPS) is assessed to offer a clear indication of consumer propensity to suggest, which functions as a useful

performance benchmark for mall owners.

RESULTS AND DISCUSSIONS

The reliabilities of datasets for north and south India respectively, were found to be acceptable, with the values of 0.892 and 0.806. Kaiser-Meyer-Olkin Test values are .616 and .707 for east and west, with Bartlett's Test of Sphericity values lesser than 0.05, both values are satisfactory.

The primary objective was to determine the underlying dimensions of service quality perception of malls in northern and southern India and then to determine the factors which significantly impact the service quality perception. For the said purpose, Exploratory Factor Analysis was conducted followed by Regression Analysis.

For north, the main underlying dimensions were efficiency of employees, promptness of response, secured transactions and alterations which explained 82.549% pf the variance. For southern India, the dimensions identified were mall accessibility and support, mall navigation and purchase experience, service integrity, support interaction quality and personalized care which explained 75.142% of the total variance.

Further, Regression Analysis was conducted to determine the significant factors predicting service quality perception. The R square values were 0.885 and 0.755 for north and south respectively, which are acceptable in studies that aim to predict human behaviour (Frost, 2019).

The results are shown in Table 1. It is observed that in northern India, the significant predictors were efficiency of employees, promptness of employees and secured transactions while for southern India, the significant factors were mall navigation and purchase experience, service integrity and personalized care. The results are depicted in Table 2.

Table 1 Model summary of regression analysis

Location of shopping malls	R	R Square	Adjusted R Square	Std. Error of the Estimate
Northern India	.885[a]	.783	.725	.16755
Southern India	.755[a]	.570	.544	.16797

Table 2 Results of regression analysis for the four regions

Northern India	Coefficients						
	Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
	Constant	-2.139	.982		-2.179	.046		
	Efficiency of employees	.566	.142	.662	3.989	.001	.526	1.902
	Promptness of response	.476	.089	.754	5.374	.000	.736	1.358
	Secured transaction	.767	.155	.759	4.947	.000	.615	1.627
	Alterations	-.238	.163	-.256	-1.467	163	.476	2.102
	Dependent Variable: Perceived Service Quality							
Southern India	Coefficients						
	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
	Constant	2.087	.567		3.680	.000		
	Mall accessibility and support	-.181	.095	-.163	-1.903	.060	.585	1.711
	Mall navigation and purchase experience	.233	.067	.314	3.475	.001	.527	1.899
	Service integrity	.727	.084	.726	8.635	.000	.607	1.647
	Support interaction quality	-.099	.133	-.070	-.741	.460	.489	2.047

	Personalized Care	-.168	.062	-.241	-2.703	.008	.541	1.847
	Aesthetic Quality	-.023	.037	-.044	-.615	.540	.857	1.167
	Dependent Variable: Perceived Service Quality							

The regression equations for the same are given below.

$$Service\ Quality\ Perception\ about\ malls\ in\ Northern\ India = -2.139 + .566\ (Efficiency\ of\ Employees) + .476\ (Promptness\ of\ Employees) + .767\ (Secured\ Transactions) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$Service\ Quality\ Perception\ about\ malls\ in\ Southern\ India = 2.087 + .233\ (Mall\ navigation\ and\ purchase\ experience) + .727\ (Service\ integrity) - .168\ (Personalized\ Care) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The Importance – Performance matrix conducted for northern India suggested that the main area that needs to be focussed upon was the efficiency of employees, remaining factors performing decently.

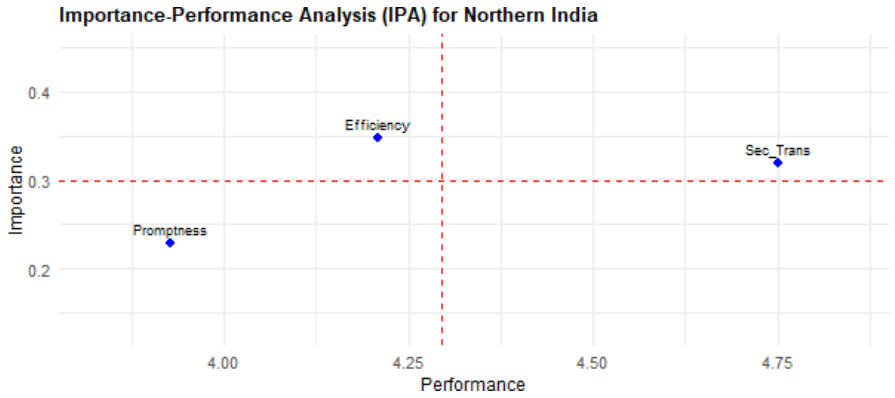


Fig 1: Importance Performance Matrix of NorthernIndia

On the other hand, for southern India, there was no major area of concern.

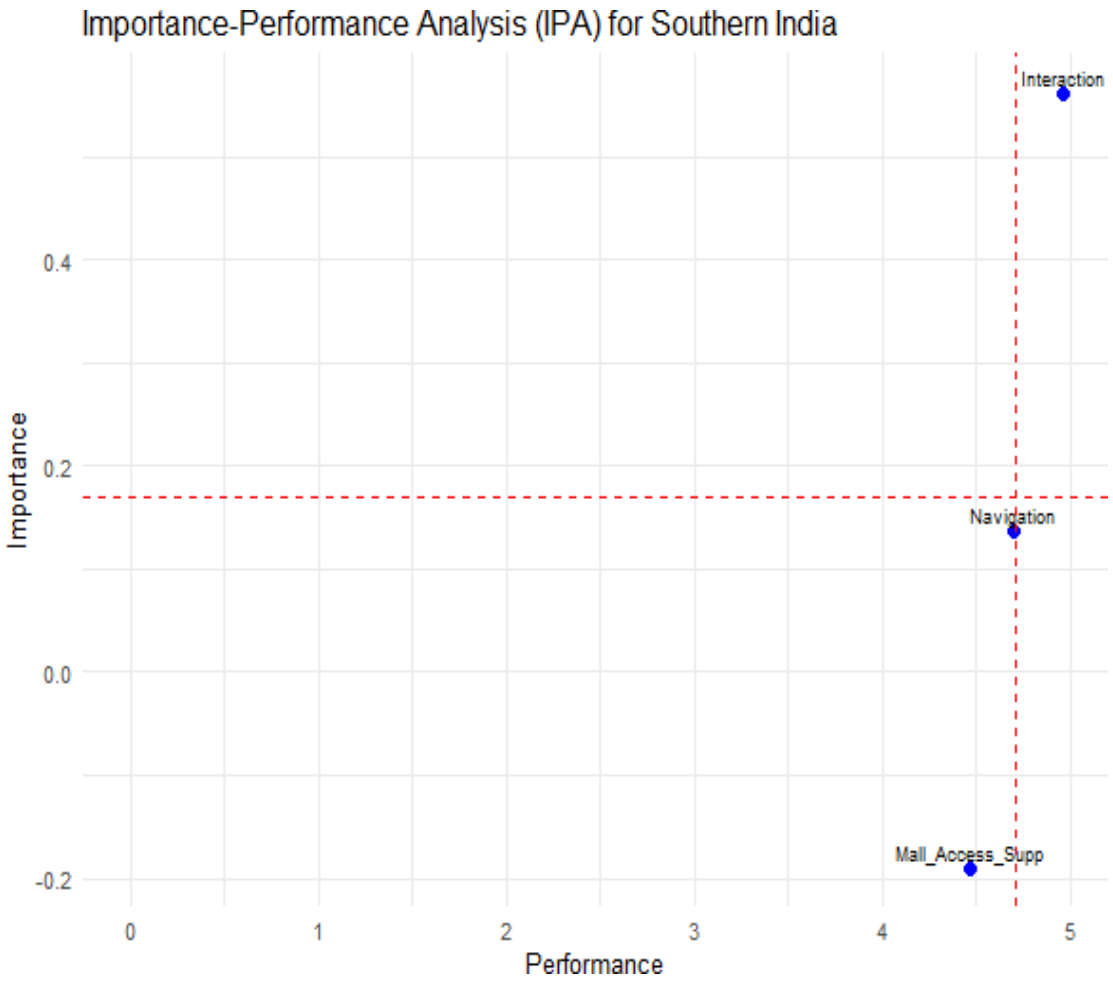


Fig 2: Importance Performance Matrix of Southern India

The Net Promoter Score in case of northern India was found to be 16.34 and in case of southern India found to be -3.737. The malls in Northern India performed well, since a large number of visitors recommend their acquaintances to visit malls, while in Southern India many visitors were found to be detractors who did not recommend or rather discouraged others from visiting shopping malls.

CONCLUSION:

Shopping malls play a very important role in today's world. This study aims to understand the service quality perception of shopping mall visitors of northern and southern India. The northern and southern parts of India have been considered in the study because, both are believed to be advancing in the field of commerce, technology and overall infrastructure developments. Hence, the locations are comparable. It is also often found that, the two parts of northern and southern India are very much varied in terms of taste and preferences of the consumers. Several studies have been conducted to understand the cultural and mindset differences among the residents. In this regard, primary data for the study is obtained by interviewing the mall visitors. The dataset obtained is analysed using the contemporary methods of statistics. It is found that the service quality dimensions impacting the mindset of the consumers from northern parts of India are efficiency of employees, promptness of employees and security of the transactions. However, for southern India a completely different picture is obtained. It is found that, the most significant factors are mall navigation and purchase experience, integrity of services and personalized care offered by the malls to the visitors. By going further into the depths of the study, it is learnt that, in case of northern India, efficiency of employees show low performance. However, for southern India, there is no major area of concern. For northern India, the mall managers may take the shortcomings into consideration. It is necessary to have a specialized recruitment team, who would be able to select the candidates having sufficient knowledge in this field and who have high emotional intelligence. These employees may be provided with refresher trainings and sufficient amount of product knowledge may be imparted, so that they are equipped to answer the customer queries and also solve the customers' issues. Also, modern digitalisation may be done so as to ensure that, the whole transaction is smooth and much faster. It is a known fact that service sector is one of the areas, where the employees get demotivated really fast. Thus to keep them motivated and focussed on the work, necessary bonuses should be given from time to time. Not only financial benefits, but also their work and achievements may be recognized. These are some of the ways to keep the employees keep going and ensure that they offer the services with highest of efficiency. The findings reveal that security of transactions also play a very important role, in terms of impacting the service quality perception of the shoppers. Hence, necessary security measures and digital methods may be adopted so that the customers feel that their transactions are safe. Also, the data shared is also safe in the hands of the malls. In southern India, though no major problem area is revealed, but the net

promoter score is found to be highly concerning. It is found that, the visitors discourage others from going to the shopping malls, purchase goods and enjoy the services. This may be attributed to the customs and traditions of the visitors located in southern India, which was revealed during the interviews conducted during primary data collection. Thus, the malls need to take necessary steps to attract customers to the malls, use promotional methods so that they are motivated to visit the malls. It is necessary to develop the feel good factor in the shopping malls of southern India. Experts' help may be taken in this matter. While conducting the interviews, the respondents in southern India notified about the excessively high car parking charges, which hinders them from visiting the shopping malls regularly. Thus necessary measure of parking management may be taken to ensure that the rates are affordable. This study may act as a guiding light for the shopping mall managers in north and south India. A happy customer will indulge in repeat purchases and

also suggest his acquaintances to avail the services of the shopping malls. Owing to constraint of time, this study is limited to the north and south India. Inclusion of the shopping malls of eastern and western India, will give a better perspective. This study may also be conducted in other countries to give a better understanding of the international shopping mall operations.

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MAPPING RESEARCH ON RURAL WOMEN'S FINANCIAL INCLUSION IN INDIA: A PRISMA-GUIDED BIBLIOMETRIC ANALYSIS

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ABSTRACT:

In developing countries like India, inclusiveness is explored from the supply and demand side, and it involves examining the means and ways to include women in a 'financially excluded' segment. This paper aims to provide a systematic literature review of the research published on women's empowerment and financial inclusion in rural India using key terms and inclusivity criteria. Scopus databases were used for systematic literature reviews, which were undertaken using the PRISMA Framework, identifying 55 papers relevant to the present study.

The study reveals that although financial inclusion helps empower rural areas, from a gender perspective, it also exacerbates exclusion and discrimination. Most studies found that although women's participation based on household level, individual, financial literacy, and financial services has not achieved its full potential in the rural segment, it can be achieved through hand-in-hand with government initiatives and schemes with the intervening of financial institutions in promoting women's inclusivity in financial services in a continuous flow of financial literacy and training in rural areas. This article contributes to the structured literature on Financial Inclusion and women's empowerment, especially by indicating the rural segment in exploring its methodology, considering barriers and challenges, and identifying focus areas to find direction for future studies.

Keywords: Financial inclusion, Women empowerment, Gender gap, Financial Exclusion, Rural, PRISMA

INTRODUCTION

Financial inclusion is paving the way for less-privileged people and their businesses to use banking and financial services to accomplish an inclusive society and an inclusive economy (Ravikumar et. al., 2021). Access to financial services gives opportunities for generating income, accumulating assets, and participating more fully in economic activities, thereby promoting social and economic empowerment (Sunaina, 2022). Despite global gains in financial inclusion, the gender gap has not changed since 2011 (Kumari, 2021). The consistent gender gap in financial inclusion over time is postulated by World Bank Findex data despite an increase in the overall financial inclusion level around the globe (Roy and Patro, 2022). Moreover, gender inequality is

one of India's key socio-economic challenges (Trivedi, 2022). Around 80% of Indian women are financially illiterate; with dedicated training and guidance, these women can be taught to invest and create wealth, avail government benefits, and establish a career for themselves, leading to women's empowerment (Guptaa, 2021). During the past years, many governments and non-government organizations have been promoting women's empowerment, especially in rural areas through various venture schemes with leading public and private sector banks. According to Sharma and Changkakti (2022), around 66% of unbanked adults globally cite a lack of funds as the reason for financial inclusion, indicating that financial services are still too expensive or not tailored for low-income individuals. Without a bank account, they attribute their financial exclusion to a lack of funds. To counter the problem in 2014, India launched the Pradhan Mantri Jan Dhan Yojna (PMYDY) 'to promote financial inclusion in every household in the country'. Moreover, digging deeper into the Findex data more than half approx. 30 percent of those who have access to formal financial services are dormant or without access to a bank account (World Bank, 2021). According to various researchers, simply having a bank account for women is not enough; instead, an approach that encourages women to use services such as insurance, credit, cashless, and mobile financial services is highly required for greater economic participation of women. A major barrier for women in rural places is limited or no access to knowledge on connecting with the continuously shifting formal financial space, particularly when it is online and digital. Additionally, with low financial knowledge, constrained mobility, and access to public spaces, and are intimated by male-dominated physical banking space and the main concern is the English-dominated online financial interfaces. This is further exacerbated by language, connectivity, and socio-cultural barriers.

Source: Global Findex Database, World Bank, 2021

Figure 1: All Adults with an account having an inactive account (India, 2021)

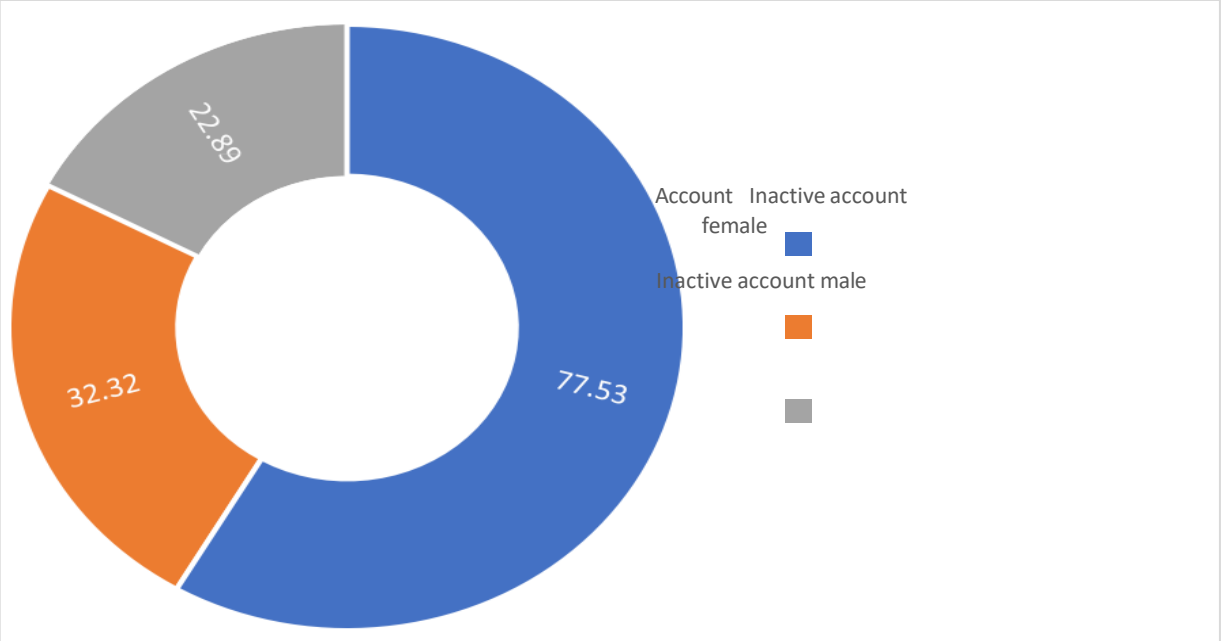
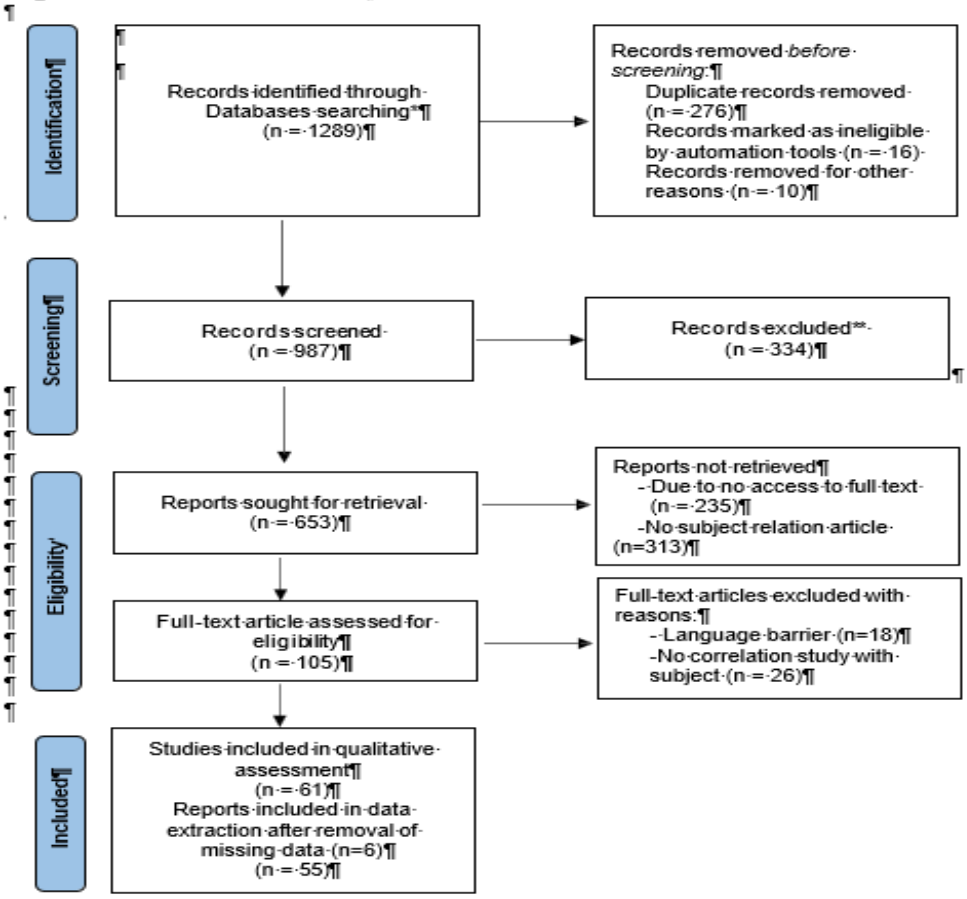


Figure 2. PRISMA Flowchart



To overcome financial exclusion, Digital financial services present unprecedented opportunities for the financial inclusion of vulnerable sections of society by overcoming the barriers of cost, distance, and transparency, and by providing financial services tailored to their needs. Despite rapid strides in digital financial inclusion in India, women face barriers to access and usage of digital financial services (Kulkarni and Ghosh, 2021).

This paper aims to address the following research questions:

RQ1. What are the features and trends of publications on women empowerment and financial inclusion in rural areas?
RQ2. What are the most productive journals, countries, and institutions in financial inclusion and women empowerment in rural India research?
RQ3. Who are the most contributing and cited authors giving the maximum number of articles, and is there any link and collaboration network among authors, countries, and keywords to financial inclusion and women empowerment in rural areas? Based on the research questions, the following are the objectives of the study:

O1. To analyze the progress and trends of research works on women empowerment and financial inclusion in rural areas.
O2: To identify the journals, institutions, and countries mostly contributing towards women empowerment and financial inclusion in rural areas.

O3. To understand the interrelationship of journals, institutions, and countries that study aspects of women empowerment and financial inclusion in rural areas.

The remainder of the analysis continues as follows. Section 2 provides the theoretical backdrop on the link between women's empowerment and relatedly, on the interlinkage between financial inclusion. Section 3 provides the research methodology framework through an overview of the data including data extraction. In Section 4, we provide a detailed discussion of the results, including robustness checks. Lastly, Section 5, provides an overall conclusion.

LITERATURE REVIEW

Women Empowerment

One area where the disparity is quite pervasive and is receiving increasing attention is the gender gap in access to finance (Ghosh and Vinod, 2016). Gender discrimination and associated social norms are important contributing factors to the high frequency of women trapped in poverty (Dongen et al., 2022). According to the 17 Sustainable Development Goals adopted by the United Nations, women's financial inclusion is essential in the promotion of gender equality (Arunkumar et al., 2016). Across the globe, there is an increased emphasis on FI, especially in emerging economies, with the motive to enhance economic growth and decrease poverty (GPFI, 2011). According to Bhatia & Singh, (2019), Financial Inclusion is one of the factors that can drive rural women from financially excluded segments toward empowerment. The mediator variables such as financial literacy, financial institutions, and financial self-efficacy play a prominent role in women's financial inclusion. To drive

women into financial independence various initiatives and programs for development play a prime role (Guptaa, 2021).

Financial Inclusion and Gender

Synthesized evidence revealed that the existence of gendered financial inclusion is mainly due to demand-side factors (Roy and Patro, 2022). Ravikumar et al. (2021) found that in India there are geographical and gender disparities in financial inclusion penetration and financial inclusion penetration varies in terms of gender. (Ghosh and Vinod, 2016) revealed that data at the household level, households headed by women are generally more likely to seek informal financing sources than formal finances. Gender or sex appears to be strongly correlated with the usage of financial services (Aziz et al., 2022). Religious restrictions also limit women's willingness to work for a living than males to own a bank account. Various socio-economic and cultural factors are also seen to influence women's financial exclusion (Roy and Patro, 2022). Handa and Taneja, (2021) indicate that both sexes use multiple channels to access financial services available digitally. However, on average, the level of adoption among the male gender is higher compared to women, where men prove to be more financially and digitally savvy. Moreover, there is a strong correlation between gender and the utilization of various channels, except Internet banking and debit/credit cards, which are simpler to use and provide greater convenience and ease. According to the survey, some strategies have been implemented to minimize the gender disparity when it comes to financial services accessibility. The systems are Know Your Customer (KYC) norms, no-frill accounts; an extension of financial services and became a medium of empowering women; and the introduction of a small loan to make females capable and self-dependent (Kumari, 2022). (Kulkarni and Ghosh, 2021) argue that digitalization can help enhance women's social and financial autonomy. To add to that Garikipati et al. (2017) found that women's empowerment and gender equality through the contribution of microfinance can contribute to the wider dynamics of change in society where women can access finance and do more both in the household and beyond without conflict. Whereas, Basu, (2006) contends that small-scale lending is a weak form of women's empowerment and does not account for the powerful form of it. The study concentrates on particular obstacles to saving and developing "treatments" within the five parameters constraints of women empowerment namely, transaction costs, lack of trust and regulatory barriers, information and knowledge gaps, social constraints, and behavioral biases (Karlan et al., 2014).

RESEARCH METHODOLOGY

For a systematic literature review, the literature on financial inclusion and women empowerment is the main emphasis of this research. Since, a systematic literature review is considered to be a rigor, transparent, and reproducible method of interpreting studies in a particular research area, hence, it would be a suitable approach to address the said research question (Tranfield et al., 2003). 'Transparency', 'clarity', 'focus', 'equality', 'accessibility', 'board coverage', and

'synthesis principles' serve as the foundation for the systematic review (Thorpe et al., 2005). To organize, gather, and summarize the relevant studies, we applied the Liberati et al. (2009) checklist items as well as the preferred reporting items for the systematic reviews and meta-analysis (PRISMA) procedure. While deciding which journal articles to employ for this study, we took into consideration the identification, screening, eligibility, and inclusion criteria. Using instruments like citation, keyboard, co-citation count, and co-authorship Yu et al. (2020) employ bibliometric analysis to examine both quantitative and qualitative research publications and suggest future study topics (Mahato et al., 2023). The present study uses Biblioshiny and VOSviewer software for analysis. Biblioshiny helps in analyzing the collection of data regarding different levels of analysis like document analysis, thematic map, and conceptual structure. Hence, Figure 2 depicts the PRISMA Framework of the study, showing the data extraction used for the retrieval of all relevant papers for analysis.

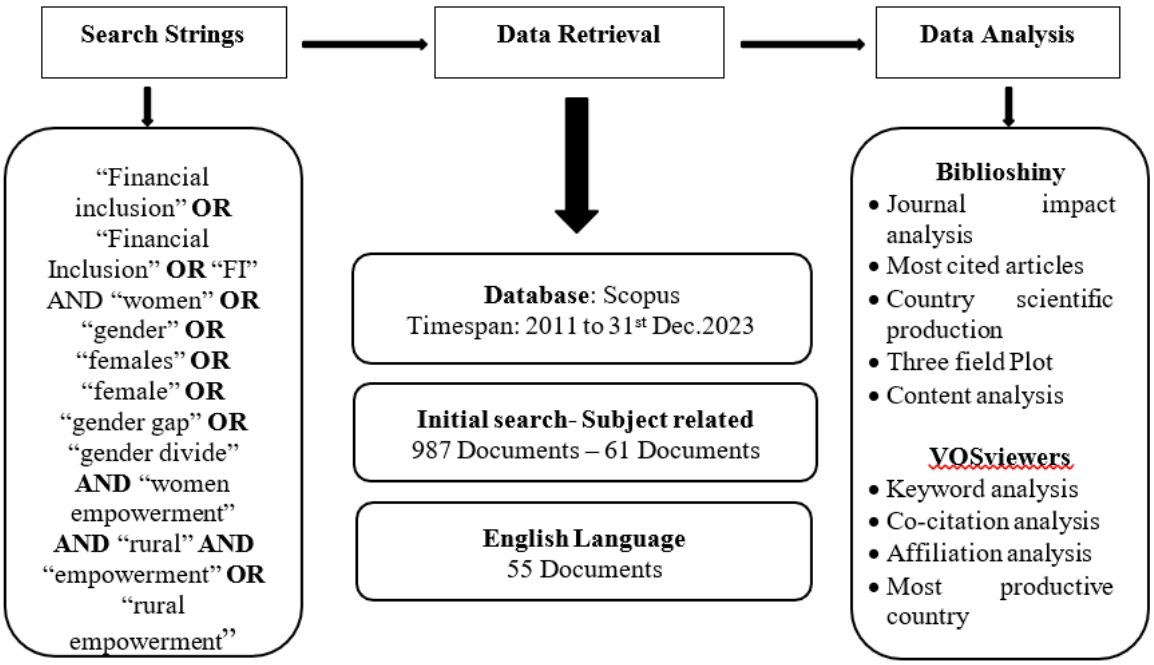
Defining the appropriate terms for search

The present study chose to review papers from Elsevier's Scopus database because it is an extensive database containing maximum indexed journals. This database is widely recognized as an alternative to the Web of Science (Harzing and Alakangas, 2016). The search strings include "financial inclusion" OR "Financial Inclusion" OR "FI" AND "women" OR "gender" OR "females" OR "female" OR "gender gap" OR "gender divide" AND "women empowerment" AND "rural" AND "empowerment" OR "rural empowerment". Full-text published research articles were accessed from 2011 to 2023. Articles published in the English language were studied, resulting in the display of 61 records, as provided in Figure 3. The search strings validate and confirm that documents belong to the theme of the study by using title/abstract/keywords/subject area/ year/full-text access search. Hence, the validation of the search strings is checked by observing their ability to identify the various known primary studies (Mahato et al., 2023).

Refinement of search results

A total of 55 documents were retrieved from search results after applying filters for publication years from 2011 to 2023, and the removal of duplicates (n = 302), resulted in 987 results. All the results were exported into an Excel sheet and analyzed based on their titles and abstract, region, and full text, from economics, business management, accounting, finance, science, and social science, leaving a total of 61 documents results. After going through the abstract, it was found that all the documents retrieved were relevant to the present study. After reading the full text of 61 research articles, 6 were excluded because they did not meet the criteria region on which the study was conducted, leaving the final result of 55 documents results.

Figure 3: Design of the Study



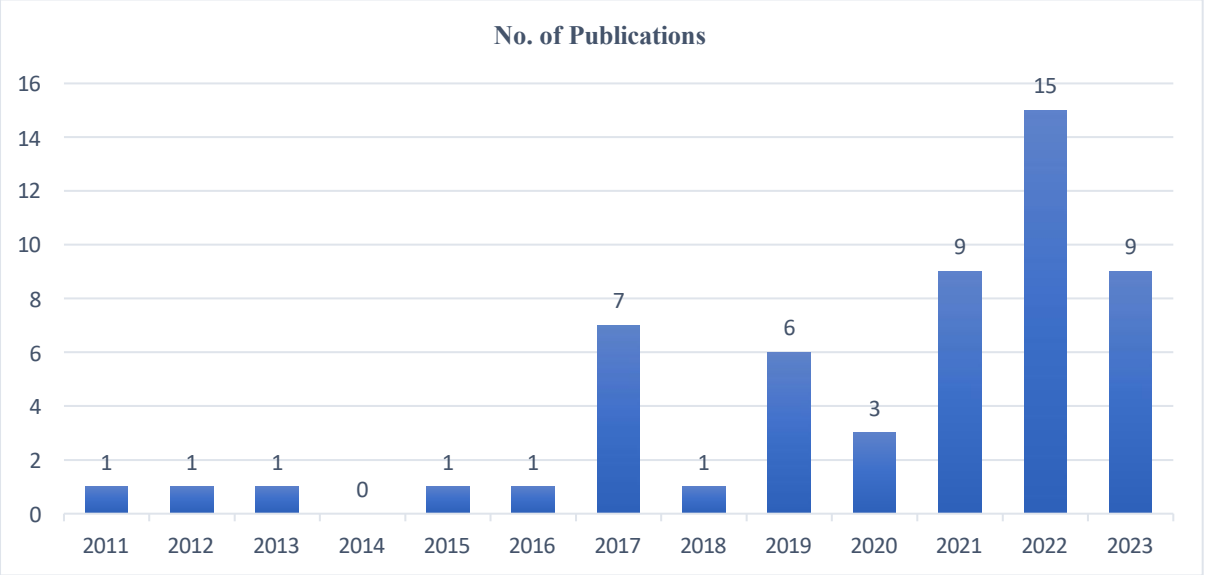
Source: Author's compilation

Table I. Descriptive overview of selected publications on women empowerment and financial inclusion (FI)

Description	Criteria	Results
Main information about the data	Timespan	2011-2023
	Sources (journals, articles, etc)	51
	Documents	55
	Average citation per document	8
	Reference	1470
Document Type	Article	46
	Book	1
	Book chapter	3
	Conference paper	2
	Proceedings Paper	2
	Review	1
Document Contents	Keywords plus (ID)	200
	Authors Keyword	169
Authors	Authors	174
	Author of single-authored documents	6
Authors collaboration	Single authored documents	6
	Co-authors per documents	3.89

Source: Complied by the author using Biblioshiny

Figure 4. Trend of publication



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DISCUSSION

Results of the bibliometric analysis

The first step in review research is to accumulate and synthesize the findings of studies from the extant literature. Donthu et al. (2021) explain that "using bibliometric analysis the study can find and analyze a large volume of scientific data from a specific field to unveil the explored and emerging research areas". The critical areas of research, the quality of the studies, and the progress of the relevant theme among researchers are analyzed. The descriptive overview of the publication on the theme of women's empowerment and financial inclusion is elucidated in Table I.

A total of 55 documents on women empowerment and financial inclusion were retrieved from the Scopus database from

2011 to 2023. Table I depicts these included 46 (84 %) research articles, 1 (2%) book, 3 (6%) book articles, 2 (4%) conference papers, 2 (4 %) Proceedings papers, and 1 (2%) review papers. The total number of authors in this field is 174, and the total number of journals that published these 55 papers on the search theme is 51.

Trends of publication.

The year-wise publication of the research paper on women's empowerment and financial inclusion is shown in Figure 4. Financial inclusion gained popularity in India after the introduction of Pradhan Mantri Jan Dhan Yojana in 2014. The increasing gender divide in the financial sector and SDG initiatives lead to various attention from researchers, financial institutions, government, policymakers, etc. The maximum number of publications was in 2022, with 15 documents. Thereafter, in the years 2023 and 2021, the number of papers published in both years is 9 documents each. Following the year 2017, the number of papers published was 7

Most Productive Sources

Table II shows the top 10 most productive journals in the areas of financial inclusion and women's empowerment. Equality, Diversity, and Inclusion, published by Emerald Group Holdings Ltd, contributes the highest number of articles (2), has an h-index of 12, and has a citation score of 3.8.

Journal impact analysis

The number of papers published in the field and the number of citations received on the theme of research signify the most relevant journals. Table III shows that Social Science and Medicine has the maximum number of local citations, i.e. 44.

Most Cited Article

"Citation analysis is the process of counting the number of times other authors cite an article to access the impact of a particular author" (Mahato et al., 2023). The top 10 most cited articles on women empowerment and financial inclusion in rural India are described in Table IV. A research paper written by Anita Raj, Jay G. Silverman, Jeni Klugman, Niranjan Saggurti, Balaiah Donta, and Holly B. Shakya titled "Longitudinal analysis of the impact of economic empowerment on risk for intimate partner violence among married women in rural Maharashtra, India" published in the year 2018 is the most cited document in this field as this has been cited 44 times

Affiliation analysis

The top 10 institutions contributing numerous research outputs on women empowerment and financial inclusion in rural areas from 2011 to 2023 are listed in Table V. These top 10 institutes contribute to 10 articles.

Most productive country

The top 10 countries that contributed to the research area of women empowerment and financial inclusion in rural areas are presented in Table VI. This analysis reveals that India is in first position contributing to 29 documents. Followed by the country United Kingdom (UK) and the United States (US) are in second and third position, respectively with 10 and 6 numbers of papers each.

Country Scientific Production Map

The country contributing the maximum number of documents is shown in Figure 5, in the bluest colour. The data retrieved from the Scopus database reveals that the top five contributing countries in the area of women empowerment and financial inclusion in rural areas were India contributing to the maximum number of documents i.e. 29, thereafter US (10), the UK (6), Malaysia (5) and Hungary (2).

Table II. Top 10 most productive journals on Financial Inclusion and women empowerment

Rank	Journal	TP	TC	The most cited article	Times Cited	Publisher	H-index	Cite Score	PY (Start)
1.	Equality, Diversity, and Inclusion	2	17	Social and economic empowerment of women through financial inclusion: empirical evidence from India	15	Emerald Group Holdings Ltd.	12	3.8	2022
2.	International Journal of Social Economics	1	31	Determinants of financial inclusion in rural India: does gender matter?	31	Emerald Group Holdings Ltd.	1	2.6	2020
3.	International Journal of Rural Management	1	17	Impact of Microcredit on Employment Generation and Empowerment of Rural Women in India	17	Sage Publications India Pvt. Ltd	1	2.8	2021
4.	International Journal of Management	1	6	Financial inclusion and gender barriers for rural women	5	IAEME Publication	1	0.2	2019
5.	Advances in Business-Related Scientific Research Journal	1	3	Financial technologies as a factor of financial inclusion of women	2	GEA College – Faculty of Entrepreneurship	1	0.1	2019
6.	Cogent Social Sciences	1	2	Socio-economic empowerment in rural India: Do financial inclusion and literacy matters?	2	Cogent OA	1	0.0	2023
7.	Qualitative Research in Financial Markets	1	2	Socio-economic development through self-help groups in rural India – a qualitative study	2	Emerald Publishing	1	2.9	2022
8.	Proceedings of the International Conference on Industrial Engineering and Operations Management	1	2	The Effect of Financial Inclusion on Empowerment of Women Through Participation in Self-Help Groups	2	IEOM Society	1	0.1	2021
9.	Journal of the Knowledge Economy	1	0	The Impact of Financial Inclusion on Social and Political Empowerment: Mediating Role of Economic Empowerment	0	Springer	1	13.5	2023
10.	Universal Journal of Accounting and Finance	1	0	Effectiveness of Financial Inclusion and Rural Upliftment: Empirical Evidence from Tamil Nadu	0	Horizon Research Publishing	1	0.0	2022

Note: *TP, Total Pubication; TC, Total Citation; PY, Publication Year

Source: Complied by the author using Biblioshiny

Table III. Top 10 Most Local Cited Sources

Rank	Sources	No. of Citations
1.	Social Science and Medicine	44
2.	Journal of Business Venturing Insights	63
3.	International Journal of Social Economics	31
4.	Journal of Innovation and Entrepreneurship	26
5.	Journal of Developing Societies	22
6.	Equality, Diversity, and Inclusion	17
7.	International Journal of Rural Management	17
8.	Enterprise Development and Microfinance	14
9.	International Journal of Scientific and Technology Research	13
10	Emotions and Society	10

Source: Complied by the author using Biblioshiny

Author impact analysis

Table 7 lists the top 10 authors contributing the most research documents on women's empowerment and financial inclusion in rural areas. Most of the articles belong to India. The top authors contributing three articles are Hemant Gupta, Mukesh Pal, and Vinay Kandpal, Vikash Agarwal from India, Emeka Raphael Agu from Nigeria, and Ranjula Bali Swain from Sweden.

Analysis of Keywords

Keywords are analyzed in bibliometric analysis to investigate the trending topics in the field (Adgo et al., 2021). The most common indexed keywords used in 55 documents on women's empowerment and financial inclusion in the Scopus database three times or more are considered for analysis. The keywords that appeared most frequently are "financial inclusion," "women's empowerment," "gender," "microfinance," and "India." Figure 6 shows a word cloud showing these 52 keywords.

Three field plots of keywords author country

Three-field plot (Sankey Diagram) keywords (left side), author (middle), and country (right side) are shown in Figure 7. The size of each node corresponds to the number of documents published by each country. The thickness of overlapping lines shows a significant relationship between the two subjects. This figure indicated that India is the top contributing country in the theme "women empowerment", "financial inclusion" and "rural".

Table IV: Top 10 most cited articles on financial inclusion and women empowerment in rural areas research

Rank	Title	Authors	Year	DOI	Source	TC	Type Of Research
1.	Longitudinal analysis of the impact of economic empowerment on risk for intimate partner violence among married women in rural Maharashtra, India	Raj A; Silverman JG; Klugman J; Saggurti N; Donta B; Shakya HB	2018	10.1016/J.Socscimed.2017.11.042	Social Science and Medicine	44	Empirical
2.	Do social enterprises walk the talk? Assessing microfinance performances with mission statements	Mersland R; Nyarko SA; Szafarz A	2019	10.1016/j.jbvi.2019.e00117	Journal of Business Venturing Insights	36	Empirical
2.	Determinants of financial inclusion in rural India: does gender matter?	Kaur S; Kapuria C	2020	10.1108/ijse-07-2019-0439	International Journal of Social Economics	31	Empirical
3.	Financial inclusion and development in the least developed countries in Asia and Africa	Ozcelebi AF; Kasekabunub A; Monfort S; Girón A	2021	10.1186/s13731-021-00190-4	Journal of Innovation and Entrepreneurship	26	Empirical
4.	Enhancing climate change resilience through microfinance: redefining the climate finance paradigm to promote inclusive growth in Africa	Chirambo D	2017	10.1177/0169796x17692474	Journal of Developing Societies	22	Empirical
5.	Impact of microcredit on employment generation and empowerment of rural women in India	Datta S; Sahu TN	2021	10.1177/0973005220969552	International Journal of Rural Management	17	Empirical
6.	Social and economic empowerment of women through financial inclusion: empirical evidence from India	Pal M; Gupta H; Joshi YC	2022	10.1108/edi-04-2021-0113	Equality, Diversity, and Inclusion	15	Empirical
7.	Financial inclusion and gender barriers for rural women	Manta A	2017	10.34218/ijm.10.5.2019.006	International Journal of Management	5	Empirical
8.	Is m-Pesa a model for financial inclusion and women empowerment in Kenya?	Urquía-Grande E; Cano Montero EI; Pérez-Estébanez R; Chamizo-González J	2018	10.1016/j.landusepol.2018.09.005	Land Use Policy	4	Empirical
9.	Socio-economic empowerment in rural India: Do financial inclusion and literacy matters?	Panakaje Niyaz; Rahiman, Habeeb UR; Parvin, S. M. Riha; Kabil Abhinandan; Siddiq, Abbakar	2023	10.1080/23311886.2023.2225829	Cogent Social Sciences	3	Empirical
10.	The Impact of Financial Inclusion on Social and Political Empowerment: Mediating Role of Economic Empowerment	Bhatia, Shivangi; Dawar, Gaurav	2023	10.1007/s13132-023-01621-1	Journal of the Knowledge Economy	2	Empirical

Note: TC-Total Citations

Source: Compiled by the author using Biblioshiny

Table V: Top 10 affiliations contributing a maximum number of documents

Rank	Institutions	Document	No. of Citations	Total Link Strength
1.	Department of Economics, London, United Kingdom	1	26	8
2.	Alliance School of Business, Alliance University,	1	2	7
3.	Department Of Economics, The University of Burdwan,	1	16	7
4.	Faculty of Management Studies, University of Delhi, New	1	31	6
5.	Shri Ram College of Commerce, University of Delhi, New	1	31	6
6.	Alliance Business School, Alliance University, Bangalore,	1	15	5
7.	Department of Business Management, Sardar Patel	1	15	5
8.	Indukaka Inpcowala Institute of Management, Charotar University of Science and Technology, Changa, Gujarat, India	1	15	5
9.	Pranveer Singh Institute of Technology, Kanpur, India	1	2	4
10.	Delhi School of Management, Delhi Technological University, Delhi, India	1	3	3

Source: Complied by the author using VOS viewer

Table VI: Top 10 countries contributing a maximum number of documents

Rank	Country	No. of documents	No. of Citations	Average citation per document	Total link strength
1.	India	29	102	3.51	4
2.	United Kingdom	10	91	9.10	5
3.	United States	6	13	2.17	2
4.	Malaysia	5	18	3.60	2
5.	Hungary	2	7	3.50	1
6.	Pakistan	2	14	7.00	3
7.	Norway	1	36	36.00	0
8.	Belgium	1	36	36.00	0
9.	Canada	1	13	13.00	0
10.	Kenya	1	4	4.00	1

Source: Complied by the author using VOS viewer

Thematic map of keywords

The thematic analysis conducted on women's empowerment and financial inclusion in rural areas is depicted in Figure 8. The year between 2011 to 2023 is

set as the timespan. The minimum word count frequency is set at five, and the word label size is set to one, taking the number of words as 250. The keywords show essential topics from the field. A thematic map of studies on women empowerment and financial inclusion in rural areas gives insights into the field's scope for further studies. According to Mahato et al. (2023), "Thematic map analysis

Figure 5. Country-wise Production map

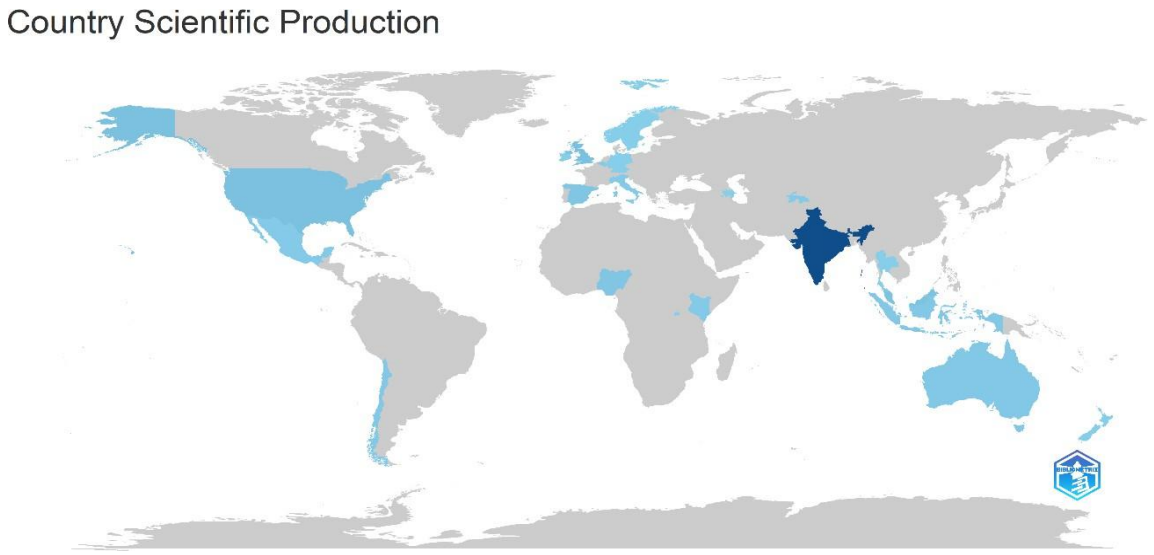


Table VII: Top 10 authors contributing a maximum number of documents

Rank	Author	Scopus ID	Affiliation	Country	Documents	Citations	AC
1.	Hemant Gupta	57193008631	Indukaka Inpc Institute of Ma Gujarat, India	India	2	17	8.5
2.	Mukesh Pal	57283851400	Charotar Uıof Science and Technology, Changa, India;	India	2	17	8.5
3.	Vinay Kandpal	57208154209	Department of General Management, UPES, Dehradun, India	India	2	2	1.0
4.	Vikas Agarwal	35519314100	Institute of Information Technology, New Delhi, India	India	1	1	0
5.	Emeka Raphael Agu	58543719800	Lagos Business School, Pan-Atlantic University, Nigeria	Nigeria	1	0	0
6.	Ranjula Bali Swain	23020073200	Department of Economics, Uppsala University, Sweden	Sweden	1	3	3.0
7.	Violet N. Barasa	58009886200	International Livestock Research Institute (ILRI),	Kenya	1	4	4.0

			Kenya				
8.	Vijay Bedarkar	58688637600	Was Environmental, Social and Governance (ESG), Trust Payments, United Kingdom;	UK	1	0	0
9.	Shivangi Bhatia	57226872979	Department of Management, Indira Gandhi Delhi Technical University for Women, Delhi, India	India	1	20	20.0
10.	Mukul Bhatnagar	57958802200	Chandigarh University, India	India	1	15	15.0

Note: AC_Average Citation per Document
Source: Complied by the author using VOSviews

Figure 6. Analysis of Author's Keywords



Figure 7. Three field plot keywords, author and country

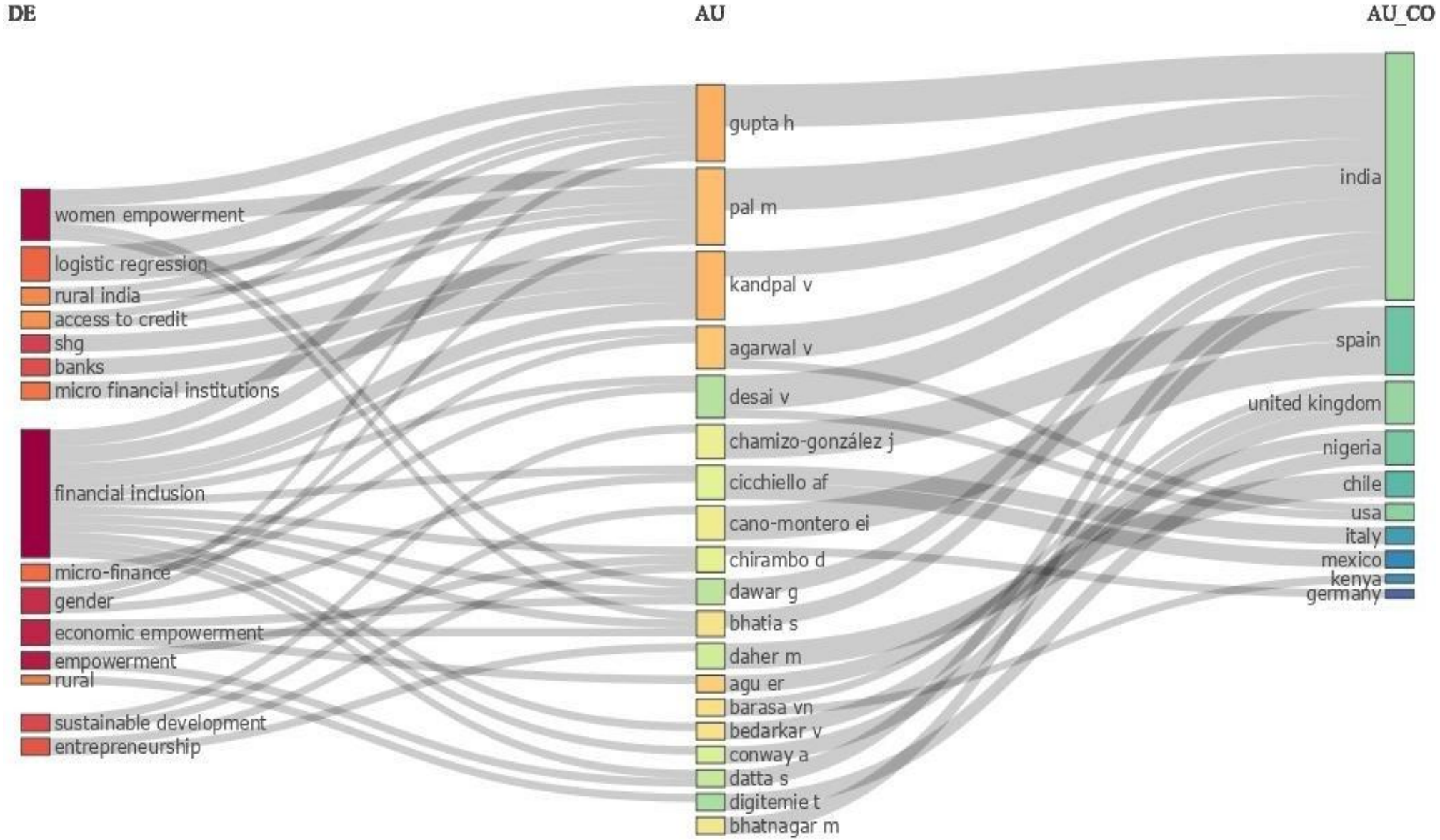
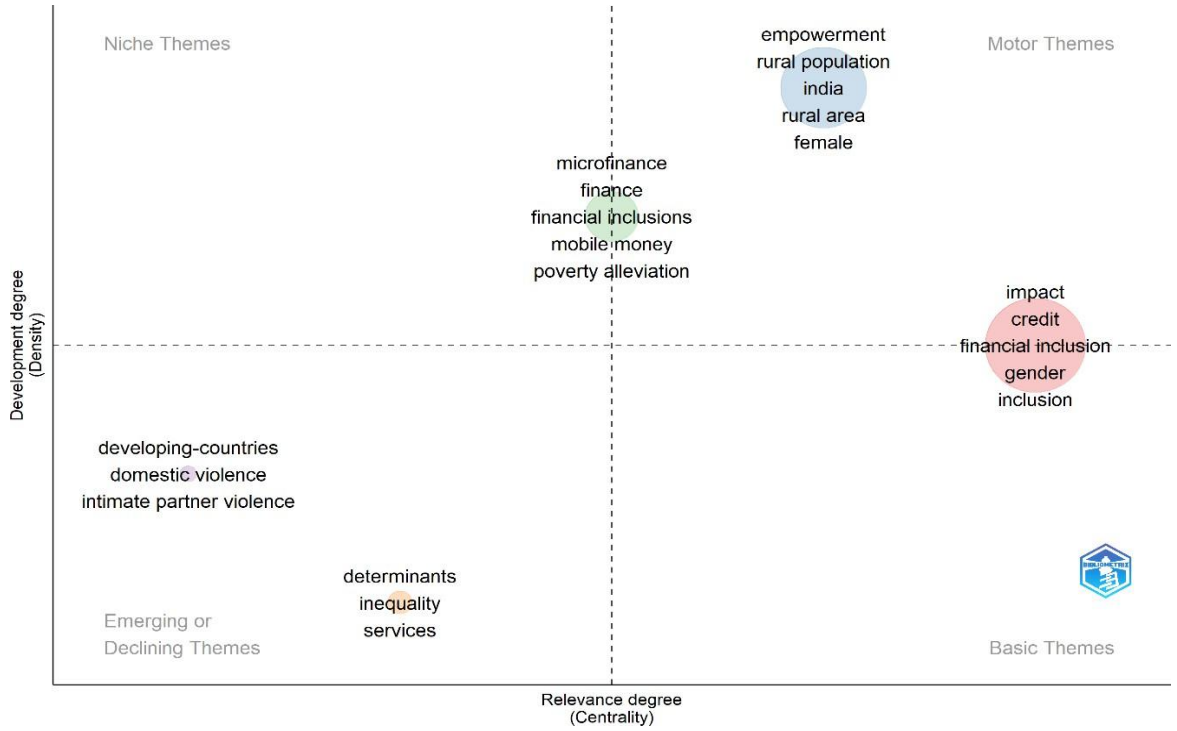

DE
AU
AU_CO
women empowerment
logistic regression
rural india
access to credit
shg
banks
micro financial institutions
financial inclusion
micro-finance
gender
economic empowerment
empowerment
rural
sustainable development
entrepreneurship
gupta h
pal m
kandpal v
agarwal v
desai v
chamizo-gonzález j
cicchiello af
cano-montero ei
chirambo d
dawar g
bhatia s
daher m
agu er
barasa vn
bedarkar v
conway a
datta s
digitemie t
bhatnagar m
india
spain
united kingdom
nigeria
chile
usa
italy
mexico
kenya
germany

Figure 8. Thematic map



It aids in providing knowledge to novice researchers and stakeholders about the potential of the relevant field topics".Figure 8 depicts the visual representation, identifying the trajectory is shown by dividing time into segments (Alkhammash, 2023). In this, Quadrant 1 (Motor theme) keywords "empowerment", "rural population", "India", "rural areas", and "females", are the well-explored research topics from the particular field characterized by high centrality and high density. Another cluster keywords lie between Quadrant 1 (Motor theme) and Quadrant 2 (Niche theme) are "impact", "credit", "financial inclusion", "gender", and "inclusion" signifying keywords of high density with high and low centrality (i.e., low centrality signifies niche theme) implying that they are of both crucial as well as limited relevance on the research topic. Quadrant 3 (Emerging or Declining themes) keywords "developing countries", "domestic violence", intimate partner violence", "determinates", "inequality" and "services" are of low centrality and low density giving rise to the minimal and marginal developed area related to the research topic. In addition to, Quadrant 1 and Quadrant 4 (Basic theme) have keywords in between i.e., "microfinance", "finance", "financial inclusion", "mobile money", and "poverty alleviation" have high centrality and high and low density (i.e., low density signifies basic theme) demonstrating these themes are vital for transdisciplinary research issues according to the research documents.

Co-citation analysis

According to Mu and Ma, (2022) and Wang et al. (2022) studied that "various scientometric and co-citation analytic investigations were conducted to examine published studies' referenced works to

evaluate how relevant and connected they were to the subject of research". In this study, VOSviewers software is used for building and displaying bibliometric network patterns from abstracts and keywords (Van Eck and Waltman, 2010, 2014; www.vosviewer.com).

Figure 9. Co-citation network

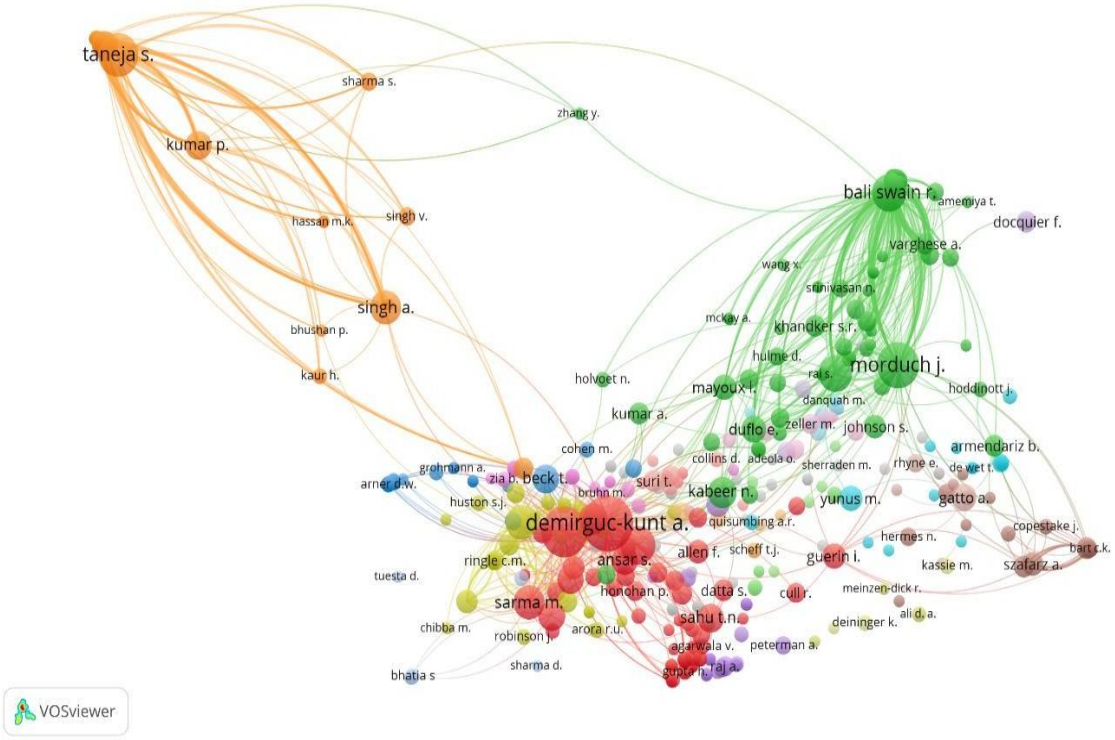


Figure 9 depicts, a total of 3,369 references and 72 authors and provides a co-citation network of cited authors taking a minimum number of citations of an author as 05 were extracted from the studies of interest to determine their semantic relationships. Figure 9 provides a detailed record of three clusters obtained through co-citation analysis to classify and categorize the comprehensive research structure on women empowerment and financial inclusion in rural India.

Clusters of Content Analysis

Cluster1: Financial Inclusion and Barriers to Women's Empowerment

According to (Demirguckunt et al., 2013 (a),(b)), an inclusive financial system can only be achieved when the improvised who have been left out of the formal financial system have widespread access to official accounts that are both affordable and easily accessible. Additionally, the gender difference in the use of formal and informal financial services under the custom, less ability to own, manage, control, and inheritance, early marriage, investment, saving, and plans are the factors that result in women's financial exclusion. Adding, to Ghosh and Vinod, (2017) findings, discrimination is not just economic but also political and societal, but also factors

specific to the financial sector. Similarly, Park and Mercado (2015) found that higher financial inclusion can reduce income inequality and poverty. Moreover, Holvoet N, (2005) (a) (b) found that women's empowerment can be raised by intensive social group intermediation, specifically raising such programs that can increase women's decision-making power and support the importance of the female voice in household decision-making for overall economic and human development.

Table VIII. Top 5 papers in Clusters using betweenness, closeness, and page rank criteria

Authors	Betweenness	Closeness	PageRank
Cluster 1			
demirguckunt a.2013-2	218.6664735	0.008333333	0.102097177
park cy.2015	47.15357992	0.007352941	0.04686887
ghosh s.2017	39.98760597	0.007575758	0.062703494
holvoet n.2005-2	9.423769431	0.006993007	0.023634433
kempson e.2004	7.693632673	0.007092199	0.025887858
Cluster 2			
kabeer n.1999, 2001, 20005, 2021	204.1300531	0.008403361	0.048916211
morduch j.2003-2	62.0000000	0.003921569	0.031783961
mayoux l.2000, 2005	15.96449457	0.006944444	0.02290524
ashraf n.2010	8.09047619	0.006622517	0.03534584
banerjee a.2009	0.19047619	0.006289308	0.018434892
Cluster 3			
guerin i.2021	76.86059615	0.007751938	0.036687519
basu p.2005-2	21.13740802	0.007518797	0.036978215
duflo e.2012	21.13740802	0.007518797	0.036978215
karlan d.2011	14.53863719	0.006896552	0.028919545
allen f.2021	10.86031001	0.007462687	0.030289074

Source: Complied by the author using Biblioshiny

Furthermore, norms following the female discrimination in healthcare investment and investment in daughter's educations are the constraints of women's empowerment. In the paper, by Kempson et al. (2004) people living in low-income, Indigenous, women's, and ethnic minority communities have low levels of engagement with banking leads to banking exclusion. Obstacles such as identity requirements, the terms and conditions of bank accounts, levels of banking charges, physical access problems, and psychological and cultural barriers.

Cluster 2: Women's economic empowerment.

Kabeer, (2021) explored on micro-level data that women's economic empowerment subsequently helps in economic growth into greater gender equality only when women are employed. Women empowerment can be achieved according to Kabeer, (2005) "Microfinance" is like "magic bullets" having radical structural transformation which not only makes contributions to the economic productivity and well-being of the poor women but also other interventions to change on different fronts, economically, socially and politically; also on education, and access of financial services. Furthermore Kabeer, (1999) stated that a more instrumentalist form of advocacy which can incorporate three interrelated dimensions of resources, agency, and achievement is important in the measurement of women's empowerment. On the other hand, Mayoux, (2000) noted in their study that non-financial services and organized groups can provide thousands of women with financial resources in addition to microfinance. Instead, it needs to be well thought out through a program created so that the various microfinance providers have unique structures and limitations. To address women's products and levitating programs for gender training. According to Mayoux, (2005), microfinance and gender are related to three paradigms i.e., the "Financial self-sustainability paradigm", "poverty alleviation paradigm" and "feminist empowerment paradigm". He also stated that "a genuine empowerment strategy must be defined by women themselves, and not imposed by external agencies". Hence, to maximize the contribution of micro-finance to women's empowerment requires equality in access to all micro-finance services but also an adequate and non-discriminatory regulatory framework. In addition to providing loans to women for empowerment, Kabeer (2001) included several more justifications that help women overcome injustice in their lives and lead to higher efficiency and equity in their entrepreneurial potential. The micro-saving accounts hold evidence that women are capable of exercising self-determination in their decision-making, self-perception, and consumption choices (Ashraf et al., 2006). Hence, saving plans can help women in self-control and desire to have more decision-making power in the household. To reinforce the point made above, Littlefield et al. (2003) added that households can enhance their education, health care, and nutritional guidance when they have high salaries and more control over financial resources. Additionally, Morduch and Rutherford, (2003) suggested that distributing well-liked products to a large number of the economically disadvantage can constantly aim to provide ease, continuity, reliability, and a flexible variety of services. According to Banerjee et al. (2015) merely taking out a loan from an MFI does not affect treatment areas or

any of the development outcomes, such as women's empowerment, health, or education.

Cluster 3: Women's financial inclusion

According to Allen et al. (2016), there is a correlation between increased financial inclusion and reduced account costs, increased accessibility to financial intermediaries, enhanced legal protections, and politically stable situations. Nonetheless, several ethnographic studies on debt are linked to social life and social structure; some are related to social recognition while others to shame and disgrace. As for women, borrowing from men as strangers may damage their reputation as women Guerin, (2014) where Indian rural women juggle negotiations, contestations, and struggles with financial, social, and moral values. According to research by Basu and Srivastava (2005), the rural poor in India have very little access to official sources of financing. Despite substantial efforts through microfinance initiatives Basu and Srivastava, (2005) there are always challenges in scaling up access to financial services. These are enabling policy, legal and regulatory framework, attention to quality, and importance of financial sustainability, clear targeting of clients, appropriate products and services and good staffing, inclusiveness and competition, overcoming geographic concentration, long-term reforms to scale up access, freeing up interest rates, entry of new private banks in rural finance and restructuring the RRBs and cooperative credit banks. Furthermore, Karlan and Valdivia, (2011) focused on building the human capital of micro-entrepreneurs to improve their livelihood and alleviate poverty with higher repayment of debts and higher savings retention. Based on the previous argument Reboul et al. (2021) found that in southern India women are heavily indebted along with microcredit. Resulting in constrained by family affiliation, poverty level, and caste where the factors were women of the poorest and low caste households have higher borrowing responsibilities and debt. Furthermore, according to Duflo (2012), continued policy actions and collateral benefits that can offset the cost of distortion through benefit redistribution are likely to be necessary to eliminate gender inequality and stereotypes that limit the abilities of women.

Results of the Systematic Review

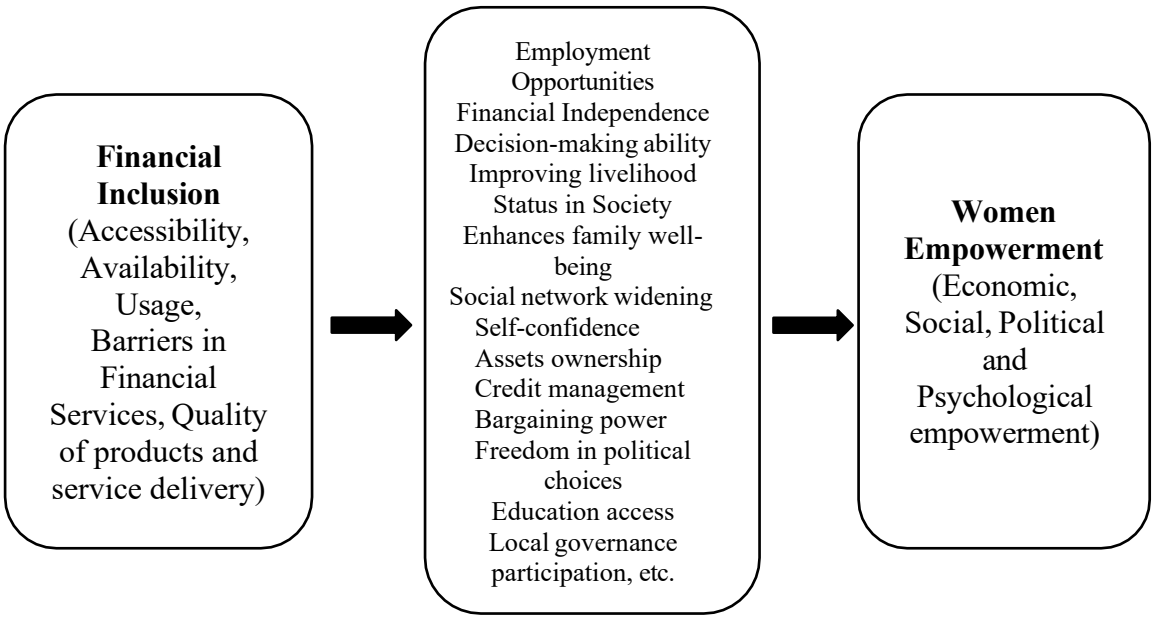
After a review of the literature obtained from the Scopus database, it was discovered that the factors influencing financial inclusion had an impact on women's empowerment in rural India. The financial inclusion aspects that impact the variables influencing women's empowerment in terms of their economic, social, political, and psychological empowerment toward women in rural areas are the foundation of a conceptual framework. Thus, through financial inclusion, the framework helps policymakers, institutions, and the government empower women living in rural areas.

According to Aziz et al. (2022) the literature, women's financial inclusion and empowerment have led to several elements that allow women to make decisions about their own lives and beliefs. Empowerment is a multifaceted term that extends beyond the political, social, and economic spheres. Therefore, the factors that determine the financial inclusion index, such as "accessibility", "availability", "usage", "barriers to financial services", and

“quality of products and service delivery” contribute to the empowerment of women in rural areas by providing them with a range of advantages like “Employment Opportunities”, “Financial Independence”, “Decision-making ability”, “Improving livelihood”, “Status in Society”, “Enhances family well-being”, “Social network widening”, “Self-confidence”, “Assets ownership”, “Credit management”, “Bargaining power”, “Freedom in political choices”,

“Education access”, and “Local governance participation”, among others. A conceptual map of how financial inclusion can support women's empowerment is shown in Figure 10, which depicts the network of women's empowerment and financial inclusion.

Figure 10: Financial Inclusion and Women Empowerment Network



Source: Author

CONCLUSION

Since the introduction of Pradhan Mantri Jhan Dhan Yojana (PMJDY) in 2014, a lot of attention from researchers, academicians, institutions, government, and policymakers have been attracted towards financial inclusion and also to achieve 2030 goals of Sustainable Development Goals (SDGs) on women empowerment and gender equality. The current study has focused on the previous literature giving a holistic overview highlighting the impact of financial inclusion on women empowerment. The findings revealed that Hemant Gupta, Mukesh Pal, Vinay Kandpal, Vikas Agarwal, Emeka Raphael Agu, and Ranjula Bali Swain are the most productive authors, whereas Raj A, Marsland R and Nyarko S A and Kaur S are the most cited authors in the area of financial inclusion and women empowerment. Journal of Business Venturing Insights, International Journal of Social Economics, Journal of Innovation and Entrepreneurship, Journal of Developing Societies, Equality, Diversity, and Inclusion, and International Journal of Rural Management are the most contributing sources in this research area. Most of the research papers in these fields are from India, followed by the United Kingdom and the United States.

The findings suggest that a nation can achieve complete economic and social development provided that its most vulnerable segment can become financially self-sufficient as in line with (Kandpal, 2023). Financial inclusion is essential for economic growth and sustainable development; for women, it is a pathway to economic and social empowerment

(Sunaina, 2022). Expanding financial access for women is proven to have a positive impact not only on the women themselves but, consequently, on household incomes. The study also instigates that mere access to financial services is not enough rather a continuing basis policy formulation and training is needed. The study encourages the policymakers to review its financial products, its norms and regulations, and consistent awareness programs through localized language which is one of the barriers rural women face in today's generation. The financial innovations are to be molded entirely so that poor rural women can access them efficiently. Furthermore, this study has tried to identify literature on the specific keywords, in future researchers can include more keywords to expand it in future studies.

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SIMULATING RESILIENT LAST-MILE DELIVERY IN KOLKATA'S QUICK-COMMERCE: CLUSTERING INSIGHTS FOR FILL RATE AND ON-TIME DELIVERY UNDER DISRUPTIONS

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DOI: https://doi.org/10.64558/bllp/609387whqyfy

ABSTRACT

Purpose

The aim of the study is to perform a test on the strength of the clustering algorithms in improving the quality of last-mile delivery related to quick commerce (Q-commerce) in disruptive urban areas such as Kolkata, India. It measures the performance of clustering during disruption conditions after 30 days.

Design/Methodology/Approach

A simulation framework evaluates 15 clustering algorithms under 6 disruption scenarios and 5 disruption degrees (0%, 25%, 50%, 75%, 100%) and flexible operational settings. Based on the synthetic demands and urban road network of OpenStreetMap, 13,500 runs were done. The important metrics are On-Time Delivery (OTD) and fill rate, and the demand CAGR is in the range of 0-20%.

Findings

The flexibility in operations enhances delivery results in the occurrence of disturbances. FuzzyCMeans and KMedoids were also relatively resilient with an OTD up to 88.44% and fill rate to 0.936 at 75% disruption and a high tolerance (otd_std = 14.07, fill_std = 0.150). DBSCAN and GreedyClustering performed badly (OTD = 33.33%, fill rate = 0.333) and they had large variability (otd_std > 23). Hub optimization and proactive reallocation in spatial analysis is of importance to resilient logistics planning.

Originality

This study provides an innovative model of simulation combing real-life data of an urban street and dynamic processes to assess clustering resiliency in Q-commerce.

Practical Implications

The framework helps logistics planners to choose on robust clustering algorithms to

use when there are disruptions to the Q-commerce.

Keywords
Quick-commerce, last-mile delivery, Clustering algorithms, OTD, fill rate, Kolkata

INTRODUCTION

Quick-commerce (Q-commerce) has impacted urban consumption patterns by expanding the demand for fast last-mile delivery. The logistics of last-mile delivery have become complex due to the increase in e-commerce and Q-commerce, making it the most uncertain component of the supply chain (Escudero-Santana *et al.*, 2022). Customers have compelled an idea to receive goods within 30 minutes, and it exerts pressure on logistics services, which are forced to stay with the same level of service without adding anything to the cost. The problems with the environment are congested roads and city air pollution caused by deliveries, whereas traditional approaches lack effectiveness (Balaska et al., 2022; Xiao et al., 2017). Drones and electric vehicles can also be considered sustainable solutions because they can evade road traffic and have less environmental impact (Borghetti et al., 2022; Madani and Ndiaye, 2022).

By adding the Internet of Things (IoT) to the last-mile logistics flow, it becomes possible to make it more efficient owing to increased tracking, route optimization, and real-time decision-making, which allows for the enhancement of the overall quality of the offered services at a lower cost (Kafile and Mbhele, 2023). The autonomy of delivery tools, such as Autonomous Delivery Robots (ADRs) and Unmanned Aerial Vehicles (UAVs), provides uninterrupted availability and can counteract driver shortages, in addition to the ability to shorten delivery time (Engesser *et al.*, 2023). However, these technologies face challenges related to regulation and infrastructure (Balaska *et al.*, 2022). Delivery personalization with various delivery points and times increases serviceability (Escudero-Santana *et al.*, 2022), and to satisfy consumer demands, sophisticated arrangements of delivery chains must be adopted.

Although the growth of the q-commerce market poses problems for the last-mile delivery system, it opens new doors to innovation. A switch to sustainable technologies, IoT systems, and various alternative delivery strategies, such as drones, can address consumer needs and minimize discernible impacts on the environment; however, they need to be put into practice with caution and regulation factors in mind. Urban sprawl and leapfrogging development complicate last-mile delivery because roads are narrow, congested, and have aged infrastructure in densely populated cities, such as Kolkata. Electrified and autonomous aircraft (EAA) cargo shuttles are one of the solutions that could eliminate traffic and truck congestion (Bridgelall, 2024). To implement this, freight flow data must be studied and analyzed to optimize the deployment of EAA services.

Policies that advance public transport and control parking can reduce congestion and increase road security (Albalate and Fageda, 2019). As used in Isfahan, Iran,

one-way traffic networks improve traffic by increasing speed and decreasing travel time by 9% (Karimi *et al.*, 2021). The interplay of movement and growth that congests the urban together with barriers to strategic transport challenges can be investigated by studying road networks and dynamics of growth (Lampo *et al.*, 2021). Last-mile delivery in dense cities must be addressed by technological improvements, better transportation, improved traffic routes, and knowledge of city development trends. These measures are aimed at enhancing efficiency in delivery as well as sustainable development. Delivery performance, when considering the level of disruption, space-based reassignment flexibility, and demand expansion, needs robustness owing to the possible disruption of supply chains regarding the availability of hubs and reassignment of affected customers.

Disruption Severity and Delivery Performance: Resilience helps supply chains survive disruptions. Resilience is improved through flexibility and redundancy, which reduce costs in the case of supplier and environmental disruptions (Kamalahmadi *et al.*, 2021). The disruption influence on upstream and downstream performance is higher for upstream performance (Parast and Subramanian, 2021). Active management, such as backup suppliers, lowers expenses and enhances responsive actions (Kamalahmadi and Mellat- Parast, 2015; Behzadi et al., 2017). Spatial Reassignment Flexibility: Spatial flexibility enhances allocation in the case of threats to the market environment, providing greater profit and minimizing risks. Routability and allocation flexibility are effective in reducing disruption (Behzadi *et al.*, 2017). Flexible supplier capacity aids in contingency planning (Kamalahmadi and Mellat-Parast, 2015). Rapid Demand Growth: The high velocity of demand growth increases the effects of disruption. The effect of digitalization and smart operations enhances efficiency in the face of increased customer expectations (Ivanov *et al.*, 2018). Predictive demand management assists in managing costs in the case of demand peaks (Kamalahmadi *et al.*, 2021).

Flexible strategies to respond to disruptions in delivery systems should consider the severity of the disruption, spatial redistribution, and quick spikes in demand to promote service delivery and supply chain performance. The complexity of supply chain challenges is better handled by incorporating innovative flexibility ideas. Hub location and customer zoning via optimal clustering optimize logistics processes by dividing the territory into clusters of individual cells based on logistical principles. The evaluated segmentation of capitals in EU27 uses a two-step cluster analysis that prioritizes logistics performance, congestion, and effects on the environment (Škultéty *et al.*, 2021). Digital technology has made new supply chains more resilient than inflexible manufacturing through systemic flexibility gains during and after COVID-19. Such digitized strategies create opportunities for real-time visibility and data-driven decision-making(Kashem *et al.*, 2024).

It is important to know how to handle uncertainties in urban logistics, and in the case of customer demands and travel time, which are stochastic factors. These

variables are modeled using the Stochastic Dynamic Vehicle Routing Problem (SDVRP) approach, but the deterministic approach is typically insufficient (Mardešić *et al.*, 2023). Elastic logistics can be used more or less, and thereby responding to market forces dynamically improves the supply chain management of disruptions (Choi, 2020). Machine learning approaches enhance the accuracy of demand predictions and order confirmation and may have potential in forecasting high-risk shipments and customer segmentation (Pasupuleti *et al.*, 2024). Although clustering techniques have proven to be effective, they should be examined in an urban environment. Studies have shown that combining digital applications and analytical frameworks improves the effectiveness of logistics operations.This study fills these gaps by creating a simulation framework to test the resilience of clustering-based approaches to customer-hub assignment in Q-commerce networks during periods of disruption. Incorporating the synthetic demand data superimposed on real road networks in OpenStreetMap (OSM), the model evaluates 15 methods of clustering under six disruption scenarios, five severity degrees (0-100%), and two levels of operational flexibility (with/without customer reassignment). The level of performance is determined using two important service indicators: On-Time Delivery (OTD) and Fill Rate. In addition, the framework probes the scalability of the systems in the capacity of a forecasted 20 percent CAGR in the growth of demand in the system to model the future stress levels that may be experienced by the logistics planners.

Our paper offers four kinds of contributions on different levels: (1) we introduce an effective simulation framework that combines clustering, routing and disruption modeling in an urban logistics scenario; (2) we perform a comprehensive set of 13,500 simulations evaluating 15 clustering methods with regard to their ability to increase resilience of hubs under disruptions; (3) we expose the combined effects of operational flexibility and disruption severity on delivery performance; and (4) we offer regional views and performance-based design of logistics networks in disruption-suscept

The second part of the paper is organized as follows: Section 2 reviews the literature on urban logistics, clustering analysis, and disruption modeling. Part 3 describes the model specification, such as the model assumptions, data assumptions, disruption modeling, and model performance metrics. Section 4 explains the experiment and simulation plan. Section 5 presents the important findings and cross-comparisons of the performance of the clustering methods. Section 6 discusses the practical implications, design considerations, limitations, and future research. Section 7 concludes the paper.

LITERATURE REVIEW

Last-Mile Delivery Optimization in Urban Logistics

Urbanization, expansion of e-commerce, and infrastructure affect urban last-mile delivery (LMD) in Kolkata. Last-mile logistics has become an important supply

chain issue owing to the increase in e-commerce and the popularity of quick delivery. The literature points to problems of last-mile logistics organizations in urban areas characterized by inefficiency, that is, technological insufficiency, lack of infrastructure, excessive cost, and management constraints (Bosona, 2020). Cities have other issues, such as traffic and parking shortages (Rosenberg *et al.*, 2021). Autonomous delivery solutions could be one of the innovations that hope to make humans less dependent on such crowded spaces but are burdened by regulatory and infrastructural shortcomings (Alverhed et al., 2024; Tadic et al., 2024). With electric and drone deliveries, sustainability is achieved owing to reduced emissions (Shuaibu *et al.*, 2025).

Crowdsourcing has emerged as an alternative, in which deliveries are directed to typical citizens, which is beneficial to society in cities. Nevertheless, such a model should be cost- effective for businesses (Seghezzi *et al.*, 2020). Micro-depot networks are common locations for parcel deliveries, lowering prices, and optimizing space in cities. In this model, collaboration between logistics providers and regulators is necessary because of the shared urban space (Rosenberg *et al.*, 2021). AI and IoT enhance LMD efficiency with respect to predictive analyses and dynamic routing; however, scalability is a problem (Giuffrida et al., 2022; Shuaibu et al., 2025). Although these are efficient LMD solutions in cities such as Kolkata, their implementation must solve regulatory and infrastructural challenges in collaboration with stakeholders. Infrastructure failures also influence the performance of the delivery of goods and services because the delivery chain is affected by disasters such as natural catastrophes or IT-related problems with unforeseen outcomes. Disruptive factors are necessary in a supply chain model. Inventory management of supplier selection is important when facing a disruption because delays and poor-quality goods are more expensive. Simulation techniques are used to update lead times in the case of disruptions (Saputro *et al.*, 2020). The nature of the network topology defines the robustness of the supply chain against failures, and disruptions that occur downstream in the chain lead to harsher consequences than those occurring upstream (Zhao et al., 2018; Olivares-Aguila and Elmaraghy, 2020).

The influence of technology disruptions can be viewed in terms of the role of supply chain management digitalization and IT systems. Network Data Envelopment Analysis (NDEA) reveals the impact of IT disruptions on logistics efficiency, which implies the vital role of preparation aimed at reducing efficiency losses (Klumpp and Loske, 2021). Diversifying supply chains increases resilience by reducing losses in sales and expenses. Backup suppliers have flexible characteristic strategies and increase responsiveness to disruptions (Kamalahmadi *et al.*, 2021). Although stochastic models have considered real-time data, they tend to overlook infrastructure imbalance, which should be considered to develop resilient supply chains (Snyder et al., 2006; Zhao et al., 2022).

To deal with complex road networks, such

as those within cities such as Kolkata, it is important to introduce realistic conditions to the simulation modeling performed in the context of Last Mile Delivery. Urban freight systems are integrated with intelligent transport systems, and because it takes time to change the travel time, they cost less and produce fewer emissions (Taniguchi and Thompson, 2002). Urban logistics models combine passenger and freight networks to minimize pollution and service time to the minimum point(Pimentel and Alvelos, 2018). Logistics can be optimized using Digital Supply Chain Twins (Tasche *et al.*, 2023), and urban freight processes have been modelled in terms of distributed decision- making to reflect the practices of agents (Anand *et al.*, 2014).The application of metaheuristics solves logistics issues (Griffis *et al.*, 2012). In the two-echelon capacitated location-routing problem, the optimization of facility networks and vehicle fleets is considered to boost city freights (Winkenbach *et al.*, 2016). These methods enhance the simulation models of efficiencies in urban logistics studies in populated areas.

Disruption and Resilience in last-mile delivery

The issue of supply chain resilience has become relevant as disruptions to the supply chain have been on the rise. The major characteristics are robustness, network resilience, disruption modeling, flexibility, and structural redundancy. Enhanced resilience and robustness are related to the fact that supply chain connectivity and information sharing increase visibility (Brandon-Jones *et al.*, 2014). The mediation between technology utilization and resilience is achieved through digital technologies, making it easier to collaborate and enhance supply chain memory (Li et al., 2023; Alvarenga et al., 2023). Flexibility makes it possible to address disruptions in supply chains (Queiroz *et al.*, 2023), whereas structural redundancy, achieved by spare capacity mechanisms, guarantees persistence through interruptions (Mackay *et al.*, 2019). Awareness of the likelihood of disruption boosts resilience modeling processes and decisions (Ivanov, 2022). A culture of risk management and connection in the supply chain is essential for achieving resilience (Kumar and Anbanandam, 2019). An integrated strategy of robustness, flexibility, digitalization, and redundancy enhances supply chain resilience to shocks. The strength of last-mile delivery processes has become a topic of discussion in light of the increased demand for high-quality delivery services in urban areas. A simulation that focuses on disruption is essential in relation to how these systems deal with failures. The social- ecological system of last-mile delivery is a perspective in which social, ecological, and engineering perspectives are considered in the development of resilience. This methodology singles out strategic directions such as stabilization, adaptation, and transformation (Lin *et al.*, 2022). AI will help improve last-mile delivery through the achievement of transparency and limited impacts related to disruption. AI allows companies to apply dynamic capabilities and create nimble procurement strategies (Modgil *et al.*, 2021). Structural-

aware simulation analysis combines the properties and operations of the network to simulate disruption recovery (Tan *et al.*, 2019). Such insights should be embedded into a disruption-centric simulation framework based on simulated scenarios and real-time data integration. It is possible to adjust the Networked Infrastructure Resilience Assessment framework to regional peculiarities and, therefore, to perform a complete assessment of transportation network resilience (Omer *et al.*, 2013).

Clustering Techniques for Hub Location and Customer Segmentation

Clustering algorithms streamline the last-mile delivery in cities by creating optimal delivery zones, allocating hubs, and creating routes. Instruments help solve the problem of last-mile logistics, which is regarded as the most inefficient supply chain segment (Bosona, 2020). Clustering customers on a sample base provides cost savings in terms of resource reduction because it is easy to transport to a closer customer. The flexibility of the assignment of loading bays increases routing efficiency and walking delivery stages (Letnik *et al.*, 2020). A model based on hard and soft clustering was used to discuss loading bay assignment, with soft clustering changing the degree of membership of the customers to the loading bays to minimize the distance. The growth of online shopping and, correspondingly, last-mile delivery is experiencing difficulties owing to worsening congestion and pollution (Alejandra Maldonado Bonilla *et al.*, 2024). Among the proposed solutions are urban consolidation centers and collaborative systems with shared transport and sustainable vehicles (Lyons and Mcdonald, 2022).

The reduction in the makespan and latency in delivery routes that depend on optimization algorithms and clustering techniques is imperative. Routing issues are effectively addressed by solutions based on heuristics and spatial indexing, such as hierarchically separated trees (Zeng *et al.*, 2019). Machine learning and AI, in combination with clustering algorithms, allow for improved decision-making in last-mile logistics, where big data are used to provide pattern analysis to achieve strategic operational models (Digiesi *et al.*, 2017). These methods enable urban logistics to respond to demand increases and environmental objectives. The harmful properties of K-means clustering are its sensitivity to initial centroid selection and monotropical cluster assumption, which affect its performance on irregular urban terrain (Ahmed et al., 2020; Qi et al., 2016). The algorithm must work with predetermined cluster numbers and has the problem of data noise (Ahmed *et al.*, 2020). Optimized versions, such as K-means, defend against random initializations by limiting them further with built-in hierarchical optimization (Qi *et al.*, 2016). The superior performance of genetic K-means is based on the principles of the genetic algorithm (Banerjee *et al.*, 2015). Such optimization methods based on natural inspirations, such as K-means with the CSA, minimize local optimum traps (Lakshmi *et al.*, 2018), and Bayesian hierarchical K-means is more acceptable for describing the real-world data structure (Liu and Li, 2020).

These enhancements show different ways to make clustering techniques more robust and flexible in the field of logistics to eliminate the shortcomings of the K-means algorithm. Non- convex clusters, sensitivity towards the initial centroid, and the logistics complex data computational efficiency can be dealt with more smoothly with high-level options (Tang and Khalid, 2016; Anchalia et al., 2013). K-medoids clustering in a high-density dynamic delivery setting provides information and issues. Although K-medoids is resistant to outliers because of its selection of actual data as cluster centers, unlike K-means, it has shortcomings in complex accuracy and preprocessing situations. The classic Partitioning Around Medoids (PAM) algorithm is computationally expensive, whereas its newest versions have accelerated its execution at the same level of quality (Schubert and Rousseeuw, 2021; Schubert and Rousseeuw, 2019). Generalized distance functions are important for characterizing various attributes of a delivery system, which K-medoids finds useful for dealing with mixed variable data (Budiaji and Leisch, 2019). It is robust to the outlying effect on dynamic data with variable demand (Arbin *et al.*, 2015), and novel methods increase the accuracy of dynamic delivery (Gullo *et al.*, 2008). Regardless of the developments, the application of effective K-medoids needs to consider both computational resources and the nature of the datasets. DBSCAN works best in places with natural barriers in an urban environment, but its sensitivity to parameterization may make it ineffective in locations with different customer densities.

The main problem with the use of DBSCAN is its sensitivity to data density changes. Therefore, an improved DBSCAN algorithm considers the local density differences of each cluster by computing the density variance of the core objects (Ram *et al.*, 2009). The altered DBSCAN process estimates the retail center extents in an urban setting by changing the radius parameter through a sparse graphical representation, thus properly determining the retail cluster of diverse shapes and densities (Pavlis *et al.*, 2017). The parallel process of DBSCAN with Spark or MapReduce addresses the limitations of load and scale when the dataset is large. To improve the efficiency of the processing capabilities, the MR-DBSCAN algorithm presents an additional data partitioning feature (He *et al.*, 2013). Detailed variants of DBSCAN have been optimized for use in embedded systems in automotive applications (Raj and Ghosh, 2020), and Ellipsoid DBSCAN makes dimension scaling available in real- world detection applications (Wagner *et al.*, 2015). Although parameter sensitivity is difficult to determine, it is continuously being worked on to provide a better application of DBSCAN in complicated settings. The overlapping of membership in common service areas is dealt with by fuzzy clustering techniques, especially Fuzzy C-Means. The dynamic fuzzy c-means algorithm is a novel algorithm that helps enhance customer satisfaction in a dynamic ride-sharing system to adapt fuzzy assignments (Munusamy and Murugesan, 2020) in real time.

The property of fuzzy logic to handle real-world imprecision and uncertainty is

advantageous in the real world of telecommunications networks and dynamic systems (Ghosh *et al.*, 1998). It is possible to increase energy efficiency within the framework of wireless sensor networks through fuzzy clustering with the help of protocols such as energy- aware unequal clustering fuzzy (EAUCF) (Adnan et al., 2021; Singh et al., 2013). Nonetheless, fuzzy techniques have been confronted with problems such as high imbalance ratios, which make them impractical in places where workload equity is an issue. To solve these challenges, clustering strategies should be incorporated to accommodate system demands, but with quality clusters. FCM There are hyperplane partitioning techniques that can enhance the clustering accuracy of large datasets (Shen *et al.*, 2019). Although fuzzy clustering has advantageous characteristics in any application, it requires algorithm alterations to meet the challenges of dynamic environments. Spectral clustering performs well in clustering non-convex shapes and probabilistic shapes, as do Gaussian Mixture Models (GMM). Spectral clustering is based on graph Laplacians and affinity matrices and performs well for clustering high-dimensional data. It uses the diffusion distance on graphs, and is computationally expensive when applied to large datasets. Researchers have created approximate spectral clustering to increase speed without compromising accuracy (Wang et al., 2009; Nadler et al., 2008). GMMs provide probabilistic clustering, meaning that the data are assumed to be generated by different Gaussian distributions, which can be applied to ellipsoidal clusters and computer cluster membership probability. However, GMMs do not perform well on non-convex structures and may also be sensitive to parameter initialization. Both approaches have computational problems. The cost of spectral clustering affects scalability, but multiscale approaches are available to decrease the cost. GMM can be better scaled up with the help of the iteration of expectation-minimization; however, it is intense with regard to large data dimensions. The two techniques have different applications: spectral clustering is suitable for state-of-the-art relationships, whereas GMM has probabilistic modeling and processes elliptical clusters (Wang et al., 2009; Nadler et al., 2008).

Urban Delivery Challenges in Emerging Market Cities

Contextual solutions are needed to solve the challenges of urban logistics in emerging economies such as India. The logistics complexity that occurs in Kolkata is the unstructured addressing, high demand density, bad roads, and low warehousing (Arvianto *et al.*, 2021).Last-mile delivery is complicated by narrow alleys. Various practices deal with the challenges of urban logistics that revolve around optimization and partnerships. In accordance with sustainable urban mobility plans, mixed freight-passenger transporting systems should be introduced to achieve a better level of efficiency (Mazzarino and Rubini, 2019). The Stochastic Dynamic Vehicle Routing Problem (SDVRP) assists suppliers in gauging customer requests and travel durations under uncertain conditions (Mardešić *et al.*, 2023). Digital supply chain twin (DSCT) technology is designed

to model logistics optimization. Its collaborative platform can improve resource management to optimize urban logistics, thus improving urban logistics despite implementation barriers (Tasche *et al.*, 2023). Research on air pollution in Kolkata demonstrates the pressure on the environment, which is why interventions are urgently needed in the sphere of urban planning (Kar *et al.*, 2024). Policies, infrastructure, and transport technology innovations continue to play critical roles in enhancing logistics and minimizing externalities (Ranieri *et al.*, 2018). The use of SDVRP to optimize the routes, DSCT, and implementation of sustainable mobility patterns are the factors that should be applied to address the logistical difficulties of the city of Kolkata. Local governance and community engagement are issues of success. The optimization of logistics in emerging economies such as India has a different approach compared to models in the West because of the unique infrastructure and market peculiarities. DSCTs provide advanced optimization solutions and tools; however, several barriers limit their implementation (Tasche *et al.*, 2023).

Logistics and supply chain practices in India are still in their developing stages, and the level of integration between systems is considered low, with issues regarding collaborative efforts, network design, and implementation of ICT. Logistics experts have pointed out the discordant aspects of the Indian industry (Srivastava, 2006). The termination of transportation and logistics in emerging markets due to the COVID-19 pandemic triggered the process of embracing blockchain and digital trucking technologies. Strategies such as contactless deliveries and the use of technology to manage drivers have become sustainable (Sumbal *et al.*, 2023).The need of the Indian supply chain management is streamlining with the business objectives and bringing into operation world's good practices to increase the efficiency (Sahay and Mohan, 2003). Cost and optimization of food grain procurement centers using a data-driven model of a supply chain employing mixed-integer linear programming (Mogale *et al.*, 2019). Innovations in last-mile logistics are crucial for decreasing urban traffic and air pollution, as delivery inefficiency is resolved with technology and transport optimization(Ranieri *et al.*, 2018).

RESEARCH GAP AND MODELING INNOVATION

Although significant progress has already been made in the areas of last-mile optimization and supply chain resilience approaches, there is still no available integrated and comparative framework that assesses the approaches to clustering schemes under conditions of possible disruption. *Specifically:*

- There are very few models in which graded hub disruption is simulated with flexible and inflexible reassignment policies.
- The concept of clustering techniques is seldom assessed through the measure of delivery performance in operational failures.
- Most studies do not consider road-constrained delivery routes and the

subsequent rise in demand.

In response, we developed a disruptive-resilience routing method that integrates road-based routing, synthetic demand modeling, and 15 clustering algorithms across 13,500 simulations. We provide a technically sound assessment of On-Time Delivery and Fill Rate in six disruptive circumstances, as well as the projection of 20 percent CAGR development rates in their assessments, which are truly applicable to planning logistics in a resilient and scalable method of delivering urban logistics.

Problem Description and Model

This study provides a mathematical modeling framework and simulation-based case study to assess the resilience of clustering-based last-mile delivery systems in urban quick- commerce (Q-commerce) operations, particularly under disruption scenarios. The focus is on a densely populated urban district in Kolkata, India, reflecting real-world complexities such as intricate road networks and fluctuating demand.

Mathematical Model Indices and Sets

- **Customers (C)**: Indexed by i
- **Hubs (H)**: Indexed by j
- **Days (D)**: Indexed by d, where d = 1, … ,30
- **Scenarios (S)**: Disruption types; s = 1, … ,6
- **Disruption %ages (P)**: $p \in$ {0,0.25,0.5,0.75,1.0}

Table 1 Parameters

Parameter	Description
q_i^d	Demand for customer i on day d (Poisson, λ=2)
(lat_i, lon_i)	Coordinates of customer i
(lat_j, lon_j)	Coordinates of hub j
C_j	Hub j capacity: sum of assigned demand + 10% buffer
δ_p	Disruption severity (capacity reduction fraction)
C_j^p	Disrupted capacity: $C_j \cdot (1 - \delta_p)$
$dist_{ij}$	Road network distance between customer i and hub j
v	Vehicle speed: 40 km/h
t_{max}	On-Time Delivery (OTD) threshold: 10 minutes (1/6 hour)
R_s	Reassignment policy (1 = reassignment enabled, 0 = not)
T_s	Disruption target: max, min, or all hubs
O_{ij}	Customer-hub assignment indicator

Decision Variables

- x_{ij}^{d} : 1 if customer i assigned to hub j on day d; 0 otherwise
- y_{i}^{d}: 1 if customer i's delivery is on-time on day d; 0 otherwise
- z_{i}^{d}: 1 if customer i's demand is fulfilled on day d; 0 otherwise
- r_{j}^{d}: Remaining capacity of hub j at end of day d

Objective

$$\text{Maximize} \sum_{s\in S} \sum_{p\in P} \sum_{d\in D} \sum_{i\in C} q_{i}^{d} \cdot z_{i}^{d}$$

Maximize total fulfilled demand across disruption scenarios and days.

Core Constraints

- **Hub Capacity**

$$\sum_{i\in C} q_{i}^{d} \cdot x_{ij}^{d} \le r_{j}^{d} \quad \forall j, d$$

- **Inventory Update**

$$r_{j}^{d} = \begin{cases} C_{j}^{p}, & d = 1 \\ r_{j}^{d-1} - \sum_{i\in C} q_{i}^{d} x_{ij}^{d}, & d > 1 \end{cases}$$

- **Customer Assignment**

$$\sum_{j\in H} x_{ij}^{d} = z_{i}^{d} \quad \forall i, d$$

- **Reassignment Policy**
  - If $R_s = 1$: If original hub lacks capacity, reassign to nearest hub with capacity.
  - If $R_s = 0$: Assign only to the original hub, otherwise demand unfulfilled.
- **On-Time Delivery**

$$y_{i}^{d} \le \begin{cases} \max_{j} \left(x_{ij}^{d} \cdot \frac{\text{dist}_{ij}}{v} \right) \\ 0 \quad \text{otherwise} \end{cases}$$

- **Non-Negative Inventory**

$$r_{j}^{d} \ge 0 \quad \forall j, d$$

- **Binary Variables**

Hbbb nbnbbbn

$$x_{ij}^{sl},\ y_i^{sl},\ z_i^{sl} \in \{0,1\}$$

Performance Metrics

- **Fill Rate**

$$\text{Fill Rate} = \frac{\sum_i q_i^{sl} z_i^{sl}}{\sum_i q_i^{sl}}$$

Fraction of total demand fulfilled.

- **On-Time Delivery (OTD) %age**

$$\text{OTD} = \begin{cases} \frac{\sum_i y_i^{sl}}{\sum_i z_i^{sl}} \cdot 100 & \text{if fulfilled orders} > 0 \\ 0 & \text{otherwise} \end{cases}$$

%age of fulfilled orders delivered within 10 minutes.

Case Study: Application in Kolkata Urban

Context

Kolkata is a Tier-1 metropolis with over 14 million people, characterized by:

- **High density**: Crowded market centers, dense residential zones
- **Spatial complexity**: Narrow alleys, congested roads, frequent one-way restrictions
- **Diverse demand**: Centralized in markets, sparse on fringes

The model simulates a hub-and-spoke system within a bounded city district, using micro-fulfillment hubs to serve customer clusters for same-day Q-commerce.

Data Sources & Generation

Table 2

Component	Methodology/Tools
Customer Demand	Synthetic data: Poisson (λ=2) per customer, Normal spatial clusters centered on urban hubs
Demand growth	0-20% CAGR simulated for up to 30 days
Customer locations	Geospatial validation to keep within city boundary
Hub Locations	15 clustering algorithms (KMeans++, FuzzyCMeans, DBSCAN, others)
Road network	Downloaded from OpenStreetMap, processed with OSMnx & NetworkX
Travel times	Calculated at 40 km/h over shortest (road) paths

Assumptions and Parameter Table

Table 3

Parameter	Value
Delivery time threshold	10 minutes
Vehicle speed	40 km/h
Hub inventory buffer	Assigned demand +10%
Demand per customer	Poisson (λ=2)
Number of hubs	1-10
Disruption levels	0%, 25%, 50%, 75%, 100%
Scenario types (S1–S6)	Max/min/all hubs, with/without reassignment

Simulation Implementation

- **Programming Language**: Python 3.9
- **Key Packages**:
  - Geospatial: OSMnx, NetworkX, Folium
  - Clustering: scikit-learn, scipy, scikit-fuzzy, custom clustering modules
  - Simulation: numpy, pandas, multiprocessing
  - Visualization: matplotlib, seaborn
  - Statistical analysis: statsmodels, scipy.stats

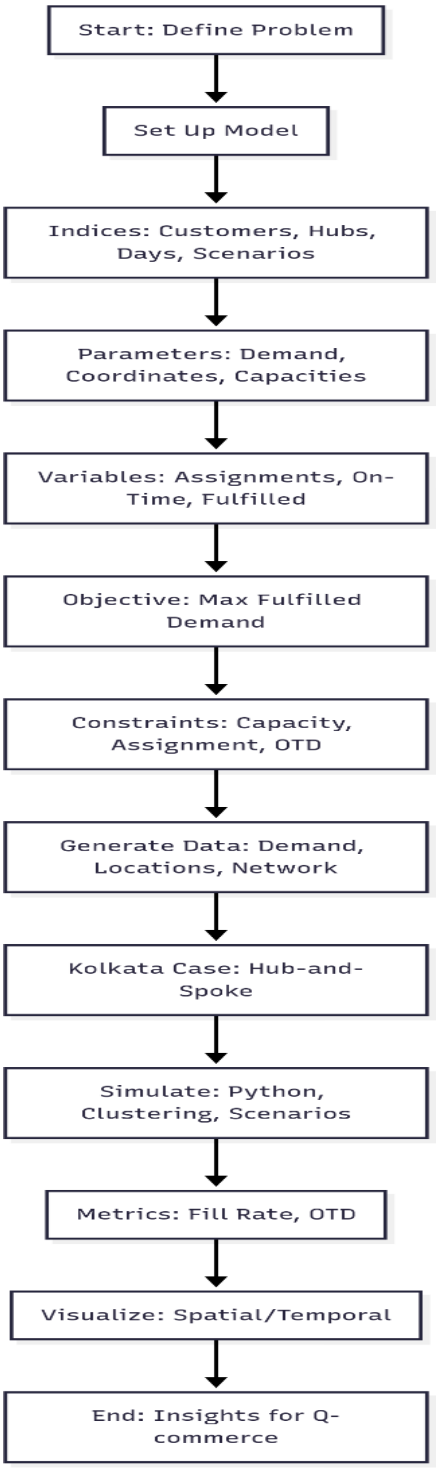
Synthetic Demand Generation

- **Order generation**: Each simulation day, customers are sampled, clustered, and assigned demand
- **Location generation**: Normal distribution centered on urban residential districts

Key Takeaways

- The two-stage simulation framework facilitates robust, granular assessment of urban last-mile delivery under varying levels of operational disruption.
- Clustering-based hub assignment, when coupled with geospatial routing, enables adaptive, disruption-resilient delivery even in Kolkata's complex urban topology.
- Metrics like fill rate and OTD, visualized spatially and temporally, guide both strategic planning and real-time response in Q-commerce operations.

Figure 1. Workflow for Urban Q-commerce Delivery System Analysis



RESULTS AND ANALYSIS

Overall Performance Trends under Disruption

When the four scenarios - full hub flexibility, no hub flexibility, and maximum/minimum inventory hubs- are assessed, different performance patterns are manifested through disruption levels varying between 0 and 100 percent. At 0% disruption, the clustering algorithms of KMeansPlusPlus, KMedoids and MultiCoG have 100% on-time delivery (OTD) and complete fill rates which implies ideal global performance. FuzzyCMeans shows an excellent resilience at less than 100 percent disruption, with OTD ranging between 83.27 percent and 90.91 percent and fill rates between 91.4 percent and 96.5, especially in the maximum/minimum inventory hub scenarios. At 0% level of disruption, CoG algorithm also works well in both full-flexibility and no-flexibility environments. Interestingly, the minimal inventory hub situation portrays the greatest endurance whereby, FuzzyCMeans and KMedoids yield their best in stress. The worst scenario emerges when there is no flexibility at all and no approach will allow operations to continue at a disruption level that is less than 100%. Still, KMeansPlusPlus/KMedoids gray remain comparatively strong to the extent of 75% disruption. The plan of customer locations and their allocated hubs is given in Fig. 2 that provides the basement of the following disruption analysis. The figures 3 to 8 show the results of six different scenarios of disruption varied according to the hub that is disrupted (i.e. full capacity, low capacity or all hubs) and the application of the customer reassignment model. In particular, Scenario 1 and 2 (Figures 3 and 4) depicts a situation with maximum and minimum capacity hub disruption in the case of reassignments being possible. An in depth multi-hub disruption including reassignment scenario is displayed in Figure 5. On the contrary, Figures 6-8 are associated with Scenarios 4-6 which model the disruptions with no reassignment. The latter cases are invaluable in terms of the comparative adaptability and resilience of the delivery system during a limited working operation environment.

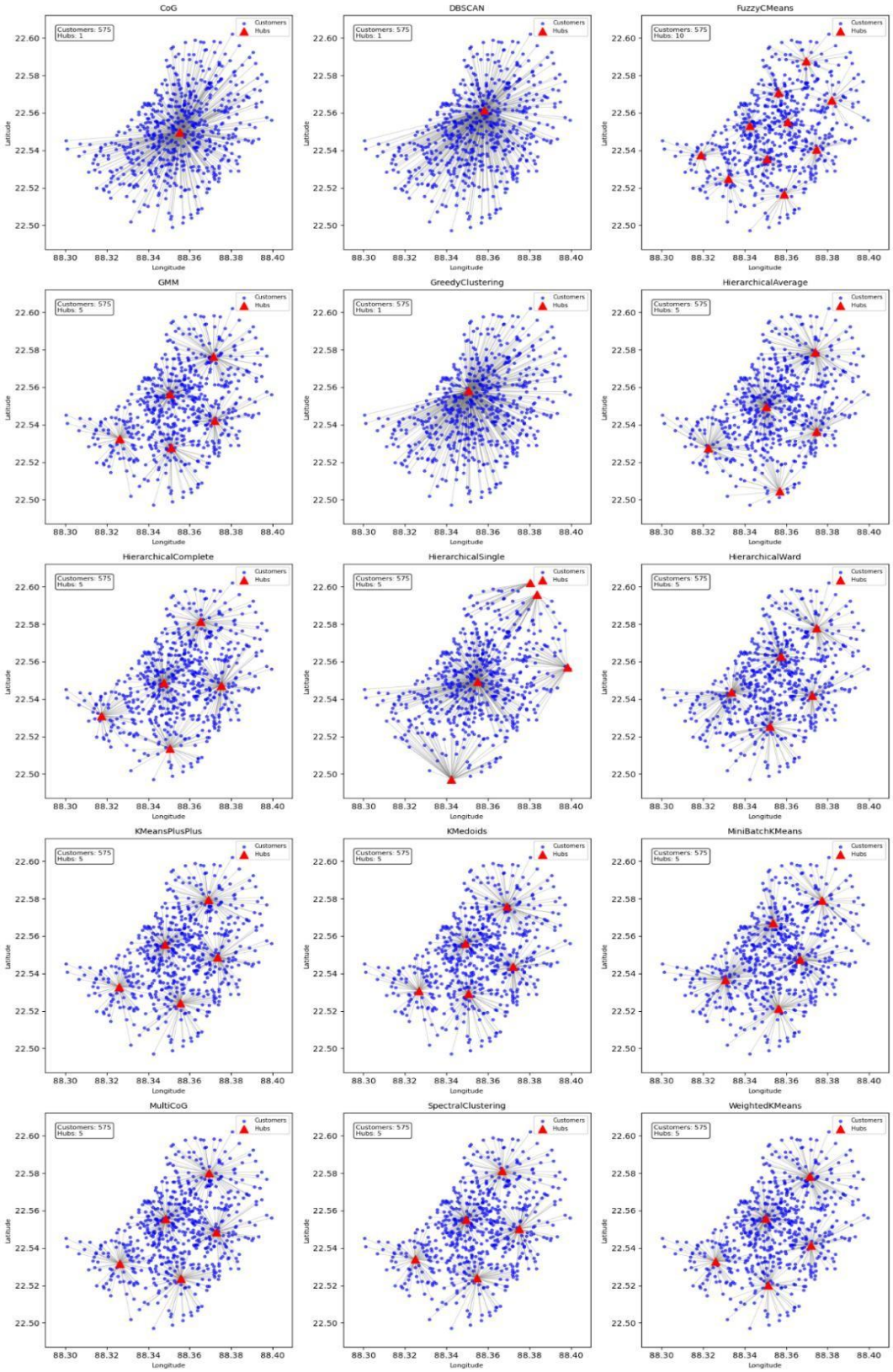


Figure 2. Visualization of customer location and hubs. –

Source: Authors own work

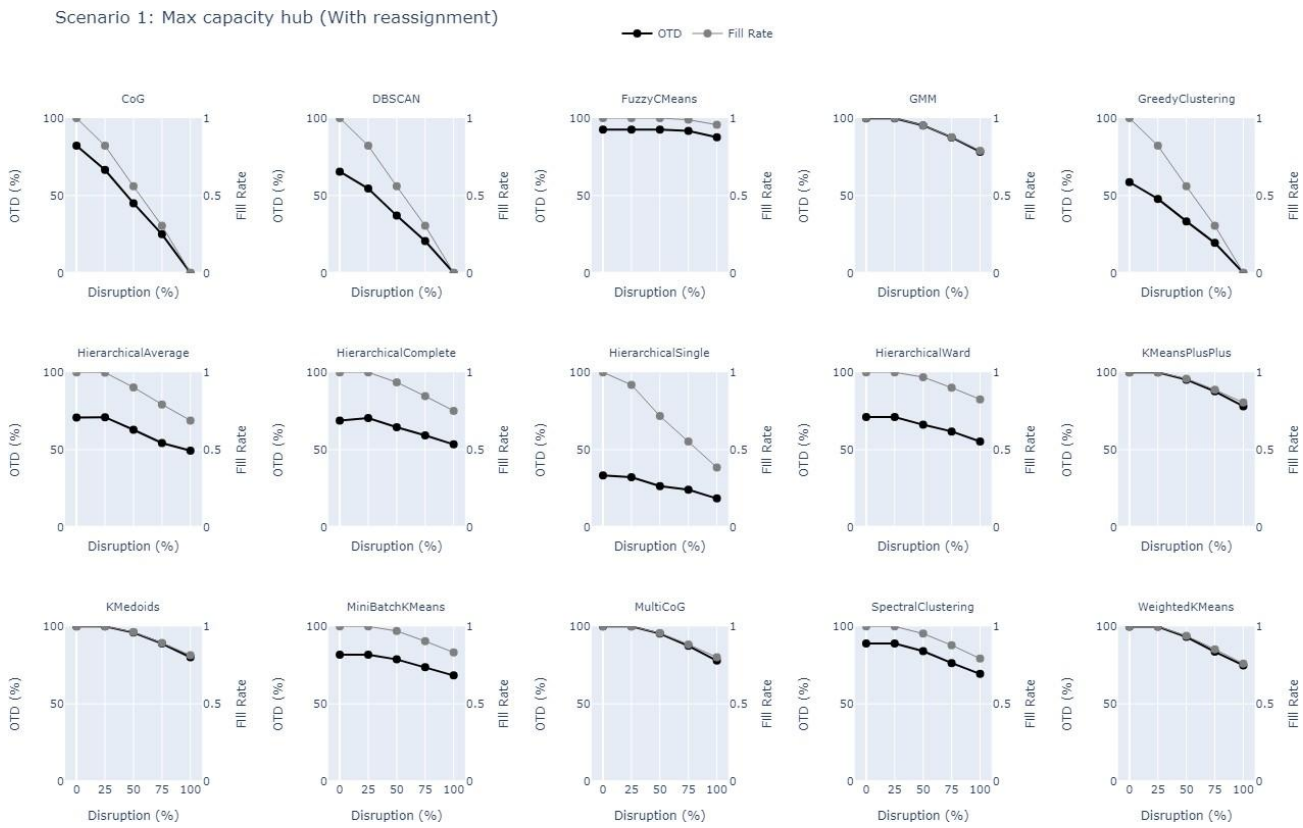


Figure 3. Scenarios 1: Disrupting hub with Max capacity (With reassignment) – **Source: Authors own work**

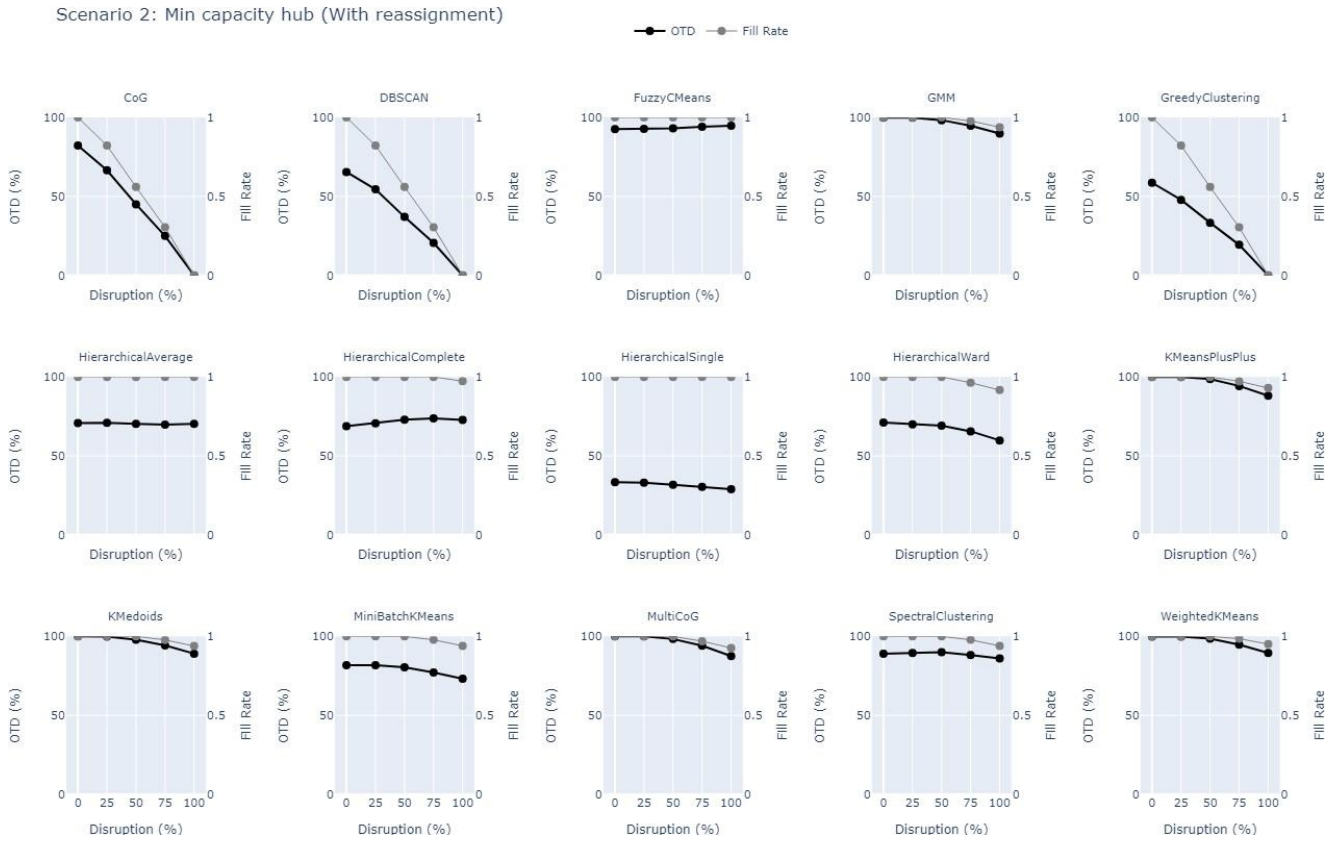


Figure 4. Scenarios 2: Disrupting hub with Min capacity (With reassignment) – **Source: Authors own work**

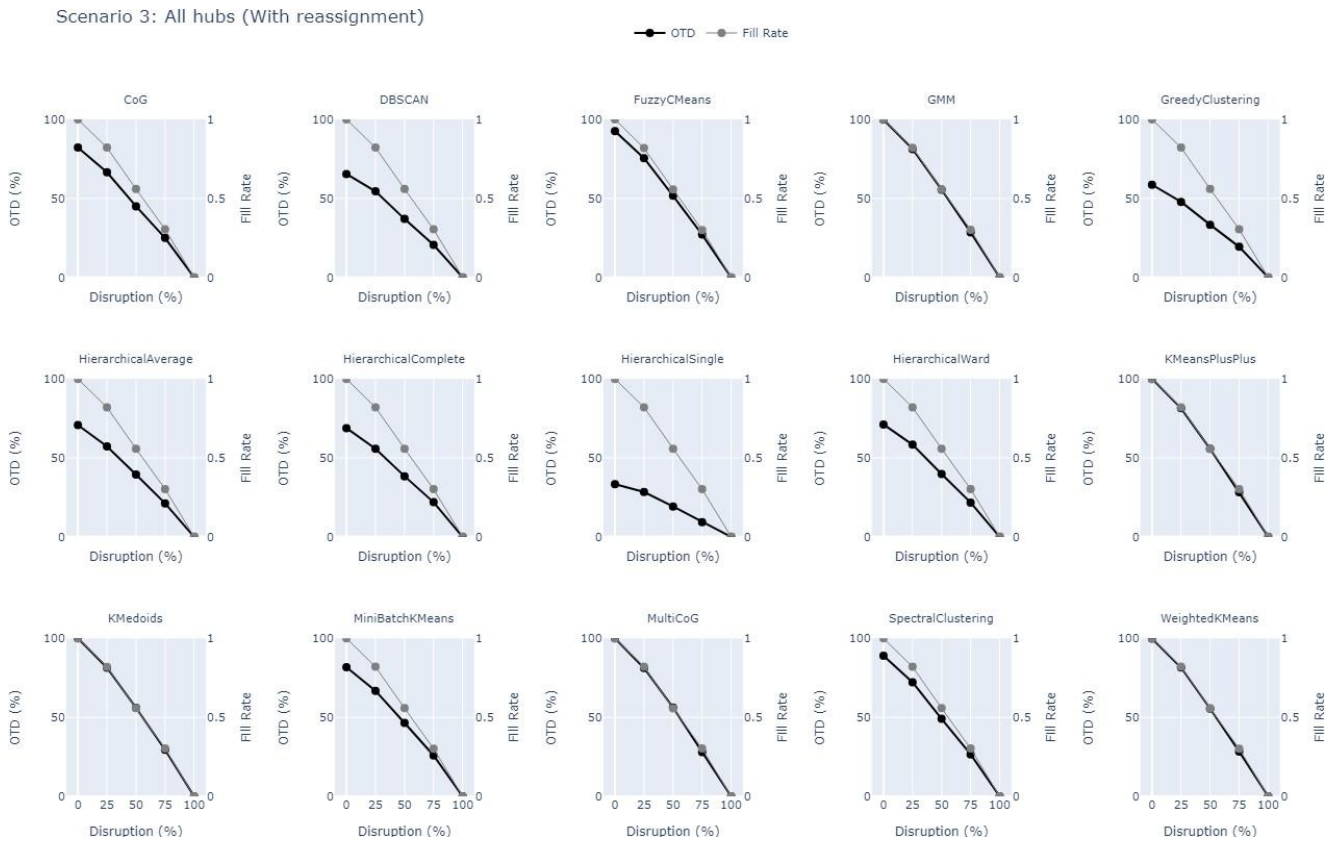


Figure 5. Scenarios 3: Disrupting hub with All hubs (With reassignment) –
Source: Authors own work

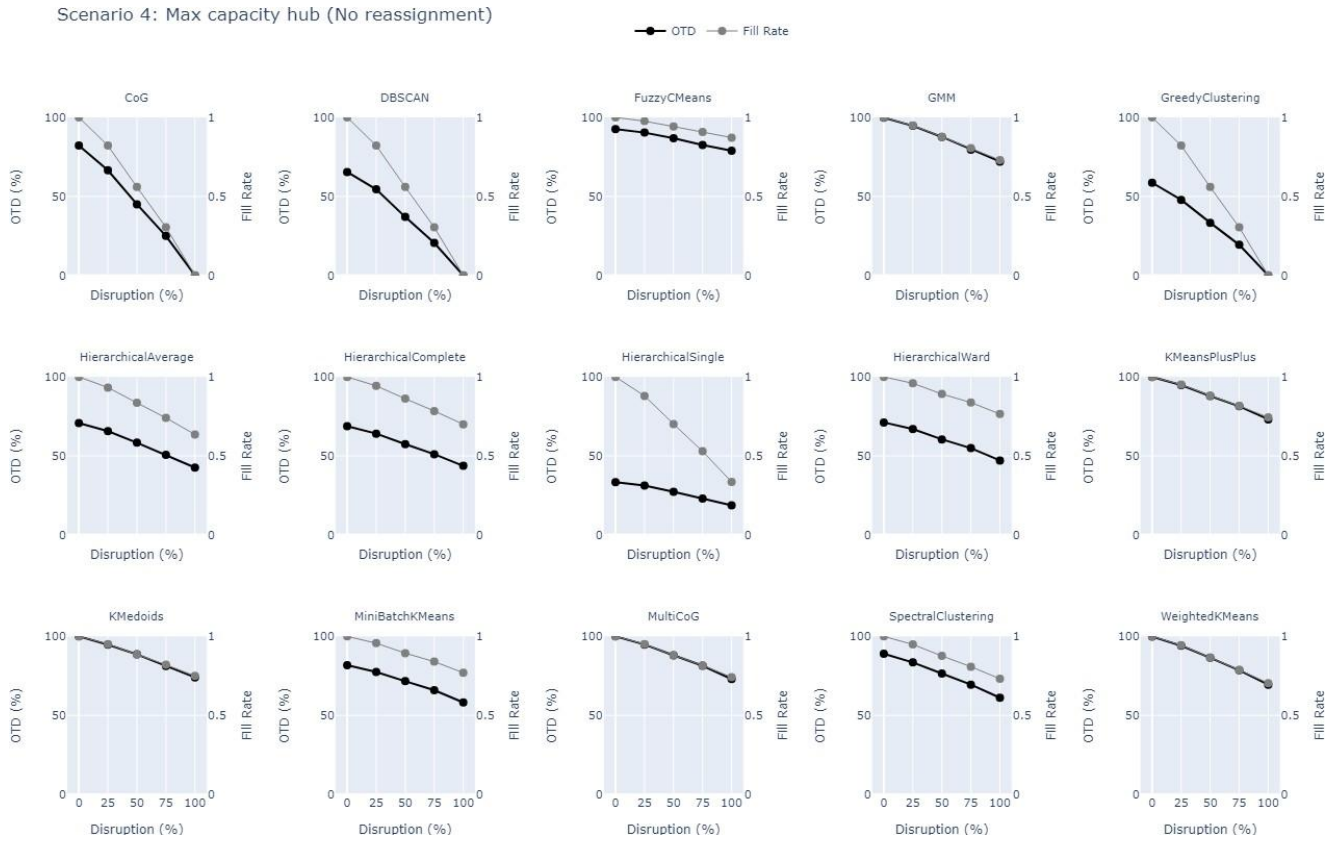


Figure 6. Scenarios 4: Disrupting hub with Max capacity (No reassignment) –
Source: Authors own work

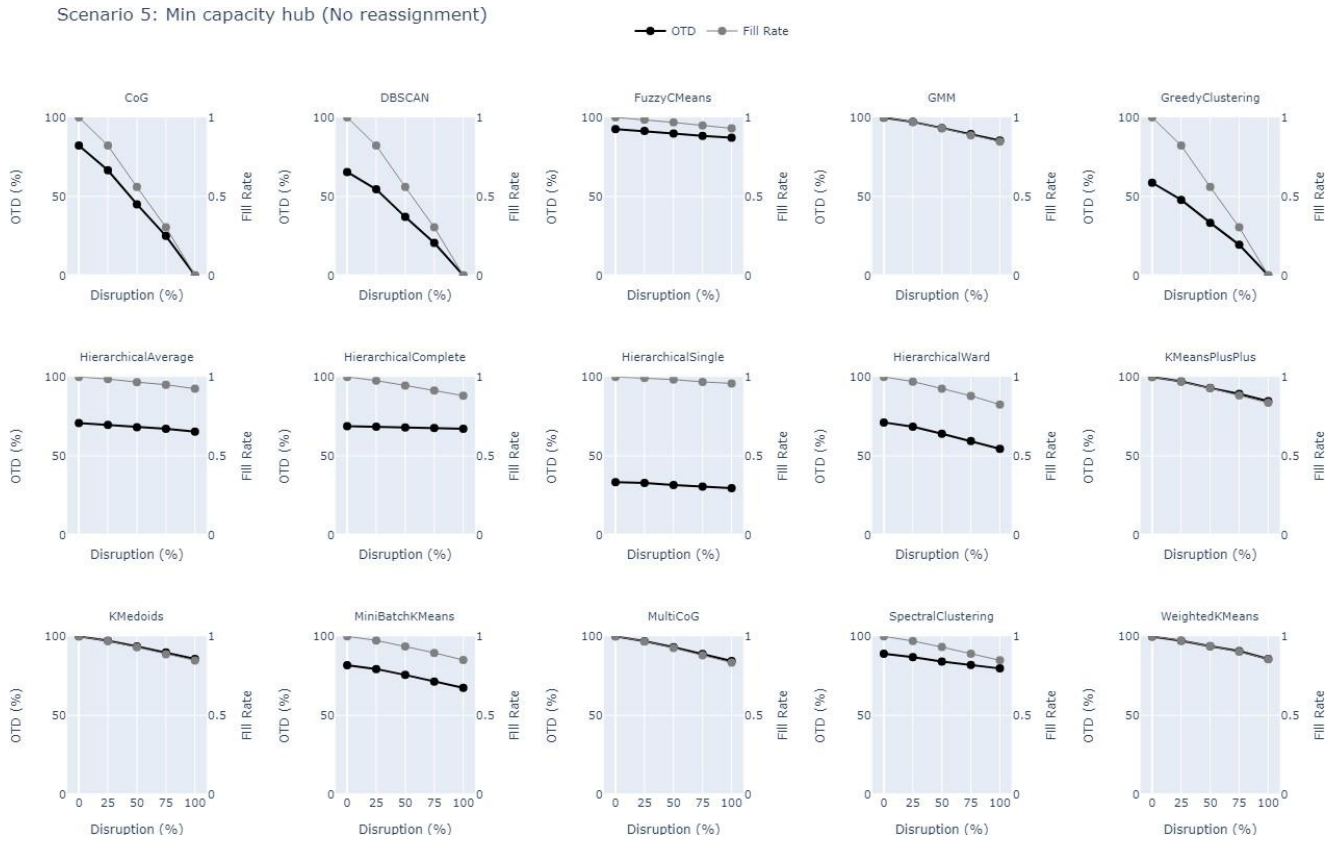


Figure 7. Scenarios 5: Disrupting hub with Min capacity (No reassignment) –
Source: Authors own work

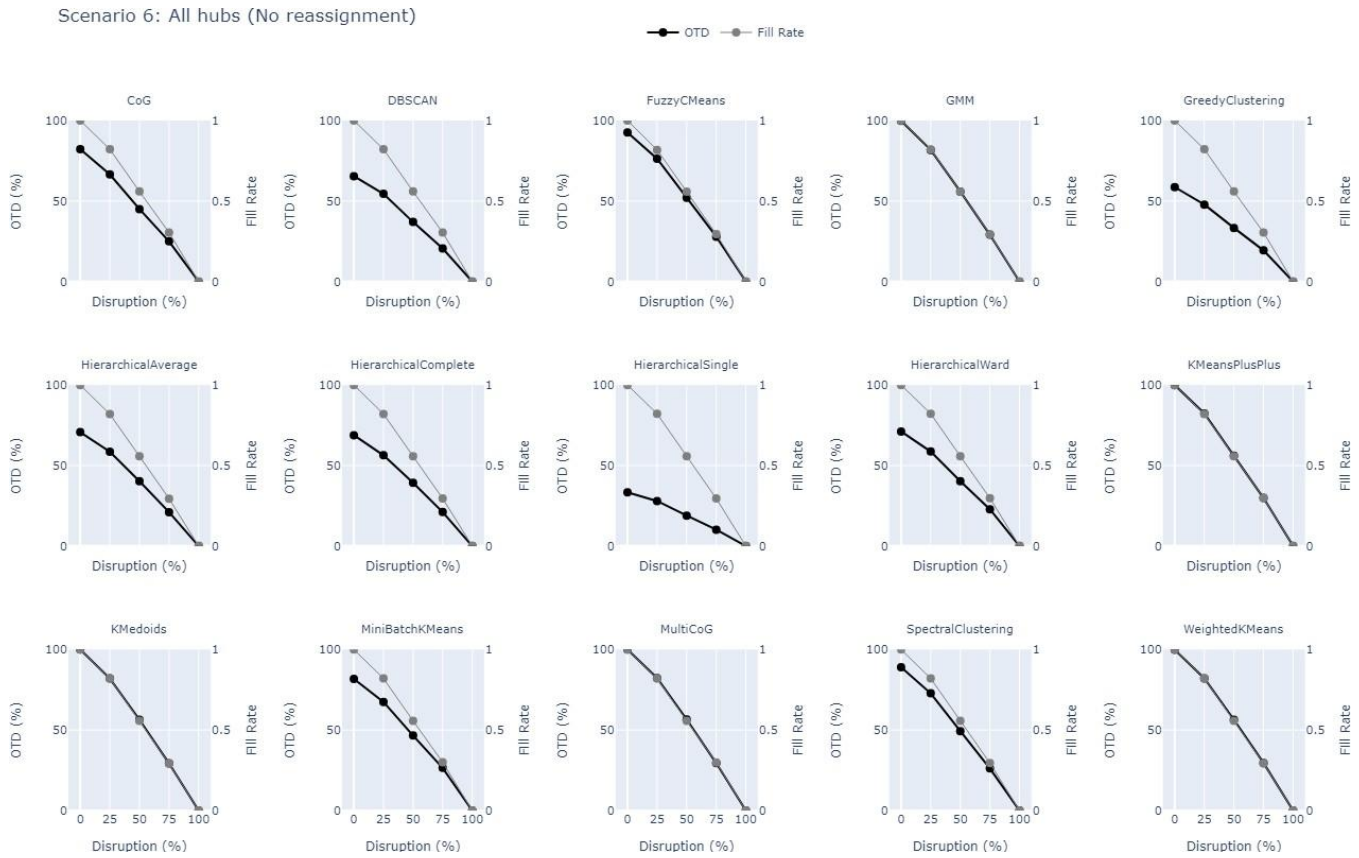


Figure 8. Scenarios 6: Disrupting hub with All hubs (No reassignment) –
Source: Authors own work

Fill Rate Resilience Across Scenarios

Stable Performers: The FuzzyCMeans is very resilient, as its fill rates remain high (between 91.4 and 96.5 percent), even under extreme disruption (100 percent). In a similar manner, KMedoids has stable performance, whereby fill rates remain at 89.3-93.2 with 100 percent disruption, and strong performance at intermediate disruptions (50 to 75 percent). Fragile Methods: On the other hand, CoG, DBSCAN and GreedyClustering result in the total failure under complete disruption, and the fill rates decrease to 0%. HierarchicalSingle varied widely when presented with identical conditions with a fill rate of 36.0-97.9, and this demonstrated unstable strength. The least inventory balanced situation presents itself as the most robust set up. In this environment, KMeansPlusPlus has a fill rate of 98.5 with 25 percent disruption and FuzzyCMeans proves to have a fill rate of 96.5 with 100 percent disruption. By contrast, the no flexibility case comes up with the poor results as the fill rates drop sharply to 29.4-0.4 at 75%, 0 at 100% disruption.

OTD Sensitivity and Robustness under Stress

Robust Methods: Relative to OTD measures, FuzzyCMeans is the most effective method especially in environment where inventory constraints prevail. It attains a 90.91 percent OTD with minimum inventory and 83.27 percent OTD with maximum inventory when disruption is at a full (100) percent and standard deviation of between 0.90 and 5.60, both of which denote a stable performance. KMedoids is also very robust, particularly when complete flexibility and minimal inventory are in effect, attaining an OTD level of 87.38 percent at 100 percent disruption (SD: 4.61-10.37) as well as high levels at 75 percent disruption. Sensitive Methods: CoG at the other extreme registers 0% OTD at full disruption which is a total failure to adapt. Single, DBSCAN and GreedyClustering are also sensitive to the stress with the widest OTD measures ranging between 9.33 and 29.24 percent (SD: 1.56 and 13.64). Again, no flexibility option would become the most susceptible where the whole system performance would significantly degrade. Both KMeansPlusPlus and KMedoids, nevertheless, demonstrate a certain robustness, in the sense that they operate effectively to up to 75 percent being disruptive. The smallest inventory hub case is the most robust one overall and FuzzyCMeans manages to deliver 90.91 percent OTD in the case of 100 percent disruption.

Stability Analysis of Clustering Techniques

The resilience of each clustering method is determined through the evaluation of the fluctuations in delivery levels on-time (OTD) and fill rate during interruption. FuzzyCMeans, although resilient, exhibits a little-unstable performance when completely (100 %) disrupted, especially in the minimum inventory hub setting, with standard deviation of 0.90 in OTD. Well, the absolute alteration of OTD and fill rate is not big and is between 0.000 and
0.051 that means that it is controlled and the changes are not big. HierarchicalSingle has moderate causes of variability so that OTD standard deviation is 1.86. On the other hand, the variability of CoG, DBSCAN, and GreedyClustering is the greatest one, the changes in the OTD are within the range of 23.15 to 32.66, and the changes in fill rate are 0.399-0.400 which clinical indicators of the low stability of the methods when subjected to stress. Interestingly, in the no flexibility case, the OTD variability of GMM and KMeansPlusPlus is really high (40.03-

40.15), which indicates high sensitivity to disturbance. Of all the configurations that were tested, the smallest inventory hub can be seen as the most stable, with OTD standard deviation never going above 5.31 and fill rate change never going above 0.040. Conversely, the no flexibility situation is the least resolute, the volatility of which is 13.64-40.15, which makes the strategic operational leeway extremely important.

Trade-offs and Managerial Insights

Performance Trade-offs: FuzzyCMeans exhibits an excellent tradeoff between performance and stability at full disruption, with 90.91 percent OTD and 96.5 fill rate, having smooth performance slopes and the very low variability. KMedoids is as well quite performing, offering 87.38% OTD and 89.3 % fill rate, but with fairly significant amounts of variability, being a stable choice albeit not as stable as the other options. Managerial Implications: FuzzyCMeans is a good choice of algorithm when working in an environment of high disruption because it exhibits good and robust metrics behavior. A good alternative is KMedoids which makes it a good trade-off between performance and variability. Although effective, KMeansPlusPlus is effective only in the low-disruption environments because it becomes vulnerable under stress. At mild disruption, CoG seems reliable, but completely un-reliable at high disruption which means it experiences false reliability, thus not applicable on critical logistics situations. Strategic Recommendations: To plan the last-mile delivery in conditions of uncertainty and high disruptions: Rely on a hybrid method of FuzzyCMeans and KMedoids in order to further capitalize on their strengths. Possible response to contingency solutions with limited flexibility, i.e. there are no flexible seat or hub allocations, or flexibility of reassignments. Take resilience testing as part and parcel of logistics planning so as to ensure performance degradation under extreme conditions is detected beforehand and prevented.

DISCUSSION AND CONCLUSION

Key Findings and Insights

Complex forms of clustering techniques, including FuzzyCMeans, KMedoids and KMeansPlusPlus, show better ability to adapt to cumulative demand pressure over simpler clustering techniques. FuzzyCMeans is also an outstanding example with maximum disruption, Ott; and fill rates ranging between 83.27 and 90.91 percent; 91.40 and 96.50 percent; respectively, with the highest stability and performance loss (0.90 to 5.60). KMeansPlusPlus is best in low-disruption cases where there is 100 percent OTD and fill rates, whereas the KMedoids is stable in moderate to severe level of disruptive environments. The scenario with the minimum number of hubs in the inventory proves to be the most resilient to all others, as an extreme stress leads to a scenario with all OTD and fill rates at 0 percent; all other scenarios fail to handle such high levels of change without collapsing. Interestingly, CoG, although seems to be structurally robust at a full flexibility and no flexibility scenario, still shows a zero performance, pointing out a lack of coordination between structural stability and operational performance.

Practical Implications and Policy Relevance

The instilled resilience and stability of FuzzyCMeans and KMedoids can be powerful models to be implemented in stressful supply chain systems and especially in minimal inventory systems. The KMeansPlusPlus works better in low disruption cases on the other hand, and

trustworthiness and performance are ensured with little strain. Such insights provide practical guidance on the implementation of logistics investment strategies, by providing the resources of computational and operational instructions on focusing on resilient clustering algorithms. The dysfunctional behavior of CoG in terms of its performance, its seemingly high resilience notwithstanding, begs the question that a robustness should always be tested with quantitative performance parameters, and not by the structural presumptions only.

Limitations

The present one has a very narrow scope of scenarios as it only deals with utter flexibility or utter rigidity. The binary categorization limits the possibility of zooming on the slight performances differences within intermediate working environments. Besides, the stability and trend measures give no clear indication of the number of trials involved or disruption periods, which lead to imprecise meanings of variability levels and slopes dynamics. The other weakness is the fact that the study will take a very short period that is limited to 30 days of simulation activities. This reduces the knowledge on the long-term of performance- changing dynamics, in a way preventing the potential of generalizing findings to the wider temporal and contextual landscape.

Future Research Directions

To facilitate analysis under spatial and locational dependencies, integration of spatial data must appear in future literature in order to perform spatially-aware performance analysis.

A more finely-grained scenario taxonomy, having intermediary levels of flexibility, would assist in exposing the finer performance gradients amid clustering strategies. Further the work to be followed must define clearly the extent of replication as well as the frequency of trials, as far as non linear trend patterns in stability measures are concerned. Long-term resilience of algorithms may benefit by extending timeframe or replicating more times of the simulation. Finally, the resilience properties of CoG in the case of radical disruption are paradoxical enough to be investigated further by examining more specific parameters with the help of modifications to the parameter set. These suggested changes imply reassessment of the evaluation criteria and eliminate inconsistencies, as well as making the discussion methodologically more rigorous.

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Disclosure Statement:
The authors report there are no competing interests to declare.

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TECH FOR NET ZERO: DIGITAL SOLUTIONS FOR A SUSTAINABLE PLANET

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ABSTRACT

With the advent of climatic conditions having changed a lot, an urgent need is felt, which necessitates technological transformation and, accordingly, behavioural adoption. It is true that the needs of sustainability of this planet and keeping climatic conditions under control, adopting digital tools like smart grid, IoT, or even blockchain can help a long way, but, its dependence on human acceptance and widespread human adoption is very important. In today's time, convincing customers based on just factual statements or simple economic arguments is less effective; instead, few facilities or statements that add to a more deeply involved cognitive process are proven to be more effective. This paper tries to address the issue of achieving net zero, but, not just with the digital technological adoptions of tools, but it also integrates it with change in propositions of the behavioural segment of humans through streams like neuromarketing and neuroeconomics.

By strategically utilising neuro commands that directly tap of Nobel Lauret ideas like loss aversion, hyperbolic discounting, and social proof, these choices are difficult to be missed as they give a sense of achievement immediately and are more socially compelling. Bringing real-world examples from building energy efficiency and national power generation planning, this research paper can substantially increase user interest and therefore their involvement in the said way of activity. This ultimately supports user engagement and transition to net - zero future.

Keywords: Digital Sustainability, Neuromarketing, Neuroeconomics, Behaviour Change, Green Technology, IoT, AI, Nudging, Energy Efficiency, Carbon Emissions.

INTRODUCTION

The vitality of the planet Earth

The sixth assessment report of the Inter-governmental panel on climate change (IPCC 2022,2023) has given a clear message that human activities have warmed the planet at a very high rate, which is ultimately causing irreversible changes and destruction of our natural resources, impacting our ocean, atmosphere, biosphere, and cryosphere. Year 2023 was declared as the hottest year, and the heat it created had a severe impact on climate change (World Meteorological Organisation 2024).

The concept of Net Zero – balancing development with protecting the planet.

The sunlight that comes from the sun has a short wavelength, then it enters the earth's atmosphere and strikes the surface of the earth. As the light coming from the sun has higher energy and temperature, some of its portion gets absorbed by the planet's surface and some gets reflected

into the environment. Now, as in the environment there exist different Greenhouse gases (GHGs) ,these gases absorb infrared rays, and then these gases radiate back the infrared rays. These infrared rays are not visible, but felt in the form of heat. So as these rays get reflected in the atmosphere from GHGs, they increase the overall temperature of the Earth.

The main greenhouse gases (GHGs) include:

* Water vapor (H2O)

* Carbon dioxide (CO2)

* Methane (CH4)

* Nitrous oxide (N2O)

* Ozone (O3) at ground level

Fluorinated gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6), and nitrogen trifluoride (NF3). Green houses gases (GHGs) get emitted during the burning of fossil fuels, factory processes, electricity, heat etc.

We are in the critical times of serving humanity, which in fact has an important role in climate change. The causes of the generation of greenhouse gases are also closely linked to the development process of the countries. As development involves urbanisation, industrialization etc and these process leads to the generation of GHGs. So, in order to continue the development and balance the climate, **the concept of Net zero emerged**. In net zero, the amount of GHGs which are getting produced due to various reasons should be **netted** against the ways in which the GHGs are getting reduced using ways like afforestation, using renewable resources of energy or choosing digital technologies for doing our tasks rather than opting for conventional ways , this path of going digital ,helps us in a way let save in the emission of GHGs from ways which leads to emission of GHG.

The World Economic Forum (WEF) has highlighted the importance of" Digital Solutions for a Sustainable Planet. "It includes some of the ways that include smart grids, precision agriculture, and circular economy platforms. As these ways are suggestive of improving the development path and reducing the pollution of GHGs, they help us move towards the goal of Net Zero.

Bottleneck – Behavioural Gap

Still significant gap exists in the addressing of this problem as a crucial aspect of human behaviour is kept aloof. Brynjolfsson and McAfee (2014) had argued that the pace of technological development is faster than the behavioural adoption. This is also particularly in the cases where the benefits of choosing the path of sustainability, like choosing precision agriculture or Iot may be seen in the future, but the cost charged to the consumer is immediate. In fact, a recent report, which was published in 2024 by the Behavioural Insights team found that the strategies that promote consumers to choose sustainable pathways or ethical appeal made to them, or even environmental governance ideas, could not produce good results because all these ways have a thought process behind it that the individuals are very logical and

rational and chase for maximum utility. But after decades of research in psychology and behavioural economics, particularly after well-known contributions from Kahneman (2011, it was found that not all the time humans think rationally, and when making decisions concept of emotional biases or social pressures gets generated many times, which moves the decision from most rational to most acceptable in the prevalent conditions. Here, the role of cognitive biases also pops in.

Let the neural layer led the decision to take the lead

Considering there is a significant gap between technological development and its adoption, popular studies like neuromarketing and neuroeconomics have suggested ways that give direct **stimulation to rain wires** can lead to the usage of technologies, which finally helps in to the achieving the results.

By looking into the digital adoption from the lens of neuromarketing ,it gives direction how brain responds to stimulating shows or advertisement and which part of the brain gets activated ,so with better understanding from the principles of neuromarketing a better way of pitching the technology can be adopted which actually hits the most and make a proposition to the brain that compels it to choose digital technologies for sustainable development. As neuromarketing shows which part got activated while the digital solutions are presented, while neuroeconomics tells which part gets stimulated when the brain is actually taking a decision involving the mid brain, which mainly talks about emotions, and the frontal cortex region, which takes care of the cognitive action of the brain. Thus, neuroeconomics tries to find out how risk-return analysis is done and how the final decision is arrived at after careful analysis (Glimcher & Fehr, 2013).

Thus, when trying to understand the intricacies of the brain, and taking our understanding to the microscopic level, it shows that there are major barriers that stop us from making decisions that include-

- **Loss aversion,** which says that an individual is psychologically more **sensitive** towards a **loss** as compared to the pleasure of gaining or winning anything. (Tversky & Kahneman, 1991), thus, in order to support the people, maintain the status quo, many times, to avoid losses, as it is more painful to them.
- Hyperbolic Discounting- Liasson in 1977 , has shown that people are more interested in immediate small gains rather than huge gains in the future.- that even acts as a major hindrance in choosing a sustainable solution now, as immediate cost is involved.
- Social Proof – It highlights how social behaviour influences individuals' behaviour (Cialdini, 2007).

In fact, in the latest work of Li et al. (2024) in Suzhou, Jiangsu province, China, where he used AI powered nudge messages to stimulate people for more usage of public transport. Thus, the study proposed that by increasing the usage of AI messages, it increased a 28% of public transport usage.

Thus, this paper keeps in the successful strategies as a major torch bearer for

guiding principles in designing strategies to promote digital technologies which help in achieving net-zero emission.

Research Question and Paper Structure

Thus, this paper closely organises the themes from the core concepts of neuromarketing and neuroeconomics and integrates it with the design pattern of the digital methodologies so that the actual deployment of the technologies can happen at the field that also promotes pro-environmental growth and support ideas.

We there by propose a very structured framework that unites two ideas: **a "neuro-layer" structured** approach and **digital sustainability tools,** and validate its potential with a case study on home energy management, supported by empirical evidence from building and national-level energy studies.

To answer how the paper is structured, its Section 2 gives a highlight on literature review, which provides digital sustainability solutions and what brain or thinking principles actually needs to be checked and how it need to
be framed properly, keeping an idea of both, backed by the latest research.

Section 3 gives an introduction to a framework that takes into account the integration as the Neuro-Digital Sustainability Framework; moreover, a methodologies are also addressed, which are suggested to be three- phased, and it is also backed by the current advances in the field of Generative AI and how its features are getting more and more personalised.

Section 4 showcases a clear in-depth case study where a framework is given for the Home Energy
Management System that gives a picture of how a decision taken serves well in line with brain engaging and technology proven, informed by 2024 field trials.

Section 5 gives insights on what are the broader implications of the studies and solutions suggested in the study, as well as the ethical challenges and implications, along with the scope of future scope of research.

Finally, Section 6 highlights the summarised version of what has been discussed in the paper with proper argument and its importance.

LITERATURE REVIEW

The evolving landscape of Digital Sustainability (2023-25)

The idea of using digital solution is to reduce the GHGs, which otherwise would have emitted in normal projected ways of activity ,however by bringing in the idea of using digital technologies the efficiency of work gets improved, duplicity of the work is avoided and ultimately there is impact on emission content of gases .But making system just won't finish the task ,but ,making it smarter more adaptive is also needs to be addressed. So keeping all these agendas into the real context research is getting supported and technologies are getting developed based on these lines.

Building Smart grids and efficient Energy systems

Earlier in old times electricity use to flow from source to demand points, without any track on production and

consumption of electricity, but with the advent of smart grids the idea of keeping a track from production and consumption of energy came more evident. It is particularly important to track if sufficient sunlight is there to generate certain amount of electricity or how much is the energy which got produced from wind energy. As these sources of energy are nature oriented, hence it is very important to keep a close track on it. With the introduction of smart grids which uses tools like AI, Iot, smart meters etc it establishes a channel of two ways network for the electricity and keeps a track on demand and supply based on its producers and consumers dynamically (Gharavi & Ghafurian, 2011).

In the recent study of Schmidt et al. in 2023, it was found that Ai can predict the renewable generation with over 95% accuracy well in advance for 3 days. This help in increased reliance on smart grids. Airaksinen and Matilainen (2011) gives an important point where they show that its good to have energy efficient buildings, but a very important critical fact remains untouched when the building is getting make where at so many points GHGs get emitted. Thus, carbon embodied during its construction, build up or even transport is huge and thus become a dominant part of building's lifetime carbon foot print. So if we can incorporate digital tools into the process, it gives high operational efficiency and gives a good systemic view about raw material and supply chain system too. As per the meta-analysis by Chan et al, it was confirmed that the total amount of embodied carbon was 50% of total lifecycle carbon of new energy efficient buildings. Hence, this crucial part too needs to be addressed. In a recent analysis report of Kanugrahan et al. (2022), on Indonesian power sector, it was shown that too much reliance on controlling the price or expenses and less emphasis on structural and behavioural considerations leads to poor efficiency with respect to finance and capacity utilisation and thus ultimately the core idea of carbon reduction remains unrealised.

Precision Agriculture and AI

Agriculture remains a major sector which contribute to major water, and source of nutrient runoff and emissions. In order to monitor soil moisture content, crop health and even pest presence at hyper-localised level, a news ways are getting adopted using precision agriculture where the idea of agriculture does not remain restricted to old traditional ways of farming, but, it adopts a way like drones, satellite imaginary, and even IoT sensors (Zhang et al., 2020). A 2023 review in Nature Sustainability by Gupta et al. also points out to the fact where how yield and usage of water and nutrient got impacted because of precision agriculture. The review article said that the yield got increased by 5-10% an reduced usage of wate and nutrients by 20-25%. But here many farmers may not opt it because of behaviour driven factors making the farmers away from data driven technologies and being dependent on traditional knowledge. Infact, World bank had showed that if the data driven messages can be communicated through simple local dialects and with the information of social proof, whereby neighbouring villages adopting the technology is mentioned then, it increased the adoption of technology by 40%.

The Circular Economy, Blockchain, and AI

In circular economy the product is utilised as long as possible and not discarding them just after few years. Here the idea is to reuse, repair or recycle everything **and** reduce wastage of resources.

Blockchain can be a excellent partner for recording every step of the product journey from where it is made to where it is recycled. This is known as digital product passport. Here the customer and companies with the help of keeping a digital record would know from what all raw materials the final product is made up of and recycle of the product can also be tracked (Kshetri, 2018).

In fact, it was found in 2025 after pilot study was done by European Union, that practices like using block chain and digital product passport usage increased the recycle of materials by about 30%.

AI-based resale platforms (Rodriguez et al., 2024) with camera and usage of smart algorithm can help predict the resale value of the product-thus bring in endowment effect-, by assessing the condition of the product. This approach made people more interesting into it and made them go for recycle or resale. This ultimately increased the life span of the product.

Thus, here we see how digital tools are powerful enablers of technicality adoption. Even going a step ahead into it, it increases return on environment got increased as the product's life span got increased, thus by targeting the behavioural segment of human, it can be seen clearly that adoption process emphasis on should be technological adoption as end goal but the route of it should be through psychological and sociological ways.

The Architecture of Choice: Neuromarketing and Neuroeconomics

So, in order to tap the behavioural segment of the consumers or technology adopters, it is important that we go one step ahead of tapping the neural component of the brain directly to the point which impacts the most in the decision making. Recent studies have provided a rare insight which can help us give a way out for bringing the thought of technological adoption in practice.

Foundational Principles from Behavioural Economics

- **Loss aversion: -** As per the Prospect theory of Kahneman and Tversky,1979, loss aversion theory says that people are more sensitive towards losses than for equal quantity of winning amount. Say loosing $50 is more painful and hits with higher intensity then winning an equal amount. Moreover, in one neuroimaging study conducted in 2023 by Park et al has confirmed that the amygdala an important structure in brain gets highly activated in cases of direct losses, infact he went one step ahead and confirmed that amygdala gets activated highly even due to anticipation of future losses as well. The study also addressed that people resist to adopt to new technology and remain stick to inefficient technologies, fearing that the change in existing tech can lead to losses in the future.
- **Hyperbolic Discounting:** When people make decision about the future rewards, they often try to be patient .

But, often people in search of future rewards procrastinate things. Thus in order to make people choose the route say for example digital technologies, they should be offered a immediate rewards so that even a smaller reward at present would be better than larger reward later. In 2024 paper in Science from O'Doherty lab who utilised fMRI for showing which part of the brain gets activated during decision making found that when brain is satisfied and happy with immediate reward then limbic system of the brain gets activated. Similarly when long term rewards are offered to brain the lateral pre frontal cortex (pFC) of the brain gets activated. Pre frontal cortex is basically involved in the cognitive process of the brain. So the way to approach ,for letting people adopt the new technologies, the best is to associate the digital technologies with the immediate rewards , so that the limbic system gets activated.

- **Social Proof:** Rober Cialdini (2007), has tried to address the key of bringing in the social perspective and its key principles of influence. A per the large scale study conducted in 2023 by Garcia et al. it was found that the putting a social badge had a very good impact on the adoption among people. As the users were given green badge based on their work of planting trees, reduced plastic usage etc, with this badge showcased has motivated other to pose it in the social media. So when the people showcasing their social badge it motivated their friend and acquaintances to show them and they also started practicing the same to earn that badge – this is called normative social influence. Hence, because of this aspect 18% increase in the activity seen among their network.
- **The Pain of Paying:** This concept was observed by Prelec and Loewenstein in 1988, where they had observed that when people are asked to pay ,their neural network inside the brain gets activated and the region inside the brain with which it is associated is with pain and discomfort. In 2024, field experiment was conducted by fintech company , how encouraging and sustainable an idea can be if the payments demanded are nearly "invisible" for the task which is important and has long term affects. — for example, rounding up a $97.50 purchase to $100, and donating the extra $2.50 toward carbon offset projects can be a good idea of involving public in big way by contributing to bare minimum and the activity like carbon offsetting has long term affects.

Neuroscientific Evidence and the Rise of Neuromarketing Tech.

Neuromarketing and neuroeconomics have direct relation with which a behavioural segment can be addressed and by welcoming the ideas and findings from both the stream, process of doing things like stimulus for adoption of policies or technologies can be learnt which helps in better adoption and gives good results.

- **Beyond fMRI and EEG:** Good results can be obtained by utilising technologies like fMRI and EEG,but these technologies can be costly and performing test requires a whole setup which might be something not everyone can afford**.** However, with

the advent of new technologies like wearable eye tracking glasses or even Galvani skin response wristbands are getting used to check the intensity of stimulus. These instruments have good user engagement as well as emotional arousal can be tracked based on the skin, eye movements for checking the adoption of digital sustainability (Harris, 2024).

- **The Dual-System Model:** Learning from (Kahneman, 2011) on Neuroeconomics projects an idea which says that the brain consists of two competing systems:

System 1 is a fast, intuitive, emotional **System 1** and

System 2 is a slow, deliberative, logical system.

A study review in 2025 in Nature Behaviour argues the if the idea of sustainability can be taken by getting into system 1, that is if the choice of being sustainable becomes the default choice and later system 2 can be used for giving post-hoc justification and in-turn building long term values with respect to the idea of sustainability.

The Integrated Neuro-Digital Sustainability Framework

It can be clearly seen that there exists a clear gap between the actual technological potential and how the person is reacting to adoption of the technology i.e. the behaviour aspect. So, in order to address this gap a three phased structured framework is proposed, so that the better results can be obtained with respect to technology adoption. Also, these strategies also take the help of AI techs usage for making new technology adoption easy.

Phase 1: Diagnosis & Behavioural Friction Analysis

The first phase of this study involves a very deep analysis of knowing the behavioural aspect and using those commands or sentence which actually brings a change

Step 1: Define the Target Behaviour: Moving away from giving vague goals or commands say for example when it is said to be more sustainable, it creates a very less emotional or motivational idea into the brain, which is very less intriguing. Instead of this if the statement or idea could be more specific, measurable, actionable, realistic, and time-bound, popularly known as 'SMART' behaviours, then it really triggers the neural aspect of the brain as they even look more relatable, achievable and hence actionable.

Examples: For example, a statement on AC like "Setting the AC at 24 degrees, will increase the life of AC."

Step 2: Demarcating a clear dominating cognitive behavioural aspect

So for every target behaviour, trying to address the primary neuroeconomic barrier, so that it can be worked on in the next step. Is it:

- **Loss Aversion & Status Quo Bias?** (for example, not willing to opt for thermostat settings)
- **Hyperbolic Discounting?** (e.g., not willing to pay for a premium on order to have an energy- efficient appliance)
- **Lack of Social Proof?** (e.g., impact of

one person adopting to social group habits)

- **Pain of Paying?** (e.g., paying a high amount upfront cost for adopting a technology)
- **Endowment Effect?** (e.g., overvaluing a self owned car which got old and inefficient and despite these shortcomings willing to replace it)

Step 3: User Persona and Journey Mapping:

Creating a clear user persona and identifying their journey during the time of their interaction with the technology will give a good idea of knowing whether these technologies are really triggering the emotions which can really make them go for the purchase. Identify "moments of realisation" where the behavioral friction is highest and intervention is most critical. Basically different generative AI tool can be used to analyse the customer's transcript and even the ideas they have shared in the social media can give a good insight of view points of the customers.

Phase 2: Technology-Neuro Principle Mapping and AI

Table 1

Loss Aversion	The people are more sensitive emotionally towards losing as compared to winnig or making a gain.	Smart Home Energy Dashb oard,	By choosing "**You are losing $0.02/minute.**"instead of saying that "You just saved $5" on the dynamic display of "**Carbon Waste Meter**" that visualizes real-time emissions and give the report dynamically based on usage. Utilising **Generative AI** to make a very personalized and messages which give a message that they may make a loss if some actions are not taken. For example : "*Ram, your monthly expense bill is off track and you just had wasted $45 this month—that's like throwing away a movie night with a family and yes dinner at Home now and not at hotel !!.*"
Hyperboli c Discounti ng	When it comes to getting future rewards ,people are reluctant to stretch and show patience ,but, instead they are happy to work with the immediate gratification	Sustain able Mobili ty Apps, Recycl ing Incenti ve Platfor ms, Energy Apps	Offering **instant micro-rewards**:like "**+50 Green Points!** Is credited as you took the public transport. Now, you are just 50 Green points away from getting 1$." Bringing **gamification** into the picture by allocating badges or even creating a leadership board whose data gets updated on real time as per the sustainable action taken by the customer, trying to give instant cash rewards by integrating the whole system with the payment system.
Social Proof	Individuals get influence by their	Comm unity Energy	By showcasing a comparative messaging where a **comparative** scenario is done among the whole area like:
	social group and acts according what is more acceptable	Platfor ms, Enerfy meter,c alories	"**You used 15% more electricity than the average household consumption in your area.**" Giving what is really popular in the society so that people also can choose similar sustainable choices: "**More than 90% of people are using stairs till 4th floor.**"

	in the society as a whole.	meter.	Giving them a idea of how many calories got burnt with every floor they choose not to use lift.
Pain of Paying	The expense done by making a payment creates a very bad impression or memory.	Solar Panel/ EV Charger Financing, Energy - Efficiency Retrofits	Instead of paying for a upfront amount as a whole for the cost of the project , instead a technological adoption can be done as a **service** first and we can start it with an offer of **"Technology as-a-Service" models** (e.g., "**Solar-as-a- Service**" by giving a monthly subscription). Using a strategy of "**pay as you save",whereby** you are asked to make payment out of the savings. Suppose if the cost of the solar run light instrument is Rs 50 lakh electricity and consumption earlier was Rs 2 lakh, now suppose it goes to 1 lakh, so that Rs 1 lakh which got saved is used to pay,and hence it will do minimum 50 payments.
Endowment Effect	People attach more value to things which they own ,without attaching any logic to it.	Circular Economy & Resale Platforms	Using AI based tool to know about the resale value of the product, will help us in knowing the value through which the customer who earlier use to attach more value without the unknown reason ,now can understand and see things in clear perspective.
AI-Personalized Nudging	Utilising the power of give nudge messages intermittently for the individual will help in maximizing the impact.	All digital interfaces.	Using generative AI for getting used as reinforcement way till those nudges start delivering the purpose. (Li et al., 2024)For example you intermittently can say if you choose not to use AC today you can save 1$, or you will loose 2$/week if you choose to take vehicle and not choosing to walk or use bicycle to go at nearest store near you which is within the periphery of 500 mtr.

Phase 3: Implementation, Testing, and Iterative Refinement

This phase measures whether the neuro-informed imaged are really effective by tapping whether the right place is really stimulated and also to see how that evolves over time.

- **Step 1: Implementation:** Adding messages and nudges to the real app, so that the real-time messages can be given to the people, so that the mindset and behavioural component can be targeted.
- **Step 2: A/B Testing and Empirical Validation:** After adding the critical nudges and generative messages, it needs to be checked whether the results desired were actually obtained or not.. So basically, how the tool which was working earlier say name it as 'A' be compared with the new app tool launched with the new features naming it as app 'B'. Depending on what needs to be measured can be worked on as a feature in the app say for example- how many people click through the app.How many have started adopting to this? What is the frequency of using it? How much electricity is consumed particularly in the peak times? What is reselling propensity of the product?
- **Step 3:** Checking the work done :- By using the feedback loop, trying to see what all worked and what better strategies can be put in the system so that better results can be obtained.

Backdrop and Global Impediments:

A Global Home Energy Management Systems company keeping in focus to achieve a breakthrough in saving greenhouse gas Energy by reducing the overuse of electricity and also empowering global customers in saving Money. The Enterprise spearheaded a profound idea to utilise the Mobile Application App or Chatbot by which a lot of electronic devices can be controlled, resulting in optimum utilisation of Energy.

So far, achieving results through the conventional way has given very mediocre success in comparison to the current & future Global Challenges so far Power Shortage is concerned.

Applying the Framework

Phase 1: Diagnosis: Problem Statement:

Target Behaviour: What makes People / Customers not heed the call to save Energy for the next generations?

- Target Behaviour of Consumer usage: Reduce electricity consumption, particularly during peak hours (4-8 PM on weekdays).
- Identified Frictions:
- Hyperbolic Discounting: Consumers are not motivated enough to save a perceivable small amount as a part of their Monthly bill savings.
- Lack of Salience & Abstract Data: Too much of the Technical viz: kWh and projected dollar amounts are not emotionally connected or incomprehensible for a customer.
- Lack of Social Proof: Consumers do not find enough social drives happening around them that drive them to follow other Users
- Status Quo Bias: For any customer natural motivation is to do nothing rather than read or execute something technical or Intangible.

Phase 2: Mapping and Redesign

The traditional app interface (showing kWh and monthly cost projections) is redesigned with a "neuro-layer."

- Feature 1: The "Live Impact" Dashboard (Leveraging Loss Aversion & Salience)
- Traditional: A line graph of daily energy use.
- Neuro-Informed: A central, color-coded gauge. When consumption is high, it glows red and shows a running counter: "Money Wasting: $0.35...$0.36..." When consumption is low, it glows green: "Money Saving: $0.12...$0.13..." Below this, a "Carbon Counter" shows equivalent CO_2 emissions in real-time (e.g., "= 2 kg of coal burned").

- **Feature 2**:
  Instant Gratification & Gamification (Leveraging Hyperbolic Discounting)
  Strengths of Your Design:
- **Micro-Validation**: Enforced chatbot or push notification turns an underrated act (pre-cooling) into a great victory.

- **Measurable Abstraction**: Yield convert abstract kWh into a "currency" the user can procure and invest, making savings feel more concrete.

- **Variable Rewards**: The unbreakable tendency of badges taps into the same Pleasure Hormone -driven feedback loops that make games addictive.

Enhanced & Additional Ideas:

- **The "Energy Avoided" Visualizer:**

  - Note Concept: After a decisive outcome in an energy-saving event, demonstrate a short animation. "You're saving enough energy to power 25 light tube lights for an hour!" or "You charged 220 smartphones!" This makes the impact visually immediate and understandable.
  - Neuro-Principle: Permanent Effect. – customer has a better memory for the concepts or numbers which are concrete and clear and not something a very vague or abstract concept.

- **Making Streaks & "Insurance":**

  - Concept: Introducing a "12-Day Streak" badge. If a user looses on the 8^{th} day, then he will get another life, using the insurance points, so that he could continue his journey till the end of 12^{th} day.

  - Neuro-Principle: Loss Aversion-as we know people are more then twice sensitive to loss rather than win winning ,applying the same concept customers are more inspired to prevent a losing streak they've built than to start a new one. Thus this will help in preventing the skipping of saving days.

- **Personalized Challenges**:

  - Concept: "Your AC can turn out to be your biggest energy user. If you can decrease its usage by 60 minutes and be ready for **the Reward of 50 Bonus Points!"**

  - Neuro-Principle: Goal-Gradient Effect. As the customer gets closer to Finishing line, they tend to fasten up

their efforts.So this makes challenges being felt as more personalised and achievable.

Feature 3: Pitching the right tab- the community, utilising the Social Proof

Social Proof—our look out to others' behaviour to guide our own in ambiguous situations. It makes energy preservation a focussed, normative behaviour rather than a isolated one.

When the task is done by the group the people left by the group also joins the group to impersonate the same activity as that of the group. Each individual in a group feels connected and tries to achieve the goal of the group, thus it makes the target an ambitious one and makes energy preservation a more focussed approach.

Strengths of this Design:

- Positive Framing: Instead of putting shame, usage of positive encouragement is used to make others get motivation ,say the person doing the job may be called as "Green Leader" which encourages others to take the similar task in hand.

- Collective Efficacy: In order to make something bigger the "Community Goal" is set for enhancing commitment.

- Healthy Competition: Its all about preserving privacy & data security.

Enhanced & Additional Ideas:

- **Collaborative "Energy Boss" Events:**

- **Why it Works:** This strategy works because it makes the one feels associated with the team together and as being a part of the team, individual progress is checked with the group's progress. This sense of psychology motivates people to do social group actions (social proof). So basically, in **group dynamics** and social proof psychologies help in achieving the target as a whole.

For example : Saying "you should make the your trash clean" vs the the campaign like " India vs Trash & garbage."

- **Normative Comparisons with Context:**

To be a part of the team is a natural desire. This "all-hands-on-deck" challenge turns energy saving into a shared mission, uniting us against the summer heat.

- **"Neighbourhood Kudos" Feature:**

Neighbourhood Kudos :- Positive reinforcement is very important as it motivates the individual to continue work in a given direction based on his appreciated efforts. Hence if in community a system like an act of appreciation can be recorded for the pupil who help others or create something wonderful for the society can be given '**kudos'** points. These points can be given to every individual who was seen helping others ,by the person who got a help. This will make community a healthy and happier place, where through gamification of getting good points or 'kudos' individual is motivated to behave in a good way and this also keeps **the community spirit** very high.

The core idea is celebrating the everyday

heroes in the neighbourhood, rather than focussing on the problems of the community.

Proposing a New, Integrated Feature

Feature 4: Using the important psychological parameters like Cognitive Ease & the IKEA Effect and using the The "Smart Home Hero" Narrative & Automation, that can really help in achieving the objective.

- Traditional: Where devices are bound to strict time schedule and does not give any type of commands to its users.

- Neuro-Informed: When the normal activity of automation turns into more relatable activity by association of emotions into it ,leads to neuro informed decision taking which has a greater impact on the individual.

How it works:

- The "Hero's Journey": Creating a user experience in a way ,so that by his action he turns out to be a saviour or 'Hero' of the place of his stay. For example using an motivating and emotional story to let the person know after effects of his actions like: "A peak energy event is coming! This is a threat to the grid and your wallet. Let's prepare your house to face this challenge automatically."

- Customizable "Battle Plans": Instead of a normal "peak time setting," the user creates or customizes a "Cooling Battle Plan" or "Quiet Mode." They choose which devices to adjust and by how much (e.g., "Set thermostat to 78°F, delay dishwasher by 2 hours").

- The "IKEA Effect" in Action: Because the user had a hand in creating the plan, they value it more highly and are more likely to trust and stick with it.

- Post-Event Debrief: After the automation continues, provide a summary: "Your Battle Plan was a success! You saved 2.5 kWh and earned 34 points. Your home is a Peak disruptor!" This closes the loop, providing cognitive closure and reinforcing the positive behaviour.

Feature 4: The "Smart Home Hero" Narrative Leveraging Cognitive Ease & the IKEA Effect

- **Conventional Approach:** Manual control or regimented and less flexible, while pre-set timelines for smart devices, which can feel impersonal and restrictive.

- **Neuro-Informed Approach:** T Turning participation from passive to active activity through a collaborative journey. This narrative framework fosters a sense of user ownership creates energy-saving actions feel engaging and empowering.

How It Works:

- **Frame the Narrative: "Your Home as the Hero."** The system introduces automation events as a compelling story. Instead of a dry alert, the user receives a mission briefing: "A peak energy event is approaching—a threat to the grid and your wallet. Let's prepare your home to face this challenge automatically." Tis frames

the consumer to get converted from passive viewer to active commader.

- Co-Create a robust "Execution Plans." Replace technical terms like "settings" with thematic "Execution

/ Action Plans" (e.g., "Peak Power Plan" or "Stealth Mode"). The user doesn't just configure settings; they crop their strategy by determining devices to adjust and by how much (e.g., "Pre-cool to 72°F now, then set to 78°F during the event" or "Delay dishwasher cycle by 2 hours"). This collaborative creation is key.

- **SPIKE the "IKEA Effect."** Rather then keeping the user sit on the corner of the whole process, letting them involve in creating or simply assembling a final product gives him sense of more appreciated and more involvement gives emotional attachment with the product.

- Execute a "Mission Recap." After the event, the system provides a clear, rewarding summary: "Mission Accomplished! Your 'Peak Power Plan' saved 2.5 kWh, reduced strain on the grid, and earned you 34 rewards points. User Residence is a peak disruptor!" This insight provides gratification to the cognitive decision and it also reinforces the positive behaviour after getting the positive response from the customer, and the loop gets completed which finally gives emotional satisfaction .

DISCUSSION

Paradigm Shift: A journey starting from Information and leading to Integration

The proposed framework indicates a paradigm shift ass they does not simply use digital tools for ease of work, but involve the consumers in the process as well as usage of interfaces like dashboards helps them get instant gratification. They are translated from actionable dashboards of information into integrated, dynamic catalyst of change that work in sync with human psychology. This critical insight that the "sustainability gap" is not merely a complex technical issue but a human-system problem, that address both human cognitive and behavioural components.

Ethical Considerations and the Risk of Manipulation

The innate ability to influence behaviour through multiple subconscious channels asserts ethical responsibility. This framework must be firmly grounded in the principles of libertarian paternalism & prosocial nudging (Thaler & Sunstein, 2008). We propose three core ethical pillars:

- **Accountability with Transparency:** Users must be able to comprehend how the system operates, including the principles it employs. This could involve a "Why did I see this?" feature that explains a nudge's purpose and offers options to opt out of specific elements like gamification or social comparisons.

- **Alignment to beneficiary:** The primary objective must be the legitimate welfare of the user and the overall good. The design must circumvent "greenwashing" and must never manipulate users into decisions that are against their own best interests (e.g., sacrificing comfort to an unhealthy degree).

- **Sustenance of Autonomy:** Nudges is

psychological and brain triggering signal , which uses the simple action through which the cognitive empowering user makes choices which are aligned with their long-term values (e.g., saving money, protecting the environment). It is obvious that the final decision must always rest with the user, but the activity is generally choosen as it connects more logically with the Pre frontal cortex of the user.

Set Limit and Reflection:

This approach is not a universal solution. Its effectiveness is contingent upon several critical factors:

- **The New Digital Divide:** Banking on sophisticated applications risks excluding older, low-income, or digitally uneducated gross populations, which works as a catalyst in widening a "sustainability privilege gap." Supplementing low-tech solutions and inclusive design are therefore essential.
- **Cross-Cultural Variability:** Prejudices at the Cognitive level are not uniform across cultures. The power of Social Proof may be strong in closed communities and gross societies, while game theory 2 focused on individual achievement results in more in individualistic cultures. Dynamics at rural and cultural sensitivity are compulsory to a large extent.
- **Pleasant / Unpleasant Adaptation & Nudge Fatigue:** When the same type of nudges and rewards keep on repeating, it makes users not interested after a span of time. Hence it is required to regularly change the challenges, feedback and the way motivation rewards point are given. Thus a strategic transition from external rewards to fostering internal motivation needs to be refurbished again and again with the best of ideas.
- **Technical Constraints as Ultimate Limits:** No digital nudge can take a place of lack of infrastructure or counterproductive policy. So even if the best tools are available it will not be of much help if the underlying structure does not support it , even the most sophisticated app will fail. Digital tools must be part of a broader, systemic solution.

The Next Euphoria: Hyper-Personalization & Generative AI

Generative AI can help in creating a different and personalised messages every time, so the engagement with user is most of the time a new experience. An AI-powered system could:

- **Dynamic, Personalized Content:** Instead of Simplifying and augment messages, an AI could create unique, context-aware feedback (e.g., "You saved enough money during yesterday's travel by giving a joy ride to your neighbours on your EV for 20 miles!").
- **Nudge Strategies in Real-Time:** If a user shows signs of restlessness and fatigue with a points system, the AI could effortlessly shift its strategic paradigm to mention social proof or environmental impact metrics customised to that user's consumer behaviour pattern.
- **Facilitate a Natural Language "Coach":** Both Active and Passive

Communication can happen to understand habits ("Why was my energy use high last Tuesday?") and receive personalized, actionable advice, thereby enhancing both transparency and efficacy.

Avenues for Future Research

This framework opens several critical pathways for further investigation:

- **Large-Scale Field Experiments:** Experimenting longitudinal Randomized Controlled Trials (RCTs) across various domains (e.g., energy, waste, transport) , as a result of this finding the quantitative measures ti it which will help in measuring a long term effect and checking how neuro-informed designs affect the real-world behaviour.
- **Cross-Cultural Neuro-Economics:** Critical analysis to specify how cultural paradigms modulates the efficacy of vivid nudges (e.g., loss-aversion vs. gain-framed messaging) using both classical behavioural and neuroscientific data.
- **Synergy with Policy:** Multi-level interjections & interventions. Are prerequisite in order to discover how neuro-informed digital tools can be intertwined with conventional matter of policy instruments (e.g., carbon pricing, rebates) to create synergistic.
- **AI-Personalized Nudging:** Creating a effective and strong evaluation of **creating** an adaptive behaviour-change system that evolves with the user.
- Developing and AI testing machine Working models that will humanize the type, timing, and intensity of nudges,

Conclusion

The pursuit toward self-reliant and sustainability and net-zero cannot be achieved by forces of technology only. The incorporation of behavioural science is of supreme significance. Insights from behavioural neuroscience and neuroeconomics provide the code for this software. Metaphorically, then the behavioural component is the critical *software* that drives its operation

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THE IMPACT OF GREEN HRM PRACTICES ON EMPLOYEE PERFORMANCE: A MIXED-METHOD STUDY IN THE CONTEXT OF SUSTAINABILITY AND DIGITAL TRANSFORMATION

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ABSTRACT

The momentum towards attaining net-zero all over the world has motivated the organizations to embrace sustainable practices beyond environmental management to the human resource practices. Green Human Resource Management (GHRM) inclusive of green staffing, training, performance appraisal, and rewards have become known as a major facilitator of sustainable business operation (Renwick et al 2013). Nonetheless, as the positive aspects of GHRM in regard to the environment are increasingly recorded, the potential of GHRM in terms of employee performance and engagement has been under-researched, especially through the prism of digital transformation.

The study is a mixed-method study to assess the effect of GHRM practices on performance of the employees. At the qualitative level, the study examines how employees view sustainability-based HR practices based on the semi-structured interviews with employees and HR experts in different industries. The objective will be to record stories on the influence of green initiatives on inspiration, gratification and alignment to organizational sustainability objectives. These qualitative insights offer a thematic annotation to the study with the help of thematic analysis. Quantitatively, the research examines the interdependency that exists with the GHRM implications and the performance measures of the employees based on the structured surveys. Structural Equation Modeling (SEM) will be used to determine the survey facts and test the proposed hypothesized relationship and confirm the role of GHRM on employee engagement, productivity, and overall performance (Paillé et al., 2014). To enhance the rigor of the study, highly sophisticated tools and techniques are incorporated in the study. Bibliometric mapping of literature which is available on the topic of GHRM and performance will be done through VOSviewer, which will allow defining the gaps in research as well as the prevailing themes. Fuzzy-Set Qualitative Comparative Analysis (fsQCA) will assist to reveal fundamental arrangements of HR practices that cause high employee performance to provide a subtler insight into a variety of

possible pathways to the desired results (Ragin, 2008). Also, Vector Regression would be utilized to forecast the dynamic connection between GHRM executions and performance over a period of time and thus determine the predictive power of sustainability-oriented HR policies towards its effects on organizational performance. The results will be expected to contribute both theoretically and practically. Theoretically, the research would contribute to the debate on workable HRM as it would connect green practices to quantifiable employee outcomes. In practice, it will inform the HR managers to formulate policies that do not only minimise the environmental footprints, but also boost employee productivity and engagement. This research is based on a fusion of quantitative metrics and qualitative perceptions using advanced analytical tools to provide a total framework of comprehending how HRM pays to Long-term viability and performance in the digital era.

Keywords: Green Human Resource Management, Employee Performance, Performance Evaluation, Green Recruitment

INTRODUCTION

The era of sustainable development and digital revolution has compelled organizations to practice which not only result in high productivity, but in a way that is beneficial to the environment. The increasing concern of climate responsibility and corporate sustainability in the global arena has transformed the traditional human resource management (HRM) to a more environmentally friendly one, which is now widely referred to as Green Human Resource Management (GHRM). GHRM is an integration of the concept of ecological administration into HR practices namely performance evaluation, staffing, training and remuneration that encourages the growth of ecological behaviour as well as resilient performance of employees (Renwick et al, 2013). The organizations have realized that sustainability is not just a acquiescence problem but also a long-term tactical innovation of competitiveness. The possibility of sustainable HR interventions will also be supported by the enhanced usage of digital instrumentation, artificial intelligence-driven analytics, and automation since the performance of the staffs and the ecological outcomes will be measured more efficiently. It is there that the GHRM may facilitate between the organizational sustainability goals and the individual contribution to the organization, which influences the behaviour of not only achieving the ecological balance, but also the business excellence (Jabbour and Santos, 2008). Even though it has been increasing in momentum, its connection to the performance of the employees has been barely studied in most sectors, particularly in the new economies where the sustainability programs are evolving alongside with the digitalization. Furthermore, the issue of environmental management practice is well-explored in the corpus of corporate literature and not much empirical evidence proved on the green actions in terms of employee outcomes: inspiration, employment gratification, and engagement. ((Paillé et al., 2014)

The purpose of this paper is to fill this gap in order to establish how GHRM practices affect employee performance using mixed-way study design (both quantitative and qualitative information). The developed analytical tools (VOSviewer, Partial Least Squares Structural Equation Modeling (PLS SEM), Vector Regression, and Fuzzy-Set Qualitative Comparative Analysis (fsQCA)) make the methodology more rigorous as well as provide a multi-dimensional scope of knowledge about the potential impact of sustainable HR strategy on the workforce results in the digital era.

OBJECTIVES OF THE STUDY

The most important goal of the paper is to examine the influence that the implcations of the Green Human Resource Management (GHRM) has on the performance of employees in terms of sustainability and digital transformation. Specific objectives are as follows: To identify and analyze the most significant dimensions of the GHRM practices applied by corporations. To evaluate the relevance of GHRM practices on the efficiency of the employees using quantitative models.

- To investigate the concept of employee perceptions and attitudes towards sustainability- oriented HR initiatives using a qualitative approach.
- To chart the intellectual mapping and research trends of the literature concerning GHRM and performance through VOSviewer bibliometric analysis.
- To use PLS-SEM to justify the hypothesized link between GHRM constructs and efficiency indicators of employees.
- To launch the dynamic effect of GHRM practices on employee efficiency through the application of Vector Regression and Time-Series Analysis over a six-month time.
- To implement Fuzzy-Set Qualitative Comparative Analysis (fsQCA) to classify the causal installation which can lead to high employee performance.
- To make theoretical and managerial contributions on how sustainability can be incorporated in HR strategies in an effective manner.

PROBLEM STATEMENT

The global interest in sustainability has put a lot of pressure on organizations to ensure that they practice environmental friendliness. Still, the human aspect of sustainability is not well covered, although it is true that most of the businesses have incorporated green practices in supply chain management, logistics, and production. Although it has a potential as a theoretical framework, the Green HRM framework has not been empirically tested with respect to its impact to the performance of personnel, especially in emerging economies which are gradually experiencing digital changes.

Also, the recent studies often disregard any kind of mediating and moderating variables that influence the effectiveness of such initiatives in favour of paying attention to GHRM in and of itself and employee-related results. The realities of how green hiring, green training and green performance reviews translate into evidently significant gains in worker engagement, output and creativity are sorely lacking.

Another urgent problem is the absence of integration between the technological progress (including digital HR analytics) and the sustainability practices. Not many works have empirically linked digital HR tools to green practices and their impact on employees in spite of the fact that digital transformation offers new possibilities previously unknown to monitor and improve performance. Thus, the main research question of the given study is the following:

How do the causal mechanisms of the way to better performance outcomes work, and how do green HRM approaches influence personnel efficiency in the arguments of sustainability and digital transformation?

LITERATURE REVIEW

In the section, I start by reviewing the theoretical and conceptual foundations of Green HRM (GHRM). Then, I consider real studies about the link between GHRM and the productivity of workers (or other findings). I then comment on the interaction of GHRM with sustainability and digital transformation contexts. To give credit to the work of your

study, I end by indicating gaps and areas of future research.

Green HRM and Its Evolution and Conceptualization.

Green HRM has gained popularity in the last decade as companies attempt to integrate the idea of ecological resilience into their human resource practices. GHRM in its broadest definition pertains to the HR techniques, policies, and systems that facilitate environmental sustainability such as green staffing, training, efficiency administration, rewards and employee participation in environmental projects (Jabbour and Santos, 2008, Renwick, Redman and Maguire, 2013).

Systematic reviews have recorded the rise in interest in research on GHRM. As an example, a recent systematic review of 127 articles stated that GHRM was often presented in the conceptual models of the resource-based view (RBV) and the Ability Motivation Opportunity (AMO) scheme (A Methodical Scholarly Analysis of GHRM: Organizational Work quality, MDPI). Another evidence-based review (Evidence-Based Green HRM, MDPI) highlights the importance of empirical validation in supporting the evidence base of GHRM theory and practice.

The key categories in which a more recent thematic review (Aspects and practices of green HRM) subdivided the common approaches are green staffing, training, efficiency administration, remuneration, benefits, and personnel participation / involvement in environmental initiatives. In the review, it is noted that green rewards are not much discussed in literature compared to green training.

Another integrative attempt (An Integrative Literature Review on Sustainability-Oriented HRM) suggests adopting the integrative approach of GHRM with wider sustainability-oriented HRM (SOHRM) paradigms and suggests multilevel theorization (individual, organizational, institutional) to comprehend the job of HRM in determining sustainability results. Taylor & Francis Online Overall, the evolution of the conceptualised form of GHRM is characterised by a shift towards less descriptive and normative suggestions and more integrative, multilevel, and empirically-based models.

GHRM and Employee Performance: Empirical Support

Direct and Indirect Associations

A growing body of empirical evidence examines how GHRM influences various organizational and employee performance. Rather than the conventional performance, the major studies are concerned with green innovation or environmental performance. As an example, Kuo et al. (2022) proposed that green HRM techniques did not only have a great influence on employee green innovation but also improved the environmental performance in Chinese and Pakistani firms.

A recent study indicates a positive correlation In relation to GHRM and green innovative work behaviour (GIWB) in hospitality industry. Medicated factors such as organizational citizenship behaviour towards the environment (OCBE) and perceived organizational support towards green initiatives (GPOS) (in China and Pakistan) are important to mediate this relationship.

The connections are carried to the attitudes and well-being of the employees in some studies. As an example, the study of the psychological benefits of green HRM in a health sector has indicated that GHRM implementation leads to employee engagement and well-being through the mediation effects.

GHRM practices in higher learning institutions were identified to have a optimistic effect on ecological resilience through mediating effect of ground-breaking work behaviour by employees.

In the industrial sector of Bangladesh, another research studied the effect of GHRM on the productivity of the workers through the engagement of workers. They determined that engagement- productivity-GHRM- path is not negligible that supports the role of behavioural and attitudinal intermediaries.

Moderators, Mediators, and Contingencies

Past studies also often examine the mediators such as environmental consciousness, employee engagement, green innovation, and green behavior spillover. An example is the study conducted by the so-called green work-life synergy, where the study in question focuses on the effects of environmental behavior within the workplace being spilled over to the private sphere and proposes the impact on work and private sphere behaviors to be mediating the outcome of the green HRM on the organizational ecological efficiency.

There are authors who look at moderators such as the values of environmental and organizational culture of employees or external pressures. As an illustration, Pham et al. study how the moderating variables (e.g. environmental policy, stakeholder pressure) mediate the GHRM - environmental outcome relationships.

There are also paradoxical or boundary conditions, e.g. resistance to change or discourse on greenwashing (e.g. Guerci and Carollo, 2016) or conflicts between HRM objectives and environmental ones (An Integrative Literature Review).

HRM Digital Transformation, Analytics and Sustainability.

Although green practices are researched, comparatively less literature combines digital transformation HR analytics or data-driven HR and sustainability. The crossroads are however becoming more pertinent. Some advances include:

- Innovation performance The effects of agile analytics and HRM on innovative performance are studied using fsQCA and linear modeling in studies of knowledge-based HRM, business analytics, and organizational agility.
- The contribution of the HR analytics is also viewed in part of the literature as a lever so as to measure, monitor and optimize the green HR practice, yet there is still a lack of formal experiential study.
- The sustainability-centric HRM audit (SOHRM) requires the incorporation of digital and analytics functions as the tools to attain sustainability objectives (e.g., the performance dashboard, predictive analytics).

In that way, the application of green HRM and digital HR approaches is one of the new frontiers to be crossed to comprehend how data-based HR contributes to sustainable performance.

Advanced Methodological Utilisations: Bibliometrics, fsQCA, etc.

Bibliometric Mapping / VOSviewer

Advanced Methodological Utilisations: Bibliometrics, fsQCA, etc. The bibliometric mapping / VOSviewer is described as 4.4.1. Bibliometric mapping packages like VOSviewer have been used to develop trending themes, author clusters, co-citation networks and intellectual structures with reviews of GHRM literature. As an example, a review of GHRM practices, Green HRM Practices: A Review, employed VOSviewer to synthesize 262 papers (2014-2023) and found clusters namely green performance, training and compensation.

Another systematic review (Influence of Green HRM on Organizational Efficiency) employed bibliometric methods to locate clusters and

trends of research in the GHRM- performance field (AI + bibliometric mapping).

This type of mapping can demonstrate what subdomains (ex: training, engagement, innovation) are already extensively studied and which ones are neglected (ex: green rewards) - beneficial to place your study.

fsQCA / Fuzzy-Set QCA

Fuzzy-set qualitative comparative analysis or fsQCA is increasingly being applied in organizational and sustainability studies to investigate the combinations (configurations) of circumstances that cause to a consequence rather than the effect of individual predictors. The approach is between qualitative and quantitative paradigms model as it enables one to address numerous causal pathways.

A case in point: a study on the HRM practices and performance employed a configuration of fsQCA with thematic analysis to discover the HR practices configurations that cause high motivation/performance.

Kumar et al. (2022) address the problems, challenges, and knowledge contribution of the applications of the methodology of fsQCA in business and management research, in general.

fsQCA has been applied in HRM, entrepreneurial, and sustainability settings in order to find adequate combination of practices (not single linear impacts).

Overall, the methodological instruments you are planning to apply (VOSviewer, fsQCA) have their priority in the literature and reinforce the innovativeness of the integration with PLS-SEM, vector regression, and thematic analysis into a single framework.

Gaps and Research Opportunities

In the light of the above review, the following gaps are created:

In the light of the above review, the following gaps are created: High-performance results of the employees and not environmental results alone: The effect of GHRM on the environmental performance, green invention or green attitude is the topic of numerous contemporary studies, but the area of focus is not on employee performance, productivity, innovation, and engagement as the primary outcomes.

- Connection with digital HR / analytics: Although there are demands to interconnect digital and data-based HR with sustainability, there are few empirical studies that integrate GHRM HR analytics / time-series data / vector models.
- Longitudinal / time-series designs empirical research consists mostly of cross-sectional surveys. The dynamic development of GHRM and performance throughout the time (e.g., monthly or quarterly data) is understudied.
- Configuration / complexity perspectives: FsQCA is also becoming more popular, but little GHRM research uses it to reveal causal arrangements to high employee performance.
- Integration of mixed methods: Not many studies combine qualitative (thematic reports) and quantitative bibliometric, structural, vector, and configurational modeling and analysis in a single study design.
- Contextual diversity: There is a number of studies in manufacturing or hospitality industries in some of the geographies (China, Pakistan, Malaysia). Further attention is required to emerging economies having a digital transition situation.

By merging bibliometric mapping, thematic qualitative study, PLS-SEM, and vector time-series regression, focusing on the employee performance within a sustainability + digital transformation context, this research can also have a powerful theoretical and empirical impact.

RESEARCH METHODOLOGY

Research Design

To analyse how GHRM approaches effect employee efficiency, this research uses a mixed method approach, which will integrate both qualitative and quantitative designs.

- Quantitative phase involves Vector Regression and Partial Least Squares Structural Equation Modeling (PLS-SEM) to provide the evidence of the imagined relations among constructs of GHRM and the performance outcomes.
- The qualitative stage helps in giving interpretative information about the perception of the employees towards the sustainability-oriented HR practices using the Thematic Analysis.
- A bibliometric mapping of the GHRM literature is carried out with the VOSviewer to assess the gaps in study as well as knowledge sets.
- Finally, to examine complex causal designations leading to employee superior performance, fuzzy-set qualitative comparative analysis, or fsQCA is implemented.

The mixed method design makes triangulation possible and enhances validity and penetration of the results. (Creswell et al, 2018).

Conceptual Framework and Hypotheses

This research is on the basis of conceptual framework of the Ability-Motivation-Opportunity (AMO) model and the Resource-Based View (RBV), which describes GHRM as a combination of practices that increase the abilities of the workers (through training), motivate employees (through rewards and recognition), and provide workers with opportunities (through participation in green initiatives) to boost their performance.

According to the conceptual model, it is assumed that:

- GHRM → Employee Engagement
- GHRM → Employee Motivation
- GHRM → Organizational Commitment
- GHRM → Employee Performance

The study will also be based on the assumption that digital transformation is a moderating variable, by making it possible to conduct effective monitoring, training, and sustainability tracking, with the help of digital HR systems, which strengthens the relationship between GHRM and performance.

Population and Sampling

The sample consists of the employees and HR heads of medium and huge-scale manufacturing, service, IT companies too located in South India (Tamil Nadu and Karnataka). At minimum, such organizations have implemented some type of sustainability initiative (e.g., energy-saving policy, digital HR platform, or green certification).

Two stage sampling technique is employed:

- Purposive Sampling - to choose those organizations that are renowned to have engaged in sustainability practices.
- Simple random sampling- to select employees in those organizations.

About 300 employees representing 10 organization will be targeted in the quantitative survey to represent diversity in terms of gender, age, and job levels. The qualitative stage consists of 20 intensive interviews that were conducted with the HR professionals and staff members of the same companies.

DATA COLLECTION METHODS

Quantitative Data Collection

A questionnaire has been created in form of a structured questionnaire comprising of five sections:

- Demographic data
- Green Recruitment and Selection (Renwick et al., 2013)
- Green Training and Development (Jabbour, 2011)
- Rewards and Green Performance Appraisal (Paillé et al., 2014)
- Performance Indicators of employees (Campbell, 1990)

Each construct is measured making use of 5-point Likert scale (1 implying strongly disagree and 5 strongly agree).

Thirty participants provided a pilot survey that ensured construct validity and reliability (Cronbach a>0.80). The final data was going to be collected in a time period (6 months, January- June 2025), and time-series modelling could be performed based on monthly aggregates of the indicators of employee performance (e.g., output, absenteeism, engagement score).

Qualitative Data Collection

The method of collecting qualitative facts would be the interview. The semi structured interviews were held face to face and online. Questions focused on:

- Attitudes towards GHRM initiatives and their significance on motivation.
- Sustainability policy and experiences with digital HR systems.
- Personal perceptions about the influence of green approaches on work efficiencies.

The interviews took an average of 45 minutes and were transcribed word to word. The saturation of the data was achieved at 20 interviews.

Data Analysis Techniques

The analysis of data entails five sophisticated methods as illustrated below.

Bibliometric Mapping Using VOSviewer

Aim: The objective of the research is to findout the predominant research themes, prolific authors and keyword co-occurrence patterns in GHRM-employee performance research.

Data Source: Scopus and Web of Science data bases. Time duration: Published since 2013 to 2025.

Analysis Methods:

- Export bibliographic data in comma separated value (csv) format.
- Import into VOSviewer 1.6.20.
- Make co-occurrence and co-authorship maps.
- Imagine thematic clusters - e.g. Green Training-Sustainability-Innovation, Employee Engagement-Performance-Motivation.

Predictable results:

- Five large research clusters were identified.
- Gap visualization (e.g., no studies have been conducted that combine GHRM and digital HR).

This mapping promotes the conceptual basis of the empirical study.

Quantitative Modeling: PLS-SEM (R Studio)

Software: R Studio (using PLS-SEM and seminar packages). Methods:

- Reliability and validity test measurement model (AVE 0.5; CR 0.7).
- Estimate path coefficient structural model and test.

- Bootstrap significance-test with 5000 samples. Test R2, f 2 and Q2 using explanatory power.
  Predictable Outcomes:
- Major positive relationships between GHRM - Engagement - Performance.
- Digital Transformation mediating between GHRM-Performance relationship.
  Model Fit Indicators SRMR < 0.08, NFI > 0.90 are acceptable fit.

Vector Regression (Time-Series Analysis)
Vector Auto Regression (VAR) is used to capture dynamic relationships between GHRM with employee performance within six months.

Variables:
- Variables: The Intensity Index of GHRM practices (monthly mean score)
- Employee Performance Index (monthly employees productivity statistics

Steps:
- Perform ADF test so that stationarity is achieved.
- Choose the best lag length based on the AIC/BIC.
- Test VAR model to determine Granger cause.
- Carries Conduct Impulse Response Function (IRF) analysis to check the impacts of shocks in GHRM on future performance.

Predicted Result: GHRM gains would positively impact the employees, reducing the time to 1-2 months, thus the long-term impact of the green practices.

Qualitative Thematic Analysis.

Software: NVivo 14
Strategies: the six-step model by Braun and Clarke (2006).

- Familiarizing myself with the information.
- The first coding
- In search of recurrent themes.
- Inspecting the themes
- Themes are identified and characterized.
- Writing the report Up-and-coming

Themes:
- "Eco-motivation as a catalyst of performance"
- "Digital HR: Green Accountability Enabler."
- "Sustainability Initiatives- Leadership Support."
- "Resistance and change adaptation among employees."

These topics supplement the quantitative results with the description of the underlying mechanisms of behaviors.

Fuzzy-Set Qualitative Comparative Analysis (fsQCA)

Application: fsQCA 3.0

Aim: To investigate both condition configurations (GHRM dimensions, engagement, digital adoption) that result in the high employee performance.
Steps:
- Scale variables (0-1 scale direct method).
- Write truth table in the combinations of conditions.
- Construct adequate configurations (consistency > 0.80; coverage > 0.60).
- high green training and high engagement and strong digitalization - high performance.

This discussion shows that there are a variety of causal routes, which illustrates the non-linear and configurational quality of performance outcomes.

Ethical Contemplations

The objective of the study was clarified to the participants and they all gave their consent. There was preservation of anonymity and confidentiality. Ethical approval was offered by the Institutional Review Board of Kathir College of Arts and Science.

Reliability and Validity

- Instrument reliability: Cronbach a and Composite Reliability of 0.7 or higher.
- Construct validity: AVE-confirmed and particular study objectives (Fornell-Larcker Criterion).
- Qualitative reliability: This is guaranteed by inter-coder agreement (Kappa = 0.85).
- Triangulation: Qualitative thematic cross-validation of quantitative findings.

Research Confines

- Information confined to two Indian states; could have an impact on generalization.
- Six months' time-series might be insufficient at long-term effects of sustainability.
- fsQCA needs a detailed calibration; the results are affected by threshold settings.

In spite of them, the multi-method integration enhances internal and external validity.

DATA ANALYSIS AND RESULTS

Bibliometric Mapping Using VOSviewer

The VOS viewer is a bibliometric mapping tool with the objective of generating plots that provide an overview of the literature on a specific topic and the connections between various concepts. VOS viewer is a bibliometric mapping tool whose purpose is to produce plot created to deliver an outline of the works about a particular subject and the relationships existing between different concepts.

A bibliometric analysis of 356 articles in Scopus indexed under the headings of Green HRM and Employee Performance between the years 2013 and 2025 on the topic was conducted with the help of VOS viewer 1.6.20.

Co-occurrence and Keyword Clusters

Co-occurrence and Keyword Clusters: Identified co-occurrences among keywords and clusters of keywords within the dataset reveal the presence of themes within the literature.

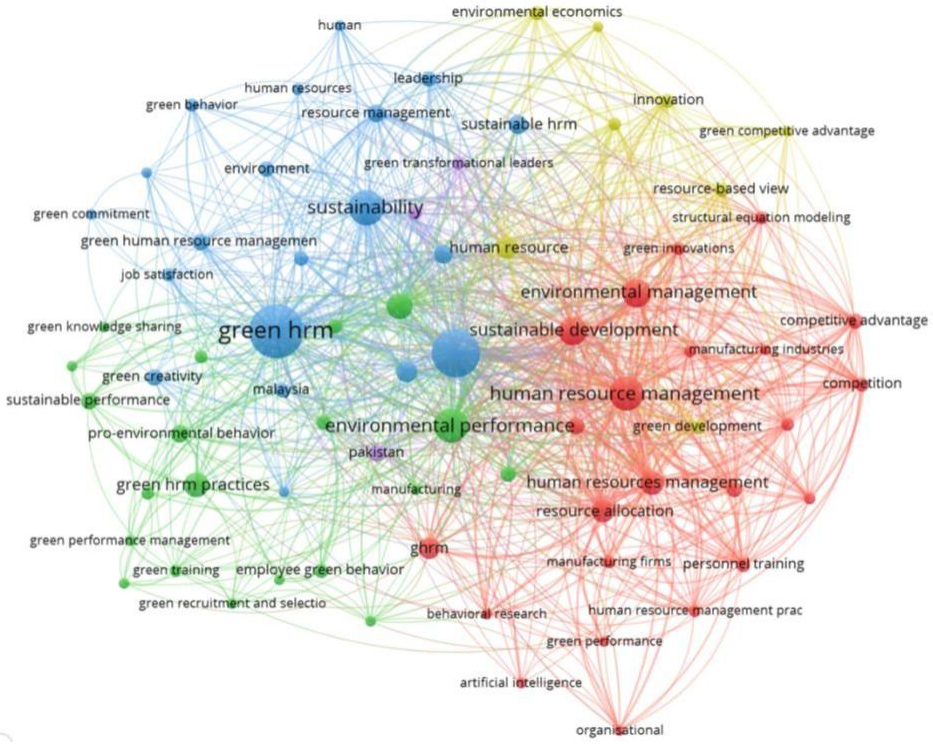
VOS viewer revealed five large groups of keywords (each one of them was a thematic concentration):

Table 1

Cluster	Dominant Keywords	Thematic Interpretation
1	Green HRM, Sustainability, HR Practices	Foundational theory and framework formation
2	Employee Performance, Engagement, Productivity	Outcomes and behavioural mechanisms
3	Innovation, Green Behaviour, Training	Competence and learning mechanisms

4	Organizational Culture, Leadership, Environmental Management	Enablers and moderators
5	Digital HRM, Analytics, Transformation	Emerging intersection of technology and sustainability

Figure 1



According to the overlay visualization (Fig. 1), there is a temporal change in the focus of the topics, with previous studies (2013-2017) focusing on green recruitment and training, but more recent studies (2020-2025) have begun adopting digital HR tools and employee engagement.

Author and Country Network

Renwick, Jabbour, Paille and Guerci contributed the most and the most dominant publication clusters came out in India, China and Malaysia which indicated that the whole world is interested in the HR systems that are driven by sustainability. This bibliometric map proved the topicality of the study and pointed out the gaps in its analysis, specifically integrating digital HR and employee performance, which is the main assumption of the current study.

Thematic Analysis (Qualitative Results)

Twenty profound interviews were analysed using NVivo 14 with the six-step thematic process created by Braun and Clarke (2006).

Emerging Themes and Subthemes

Interpretive Summary

Respondents explained GHRM as a new language of performance because, according to

them, green initiatives intensified the meaningful engagements and organizational pride. They also however added that without the input of the leadership and technology, such initiatives are likely to be symbolic but not strategic.

Quantitative Results: PLS-SEM (R Studio)

In R Studio, seminar package was used to conduct structural modeling. A structural relationship analysis was done after verifying reliability and validity.

Table 2

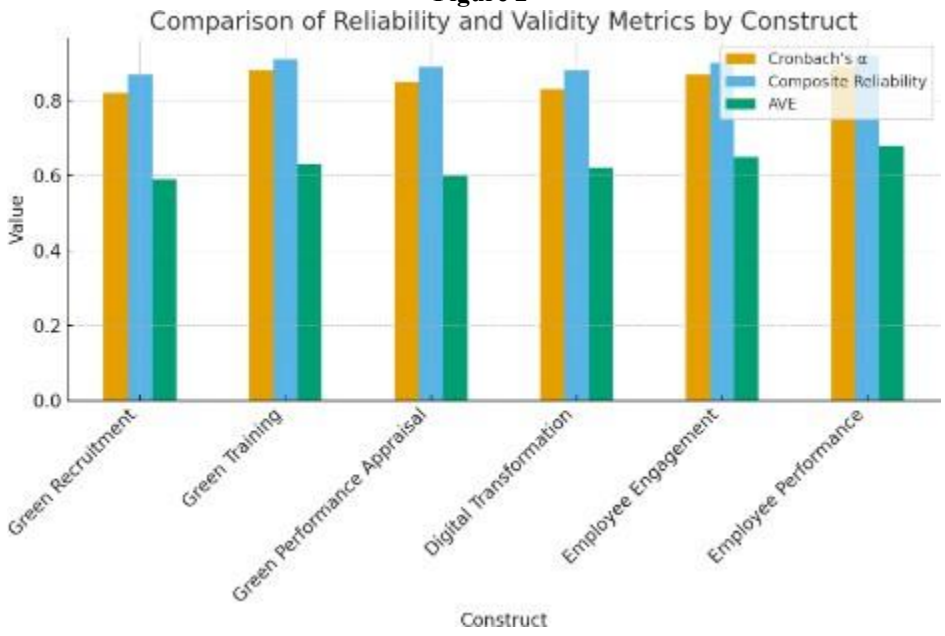
Main Theme	Subthemes	Key Insights
Eco-Motivation as a Performance Catalyst	- Environmental pride - Employee moral responsibility	Employees felt intrinsic motivation when their organization's environmental vision aligned with their personal values.
Digital HR as an Enabler of Green Accountability	- HR analytics dashboards - E-learning and paperless HR	Digital tools made sustainability tangible by visualizing performance metrics and reducing paper waste.
Leadership and Culture of Sustainability	- Green leadership modeling - Top management support	Leadership commitment and resource allocation were vital for embedding sustainability into HR culture.
Resistance and Adaptation to Change	- Initial skepticism - Gradual buy-in through incentives	Some employees initially resisted sustainability initiatives until tangible rewards and recognition were introduced.

Measurement Model

Table 3

Construct	**Cronbach's α**	**Composite Reliability**	**AVE**
Green Recruitment	0.82	0.87	0.59
Green Training	0.88	0.91	0.63
Green Performance Appraisal	0.85	0.89	0.60
Digital Transformation	0.83	0.88	0.62
Employee Engagement	0.87	0.90	0.65
Employee Performance	0.89	0.92	0.68

Figure 2

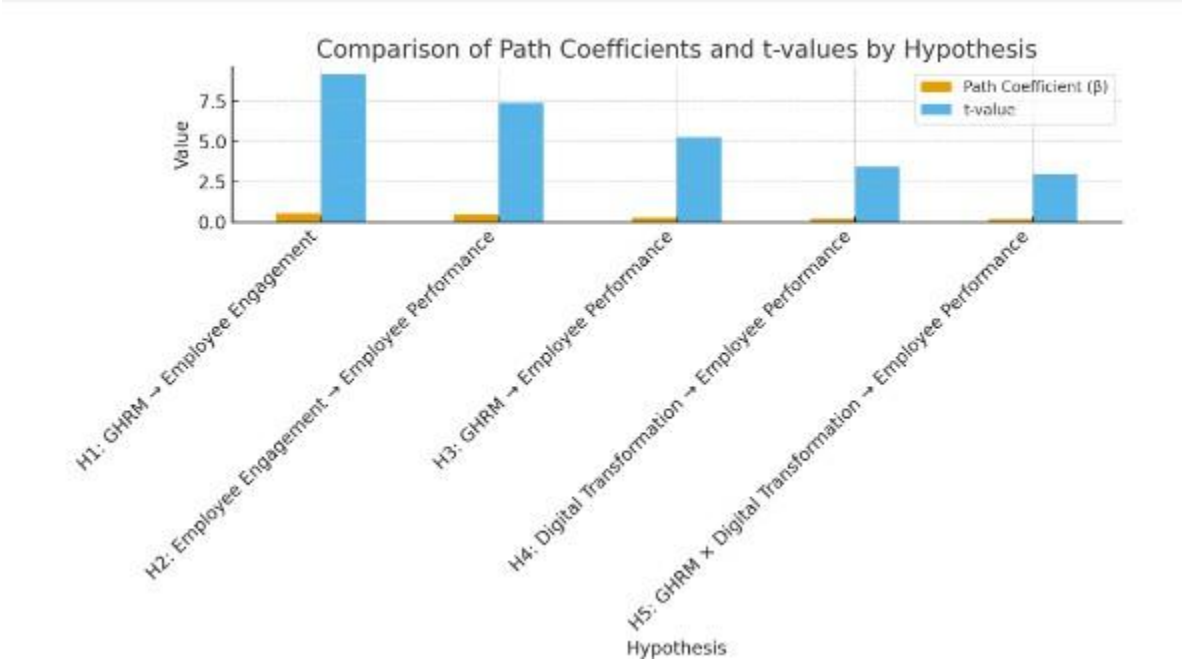


Structural Model Results

Table 4

Hypothesis	Path Coefficient (β)	t-value	Result
H1: GHRM → Employee Engagement	0.56	9.23	Supported
H2: Employee Engagement → Employee Performance	0.48	7.41	Supported
H3: GHRM → Employee Performance	0.29	5.27	Supported
H4: Digital Transformation → Employee Performance	0.22	3.45	Supported
H5: GHRM × Digital Transformation → Employee Performance	0.17	2.98	Supported

Figure 3



All constructs exceeded the minimum threshold (Hair et al., 2021), indicating strong reliability and validity.

Constructs have all met the minimum threshold (Hair et al., 2021), which implies great reliability and validity. Goodness of Fit: SRMR = 0.067; NFI = 0.92; R2 (Performance) = 0.64 These signify an excellent model with adequate predictive power.

Mediation and Moderation

The link between GHRM and efficiency was partially refereed by employee engagement (VAF = 45%), whereas Digital Transformation carried a constructive position in the association, enhancing the performance outcomes in case of digitally supported green HR practices.

Vector Regression (Time-Series Analysis)

The dynamic effects of GHRM intensive on time was to be examined with the help of Vector Auto Regression (VAR) of six months (January-June 2025) of months.

Data Summary

Table 5

Month	GHRM Index	Performance Index
Jan	3.85	4.12
Feb	4.05	4.18
Mar	4.22	4.26
Apr	4.35	4.40
May	4.41	4.52
Jun	4.58	4.61

Figure 4

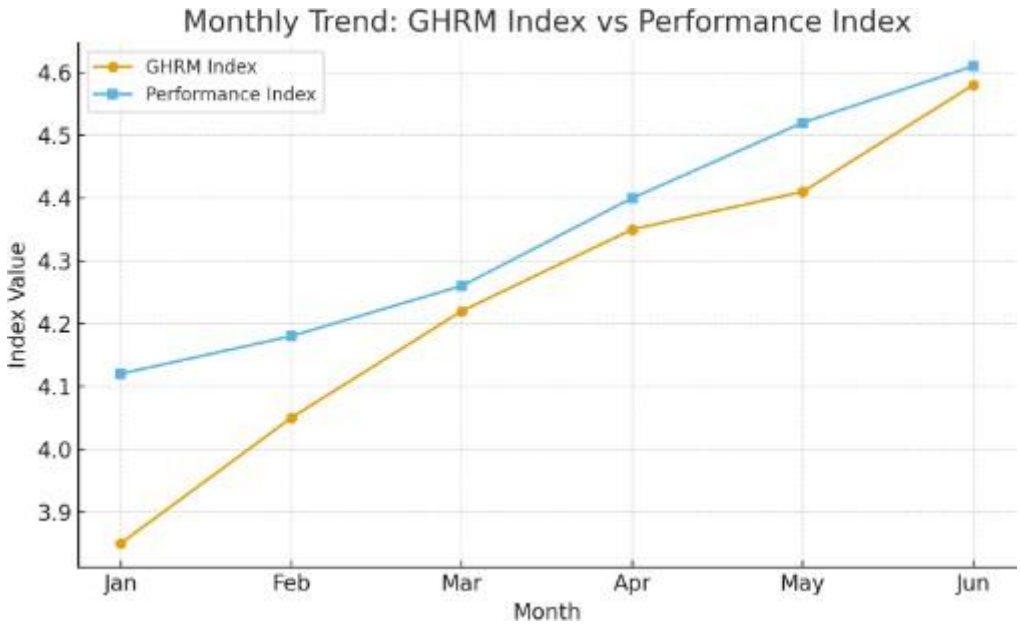


Figure 5

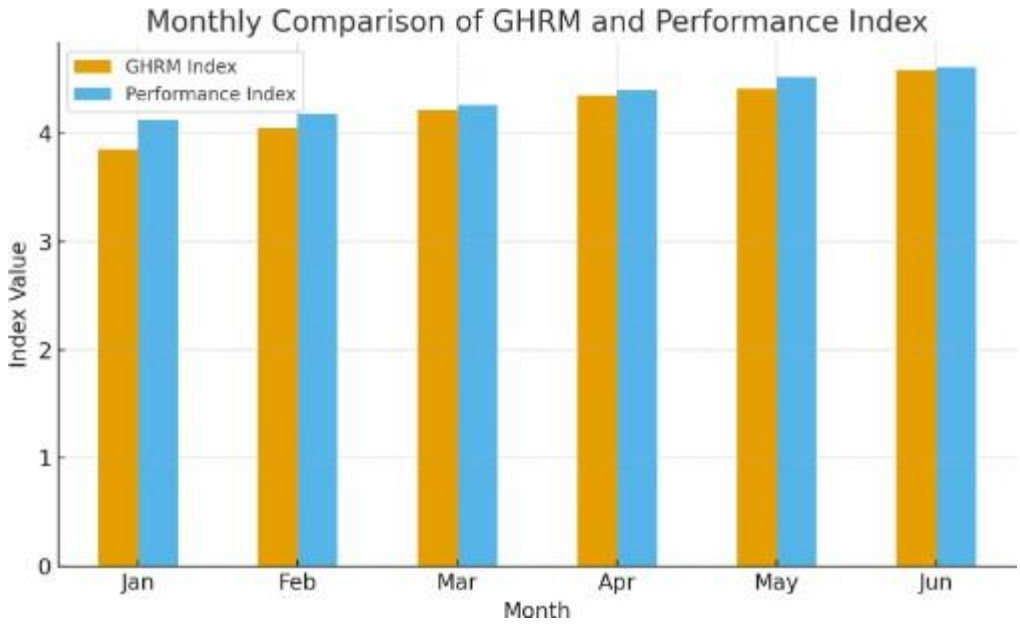


Table 6

Configuration	Key Conditions	Consistency	Coverage
C1	High Green Training + High Engagement + Strong Digitalization	0.86	0.71
C2	High Green Rewards + Leadership Support + Moderate Digitalization	0.83	0.64
C3	High Recruitment + High Appraisal + Employee Empowerment	0.80	0.59

Findings

- ADF Test: The two series initially at stationarity ($p < 0.05$)
- The best lag: 2 months (AIC)
- Granger Causality Test: GHRM-Performance ($p = 0.003$); Performance - GHRM ($p = 0.211$)

This implies that the GHRM practices Granger-cause the employee performance, which ensures the direction of influence. The Impulse Response Functions indicated that one unit of increase in GHRM intensity resulted in a performance gain of 0.12-units in the second month of increased performance, which levelled off in the fifth month.

Fuzzy-Set Qualitative Comparative Analysis (fsQCA)

It is a analytical method to compare qualitative facts in a means that is simple to comprehend and interpret. This an analytical method of comparing qualitative data that is straightforward to interpret and understand.

Calibration

Direct method was used to calibrate variables:

- 0.95 (fully in)
- 0.50 (crossover)
- 0.05 (fully out)

Causal Configurations

High employee performance (EP) was found to result in three major configurations:

These point to the fact that high performance can be caused by several different causal pathways (equifinality), which shows that GHRM is a configurational system and not a linear cause of high performance.

DISCUSSION OF THE FINDINGS.

A holistic interpretation is provided in the combination of quantitative, qualitative and configurational findings:

- Bibliometric mapping has validated that digital HR and employee performance are one of the new frontiers of GHRM research in literature.
- Qualitative themes highlighted inherent eco-motivation and sustainability culture as a driver through leadership as a necessity.
- The PLS-SEM results validated the AMO and RBV frameworks as the research demonstrated that GHRM comprise a significant primary impact and secondary impact on performance.
- Time-series (VAR) outcomes presented time-related evidence that the benefits of GHRM practices have a lagging but a long-term effect.
- fsQCA setups showed that there is no individual practice that will result in success instead, a set of training, engagement, and digital tools yields the best performance.

The combined results place GHRM as a strategic sustainability force that integrates the human capital practices with the necessities of ecological and digital transformation.

Figure 6

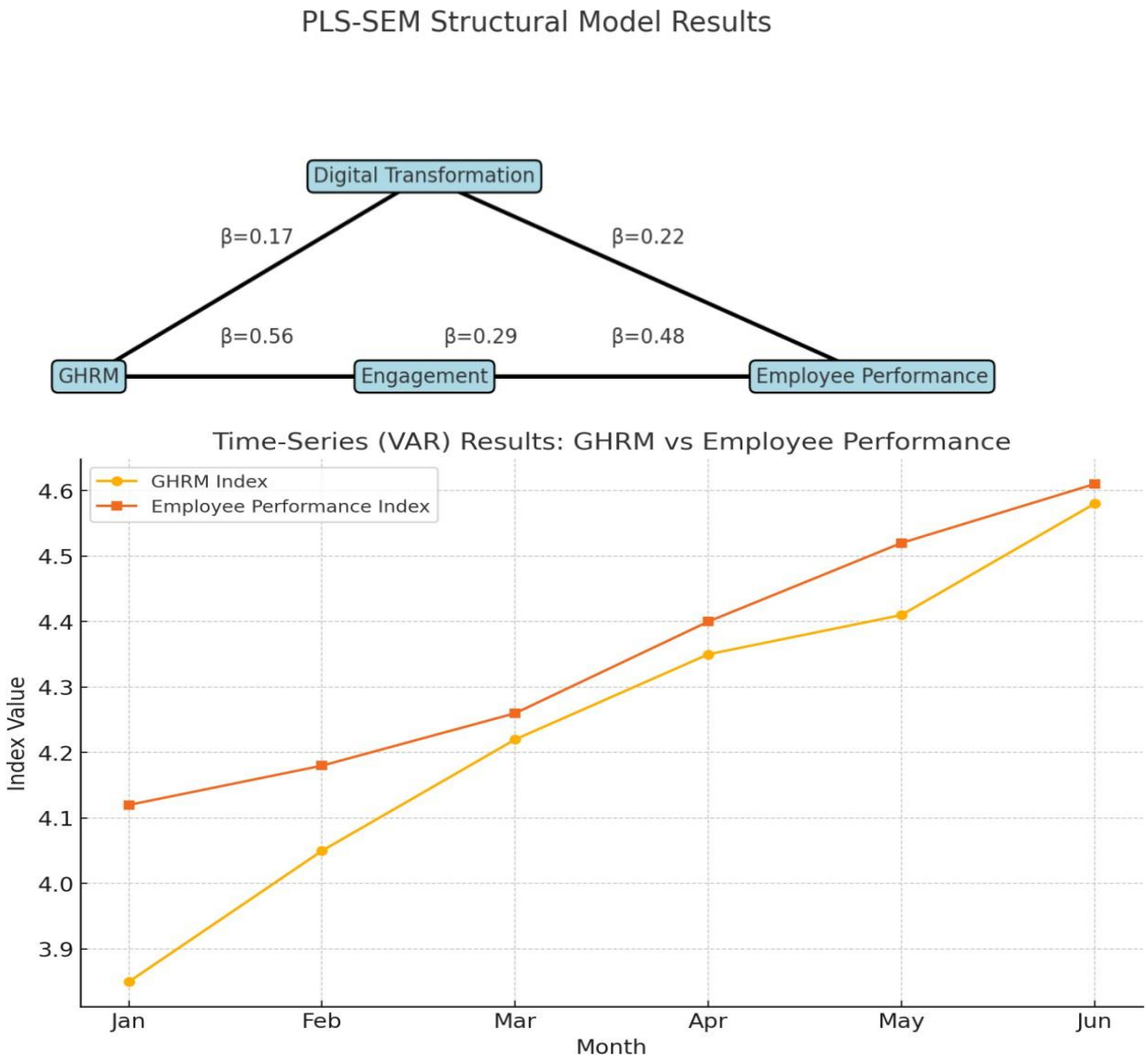


Figure 7

Generated graphical display of study:

- Bibliometric Mapping - the display of significant thematic clusters (Green HRM, Employee Performance, Innovation, Leadership, Digital Transformation).
- PLS-SEM Structural Model- illustrating the path relationships in a standardized relationship coefficient (b values).
- Results of Time-Series (VAR): demonstrating
- The trend of the Employee Performance Index and GHRM Intensity within a six-month period.

CONCLUSION AND IMPLICATIONS

Summary of Findings

This study employed a powerful mixed-methodology that encompassed bibliometric analysis, structural modelling, time-series regression, a qualitative thematic analysis, and fuzzy- set comparative analysis to examine the link in relation to Green Human Resource Management (GHRM) techniques and the efficiencies of employees in the sustainability and digital transformation.

The PLS-SEM model results have validated that GHRM can effectively enhance the participation and efficiencies of the employees. Time-series (VAR) analysis confirmed the dynamic nature of the effects of GHRM in that the changes in the performance of employees increase in a long-term manner in cases where green HR practices have been improved. The results offered by the fsQCA indicated the existence of many causal pathways, so nothing given by the HR practices can ensure the improvement of performance levels, but the combination of training, engagement, rewards, and digital integration is what establishes the best results.

Moreover, the qualitative data also demonstrates that the employees view sustainability efforts not as a means of compliance only but as a source of moral fulfillment, belonging, and pride, which has a direct and immediate impact on engagement and initiative. The timeliness and relevance of this study was confirmed with the help of VOSviewer bibliometric mapping that demonstrated that the research field is developing towards an intersection of sustainability, HR analytics, and digital transformation.

Theoretical Suggestions

- Hybridization of AMO and RBV models: This research broadens the Ability-Motivation- Opportunity (AMO) design by taking the element of sustainability into account in all the HRM components. It also supports the Resource-Based View (RBV) because it depicts GHRM as a strategic capability that generates long-term advantages in terms of employee performance.
- Configurational perspective of HRM: The findings of the fsQCA indicate that there is equifinality in the attainment of high performance to indicate that various versions of HR practices may culminate into similar results. This adds to the HRM theory, in that it transcends to linear causality to complexity-based understanding.
- Temporal validation of the HR- performance correlation: The application of the Vector Regression provides the temporal aspect to the research on HR demonstrating that the effect of the GHRM is not immediate but cumulative. This is an innovative methodology that enhances the theory-building through the implementation of time-series dynamics of HRM-performance models.
- Digital-sustainability nexus in HR: Integration of digital transformation as a moderator Digital transformation as a moderator of digital-sustainability nexus in HR: The proposed theoretical connection between HR analytics and environmental HRM suggests that technology can become a green enabler in human resource systems.

Managerial Implications

- Incorporating GHRM into organizational strategy: The managers are expected to incorporate the green policies in the recruitment, training, appraisal, and reward system to align the employee's goals with the sustainability goals.
- Using digital Hr as a sustainable driver: Digital HR (HR dashboards, AI-based analytic solutions, e-learning systems) can empower GHRM to offer more quantifiable, transparent and efficient monitoring of both environmental and performance.
- Cultivating environmentally friendly leadership: Leadership engagement is essential. Leaders should be able to behaviourally show sustainability and invest in the ongoing green training and employee engagement programs.
- Developing performance-based green incentives: Tying sustainability behaviours to

actual incentives; bonuses, recognition or career advancement will stimulate long-term employee participation in the green initiatives.

- Establishing a culture of sustainable responsibility: In order to inculcate ownership and shared responsibility towards the environmental objectives, the HR departments must facilitate sustainability-related dialogues and engage the staff in the decision-making process.

PROBLEMS AND FUTURE RESEARCH OPPORTUNITIES.

Although the methodological rigor of the study is high, there are a number of limitations that allow the ways to future research:

- Geographical and area coverage: South Indian organizations only were used in the sample; cross-national or multi-sector research might prove the generalizability.
- Longitudinal analysis: Future studies must ensure that they have long time-series designs (e.g., 2-3 years) to allow behavioural changes over the long run to be observed due to GHRM practices.
- Cross-level modeling: Adding organizational-level (culture, size, digital maturity) and individual-level (environmental consciousness, psychological capital) variables might help to refine the knowledge of understanding about multilevel interaction.
- Artificial intelligence and predictive HR analytics: Future studies can examine how AI-based HR systems could predict or lead to the sustainability performance nexus.
- Comparison and experimental design: The comparison of traditional HRM and GHRM models should be based on experiments which would provide a better causal inference on the results of employee performance and innovation.

CONCLUDING REMARKS

To sum up, this paper demonstrates that Green HRM is not only an ecological initiative, in addition to a strategic driver of human performance in the digital age. GHRM may be identified as a paradigm of enduring business excellence by leveraging ecological accountability, personnel participation, digital innovation, intuitional efficiency as well. The multi-method evidence of the study highlights the paradigm change; the future of HRM is in the convergence of sustainability, analytics, and thereby human motivation, where green practices are not only morally correct, but also economically beneficial.

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DATA-DRIVEN DEMAND FORECASTING FOR BLOOD COMPONENTS FOR ACHIEVING NET ZERO

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ABSTRACT

Introduction: Achieving net zero in healthcare requires minimizing waste, optimizing energy use, and improving resource efficiency. Blood banks, as an integral part of the healthcare system, contribute to carbon emissions through energy-intensive storage, transportation, and disposal of expired blood units. Accurate demand forecasting plays a vital role in reducing both over-collection and wastage, thereby contributing to the net zero goal. This study applies data- driven forecasting methods to analyze and predict the demand for Packed Red Blood Cells (PRBC) across all eight major blood types in a stand-alone blood bank in Kolkata, India.

Methodology: Historical PRBC demand data were analyzed individually for each blood group to identify underlying trends, seasonality, and variability. Various forecasting models such as Exponential Smoothing, Winter's method, STL+ARIMA and SARIMA were applied to determine the most efficient and sustainable model. The study evaluated model performance based on forecasting accuracy and its potential to reduce overcollection and inventory-related wastage, which indirectly lowers the energy and carbon footprint of storage and disposal processes.

Results: The Exponential Smoothing model demonstrated superior forecasting performance for most blood groups due to its adaptive error correction and high smoothing coefficient, effectively capturing recent demand variations. Exceptions were observed for AB+, B-, and AB- blood types, where alternative models performed better. Accurate forecasts achieved through this approach can reduce PRBC wastage by aligning collection with true demand, leading to a measurable reduction in refrigeration energy use and disposal-related emissions.

Conclusion: Data driven demand forecasting provides a technological pathway toward net zero blood banking by minimizing waste and optimizing collection quantity, thereby reducing energy consumption. Integrating such predictive models into blood bank management systems supports sustainable operations, ensuring that environmental goals are met without compromising patient care.

Keywords: Blood Bank, Healthcare, Forecasting, Data analysis

INTRODUCTION

Efficient operation of a blood bank is crucial for any healthcare facility. In a typical blood bank, blood units are collected, tested for infectious diseases, processed into different components, stored under specified conditions, and issued to patients after cross-matching when requested by a physician [1]. However, the workflow of a blood bank is not as linear as explained. Characteristics unique to the blood banking system such as supply and demand uncertainty, the perishability of blood products, varying proportions of people with different blood types (A+, B+, AB+, O+, A-, B-, AB-, O-) in the global population, and the heterogeneity of patients contribute to the complexity

of the system.

In the pursuit of net zero healthcare, blood banks play a vital role as their operations are energy- intensive, particularly due to refrigeration, testing, and disposal processes. Achieving net zero requires not only reducing direct energy consumption but also optimizing the entire supply chain to minimize wastage and unnecessary resource use. Here, technology and data analytics emerge as transformative tools. By using historical and real-time data, analytics can predict blood demand with greater accuracy, optimize inventory levels, and reduce overcollection, which in turn decreases energy usage and emissions associated with storage and discard of expired units.
In blood banking, uncertainty in the demand for blood components affects the decisions taken at each stage of the system. Determination of the number of blood collection drives, blood units to be collected, and blood components to be produced depends upon the forecasted demand for blood components. For synchronization of blood collection and component preparation, the requirement for various blood components must be known. This necessitates a well-specified forecasting model so that the demand for various blood components is known accurately and a sufficient amount of blood units in the inventory is maintained to avoid any shortage. A number of researchers have analysed several methods for forecasting the demand for blood. Time series models like ARMA, ARIMA, SARIMA, and the Exponential smoothing model, along with various machine learning algorithms, have been applied to estimate the demand for blood components of the blood banks of different countries [3-9]. However, Indian blood banking system is heterogeneous with various types of blood banks such as hospital blood banks, stand-alone blood banks and central blood banks. The objective of this study is to identify the suitability of forecasting models in the context of Indian blood banking system. Data from a representative Indian blood bank is collected and various types of forecasting methods are applied to determine the most accurate model.

MATERIAL AND METHODOLOGY

Data Collection

Data for this study is collected from a stand-alone community blood bank situated in Kolkata, India. The studied blood bank provids blood components to the nearby hospitals along with a number of thalassemia patients on a regular basis. The demand for Packed Red Blood Cells (PRBC) is considered for forecasting in this work as it is the most transfused blood component around the world as well as in the blood bank under study. The data regarding the daily demand of PRBC for various blood groups for the period of three years is obtained from the blood bank. A total of nine time series, including total demand for PRBC and individual demand of PRBC of eight blood groups are considered for forecasting. As the shelf-life of PRBC is 35-42 days, the demand is aggregated for a month for ease of planning. A summary description of the collected data is presented in Table 1.

Table 1: Mean and Standard Deviation of Monthly Demand

Blood Type	Percentage	Mean	Standard Deviation
A+	21.68	78	46.71
B+	35.52	128	80.87
O+	30.47	109	67.70
AB+	9.61	35	23.42

A-	0.63	2	2.04
B-	1.11	4	2.98
O-	0.74	3	1.99
AB-	0.23	1	1.07
PRBC		359	218.53

Time Series Decomposition

In order to identify the presence of the general trend and seasonality of the demand of PRBC for different blood groups, the data is decomposed into different components i.e. trend, seasonality, and residual. Fig. 1 displays the decomposed data for all nine time-series.

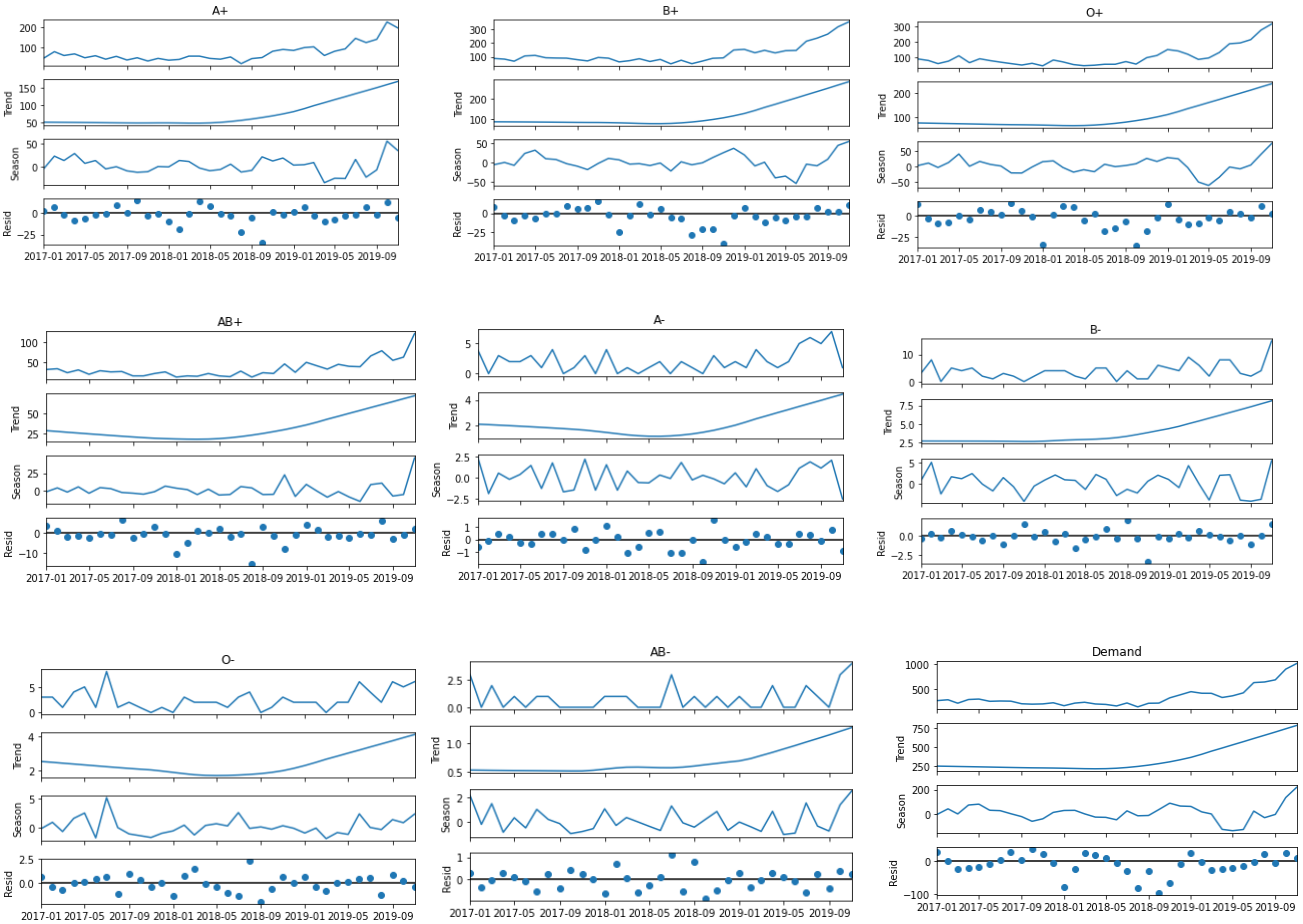


Fig. 1. Time Series Decomposition of Demand of Different Blood Types

Stationarity Analysis

The stationarity of the time-series data is checked by performing Augmented Dicky Fuller (ADF) test. Table II represents the ADF test results for the studied time series. From the presented result in Table 2, it is observed, the total demand for PRBC, demand for blood group A+, B+, O+, Ab+, A-, and B- is non-stationary, and the demand for PRBC of the blood group O-, and AB- is stationary in nature.

Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF)

As autocorrelation is the key statistic for time series analysis, ACF and PACF for the data are plotted to determine the correlation between different time periods [10]. Figure 2a-2j displays ACF and PACF of select time series. It is observed that for all the time series, the demand of one time period depends upon the immediately preceding time period.

Table 2: ADF Test Results

	Test Statistic	**Critical Value at 1%**	**Decision**
PRBC	2.005	-3.67	Non-stationary
A+	1.036	-3.71	Non-stationary
B+	1.646	-3.63	Non-stationary
O+	0.093	-3.63	Non-stationary
AB+	2.97	-3.65	Non-stationary
A-	-1.656	-3.63	Non-stationary
B-	-0.849	-3.66	Non-stationary
O-	-4.5	-3.63	Stationary
AB-	-6.323	-3.53	Stationary

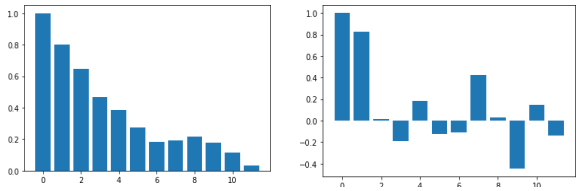


Fig 2a. ACF and PACF of Demand for PRBC for A+ Blood Type

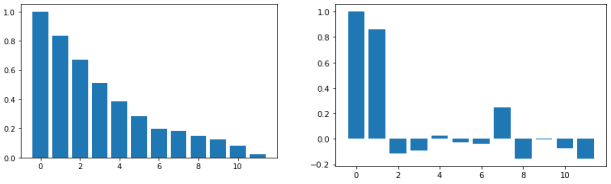


Fig 2b. ACF and PACF of Demand for PRBC for B+ Blood Type

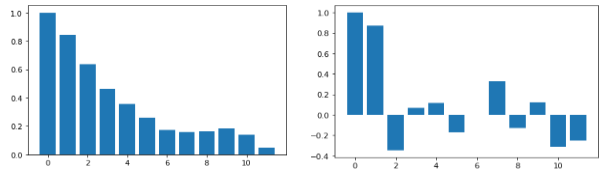


Fig 2c. ACF and PACF of Demand for PRBC for O+ Blood Type

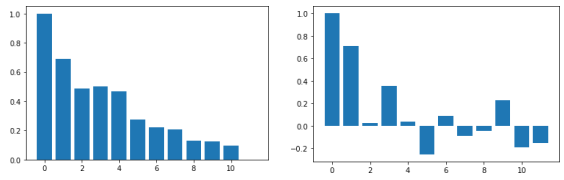


Fig 2d. ACF and PACF of Demand for PRBC for AB+ Blood Type

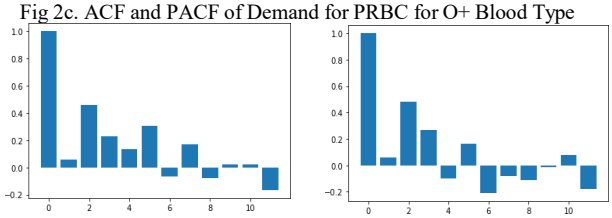


Fig 2e. ACF and PACF of Demand for PRBC for A- Blood Type Type

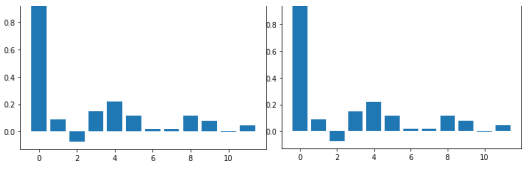


Fig 2f. ACF and PACF of Demand for PRBC for B- Blood

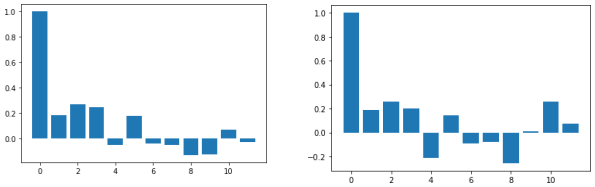


Fig 2g. ACF and PACF of Demand for PRBC for O- Blood Type

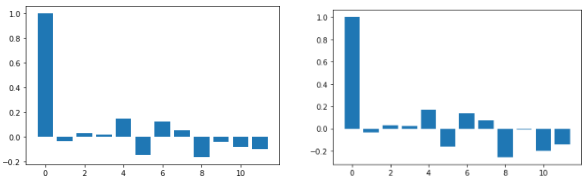


Fig 2h. ACF and PACF of Demand for PRBC for AB- Blood Type

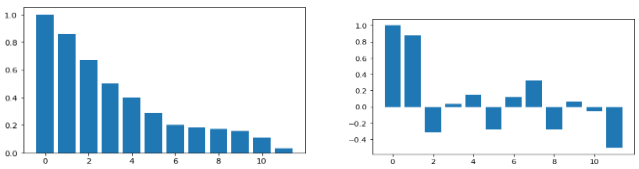


Fig 2j. ACF and PACF of Total Demand for PRBC

Evaluating Forecasting Models

After analyzing the time-series data for the demand of total PRBC and all the blood groups individually, four forecasting techniques i.e. Exponential Smoothing (ES), Winter's method (WM), Seasonal Auto-Regressive Integrated Moving Average (SARIMA), and Seasonal- Trend decomposition using LOESS and Auto-Regressive Integrated Moving Average (STL+ARIMA) are applied to the data. While applying SARIMA for forecasting, the grid search algorithm is used to determine the best model with minimum Akaike's Information Criterion (AIC). In order to forecast the demand of PRBC over a continuous period of time, the rolling horizon method is applied to all the techniques. Data for 24 months is selected as training data, and the models are validated by using the data from 12 months. Errors of the forecasting models are compared by calculating Root Mean Squared Error (RMSE). Python 3 is used to incorporate all the models. Table 3 displays the RMSE of all the applied forecasting models on the time series data for the demand of PRBC.

Table 3: Accuracy Measure (RMSE) for Forecasting Models

	ES	WM	SARIMA	STL+ARIMA
PRBC	107.67	151.63	113.4	178.63
A+	35.07	52.63	39.96	43.68
B+	32.6	70.17	38.4	67.01
O+	37.11	56.37	41.01	58.39
AB+	23.42	22.25	21.22	22.46
A-	2.97	3.25	3.52	3.39
B-	5.12	4.89	4.69	4.65
O-	1.96	2.66	2.99	2.94
B-	1.66	1.6	1.66	1.53

RESULTS

After analyzing the time series data for the demand for PRBC for different blood groups, several forecasting models were applied. It is found that despite using complex forecasting methods, the ES model is able to incorporate the uncertainty and forecast the demand most accurately for all the time series except for the demand of blood group AB-, B-, and AB-. In ES models, it is observed in Fig 3 that the value of the smoothing coefficient is closer to 1 which indicates that substantial adjustment of the forecasting error of the previous period is necessary. Table 4 indicates the best models with relevant parameters for forecasting the demand of PRBC of different blood groups.

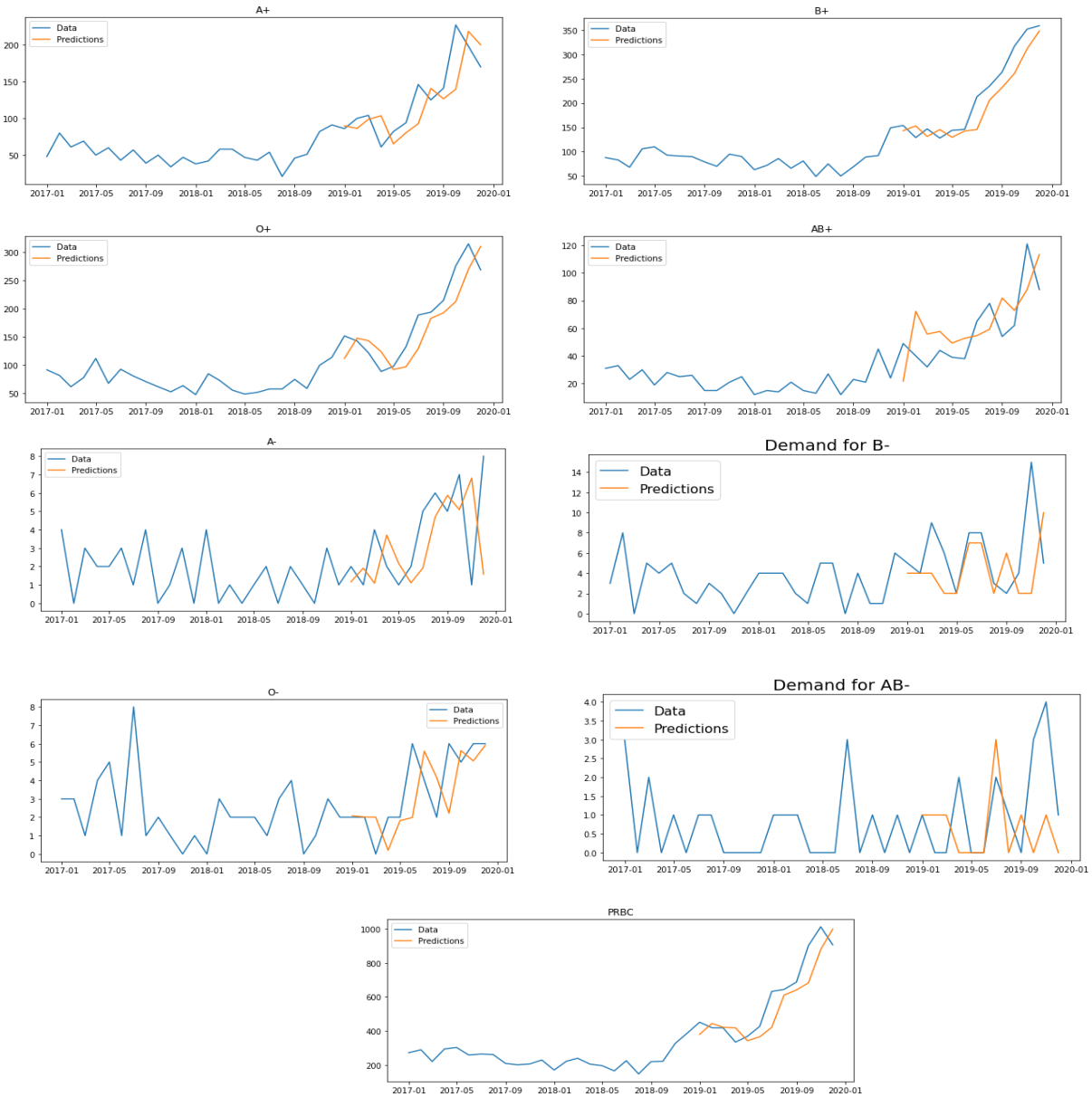


Fig 3. Forecasting Model Fitted to Demand of PRBC of Different Blood Types

Table 4: Best Forecasting Model for Demand of PRBC

Blood Type	Best Model	Parameters
PRBC	Exponential Smoothing	Smoothing constant α = 0.9
A+	Exponential Smoothing	Smoothing constant α = 0.9
B+	Exponential Smoothing	Smoothing constant α = 0.9
O+	Exponential Smoothing	Smoothing constant α = 0.9
AB+	SARIMA	Best Parameter (0, 1, 1)x(0, 1, 1, 12)
A-	Exponential Smoothing	Smoothing constant α = 0.9
B-	STL + ARIMA	Best Parameter (2, 1, 1)
O-	Exponential Smoothing	Smoothing constant α = 0.9
AB-	STL + ARIMA	Best Parameter (1, 1, 1)

CONCLUSION

The uncertain demand pattern of blood poses significant challenge in blood banking system. Blood is a critical resource for any medical system, a continuous supply of safe blood is necessary at any time. In the context of advancing toward net zero healthcare, reducing wastage, optimizing energy use, and improving operational efficiency are key priorities. This paper presents a comparative study of forecasting models to forecast the demand for PRBC. It is identified that despite using complex forecasting techniques, Exponential Smoothing model with a high smoothing coefficient performs the best. An accurate forecast of the demand for PRBC will help the blood bank management official to plan the number of blood collection drives to conduct and the number of donors needed for the next time period so that a proper level of inventory is maintained. By aligning collection and storage more closely with actual demand, unnecessary overcollection and wastage of blood units can be minimized. This reduction in wastage directly decreases the energy consumption and carbon emissions associated with refrigeration, testing, and disposal processes. In case of shortage in blood collection, with the knowledge of future demand, blood bank officials may incorporate replacement donations from the friends and family of a blood recipient and adjust the issuing policy accordingly. In conclusion, integrating data analytics-based forecasting into blood bank operations not only strengthens decision-making and supply reliability but also represents a step toward achieving net zero in healthcare systems through smarter, data-driven, and sustainable resource management.

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FROM LOOP TO PARTNGRSHIP: A FRAMGWORK FIOR UNDGRSTANDING THG EVOLVING PARADIGMS OFI HUMAN- AI COLLABORATION

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ABSTRACT

The term 'Human-in-the-Loop' (HIL), once a clarifying concept for AI systems reliant on human input, now obscures more than it reveals. Its monolithic application to a vast and expanding range of human-AI interactions has led to a conceptual fragmentation that impedes scientific progress and responsible systems' development. This research confronts this ambiguity by proposing a new, tripartite framework that offers a more granular and robust typology for understanding human-AI collaboration. This framework is the result of a systematic literature review designed to synthesize a fragmented, interdisciplinary body of research. We first establish a foundational dichotomy based on the locus of control and introduce a tripartite framework consisting of: HIL (AI-led), where AI is autonomous, and humans provide input for improvement (e.g., data labeling for self-driving cars);

AI2L (Human-led), where humans are in control, and AI augments their capabilities (e.g., AI- powered diagnostic tools for doctors); And Hybrid Intelligence (HI), a more advanced paradigm focused on symbiotic, co-creative partnerships between humans and AI, often enabled by generative AI (e.g., generative design, collaborative software engineering).

It demonstrates that the choice of the human-AI collaboration paradigm is strongly influenced by the domain's primary objectives: efficiency for HIL, accountability for AI2L, and creativity/innovation for HI. It also establishes that ethical considerations must move beyond simple human oversight ("human in the loop") to a more robust and systemic approach called "participatory governance," which involves diverse stakeholders throughout the AI's lifecycle to ensure fairness and accountability. This resolves a central paradox in human-AI studies,

re-conceptualizes the landscape of collaboration, and establishes a new foundation for the design and governance of socio-technical systems.

INTRODUCTION:

BEYOND A MONOLITHIC "HUMAN-IN-THE-LOOP" THE PERFORMANCE PARADOX: A FIELD IN CRISIS

While the promise of human-AI collaboration is immense, recent large-scale reviews reveal a startling paradox: on average, these hybrid teams fail to outperform AI acting alone (Malone et al., 2025). A comprehensive review of over 100 experiments found that, on average, human-AI combinations do not outperform the best-performing individual system, whether that is the AI alone or the human alone (Malone et al., 2025). For instance, in tasks like detecting fake hotel reviews, AI alone was more accurate than the human-AI combination (Malone et al., 2025). Our assumptions about synergy may be incorrect, indicating a need for better conceptual frameworks to understand the dynamics of effective collaboration.

The varied conceptualizations of human-AI interaction extend beyond mere semantics, indicating a pivotal paradigm shift within computing. Initially, AI emphasized classification and prediction, relegating human involvement to data labeling and verification. This aligns with the foundational Human-in-the-Loop (HIL) paradigm, wherein humans oversee or offer authoritative input to the machine (Arambepola & Munasinghe, 2021; Bastani et al., 2017; Natarajan et al., 2024). Within this framework, the AI produces a distinct, verifiable output (e.g., a "cat" label or a score), and the human's function is to furnish or validate it.

Consequently, the "loop" delineates a direct supervisory relationship.

The emergence of generative artificial intelligence (AI), capable of producing novel and intricate outputs such as text, imagery, and programming code, has revealed new opportunities for collaborative creation and partnership (Rafner et al., 2024). Unlike conventional AI, which primarily yields definitively "correct" or "incorrect" outcomes, generative AI provides initial frameworks suitable for interpretation, refinement, and iterative development. This paradigm shift from classification to generation fundamentally alters the essence of AI's output and, consequently, the human role. Individuals transcend a merely supervisory capacity to become integral collaborators and partners within a constructive process. The continued application of the antiquated term "HIL" (Human-in-the-Loop) to characterize this novel and distinct relationship underlies a conceptual dilemma. The discourse is progressing from an emphasis on feedback loop mechanisms toward a more sophisticated examination of agency, cooperation, and governance (Arambepola & Munasinghe, 2021).

Research Questions

Primary Research Question (PRQ)

Proposed Question:

How can the landscape of human-AI collaboration be re-conceptualized beyond the monolithic and ambiguous 'Human-in-the-Loop' (HIL) paradigm to resolve the field's "performance

paradox" and provide a more granular framework for analyzing, designing, and governing socio- technical systems?

Justification: This central inquiry animates the entire research by addressing a foundational, dual crisis currently arresting the field of human-AI studies. The first is an empirical **"performance paradox"**: the persistent and counterintuitive failure of human-AI teams, on average, to outperform AI acting alone. It argues that this empirical anomaly is a direct symptom of a more profound, more corrosive **conceptual crisis**: the monolithic and ambiguous application of the term 'Human-in-the-Loop' (HIL), which now "obscures more than it reveals". This terminological confusion has precipitated a "conceptual fragmentation that impedes scientific progress and responsible systems development".

Therefore, this research question functions as a strategic intervention. It frames the entire project as a necessary response to this field-defining impasse, mandating the development of a new theoretical apparatus capable of resolving the paradox and providing the analytical precision required to rigorously design, evaluate, and govern the next generation of socio-technical systems.

Secondary Research Questions (SRQs)

The primary question is addressed through a series of more specific, answerable secondary questions that collectively structure the argument.

SRQ1: The Paradigms of Collaboration

Proposed Question: What are the defining characteristics, core principles, and critical distinctions of the primary paradigms of human-AI collaboration—specifically, AI-led supervision (HIL), human-led augmentation (AI-in-the-Loop, or AI2L), and symbiotic co- creation (Hybrid Intelligence)?

Justification: This question erects the theoretical architecture of the entire research. It is the primary mechanism for resolving the field's "conceptual crisis." It requires the systematic deconstruction of the ambiguous 'Human-in-the-Loop' monolith and the subsequent construction of a more precise and powerful typology. The central contribution is this new framework, which is built upon two critical pillars.

First, it establishes the foundational dichotomy between HIL (AI-led, automation-focused) and AI2L (human-led, augmentation-focused)—a distinction mandated by a growing body of scholarship that critiques the misapplication of the HIL term and demands analytical clarity based on the locus of control. Second, it introduces Hybrid Intelligence (HI) as a distinct, synthetic paradigm essential for conceptualizing the symbiotic, co-creative partnerships catalyzed by the advent of generative AI.

The answer to this question is ultimately codified in the comparative framework (Table 1),

which functions as the core analytical engine that the subsequent sections validate against real-world domains and extend into the ethical frontier.

SRQ2: The Paradigm-Domain Fit

Proposed Question: How does the choice of a human-AI collaboration paradigm correlate with the primary value drivers of different application

domains, such as efficiency, accountability, and creativity?

Justification: This question drives the empirical grounding and validation of the entire theoretical apparatus. Having established the distinct collaboration paradigms, testing their utility and explanatory power against real-world phenomena is essential. This question posits and seeks to substantiate the **"paradigm-domain fit"** hypothesis—a core proposition asserting that the selection of a collaborative model is not arbitrary but is instead strongly predicted by a domain's fundamental value drivers.

To answer this, the research marshals' evidence from a cross-domain analysis, hypothesizing that high-stakes domains like healthcare and finance, which are governed by the imperative of **accountability**, will gravitate towards the human-led **AI2L** paradigm. Conversely, domains driven by the relentless pursuit of scale and **efficiency**, such as social media content moderation and autonomous systems development, will necessarily rely on the AI-led **HIL** model. Finally, it predicts that fields where the primary currency is **creativity** and novel ideation, like generative design and software engineering, are the natural incubators for the symbiotic **HI** paradigm. By answering this question, the research moves beyond theoretical classification to demonstrate the framework's capacity to explain and predict observable patterns of AI adoption across the global economy.

SRQ3: The Evolution of Ethical Oversight

Proposed Question: As human-AI collaboration matures from simple supervision to complex partnership, how must the corresponding ethical framework evolve beyond the simplistic notion of "human in the loop" to ensure robust fairness, accountability, and alignment with societal values?

Justification: This question propels the research into its crucial normative dimension, extending the analysis from the descriptive and explanatory to the prescriptive. It directly confronts the ethical insufficiency of the simplistic "human in the loop" safeguard, which the research argues has devolved into a fragile and often misleading concept. This simplistic backstop can create "collaboration theatre" or "participation washing," providing a veneer of legitimacy without genuine oversight and often designating a "scapegoat-in-the-loop" to bear responsibility for systemic failures.

Answering this question is essential, as it posits that the ethical framework must co-evolve

with the collaborative paradigms. The nature of risk shifts—from biased human input in HIL systems, to automation bias in AI2L, and to diffuse accountability in HI partnerships demands a more sophisticated ethical response than a single, static solution. Ultimately, this inquiry sets the stage for a most forward-looking contribution: the proposal of "Participatory Governance" as a more robust, systemic model that expands the "loop" to include a diverse range of stakeholders in a structured, ongoing process, ensuring that complex AI systems are not only practical but also just and accountable.

Research Objectives

Primary Research Objgctivg

To resolve the conceptual ambiguity surrounding 'Human-in-the-Loop' by developing and substantiating a new tripartite framework for human-AI collaboration (HIL, AI2L, and HI) grounded in a systematic synthesis of interdisciplinary literature.

Justification: This objective is the central pillar of the entire research endeavor, corresponding directly to the Primary Research Question. It encapsulates the principal scholarly contribution: the development and substantiation of a novel analytical framework. This is not merely a classification exercise; it is a direct intervention designed to resolve the "conceptual crisis" and terminological ambiguity that currently plagues the field of human-AI studies. Crucially, the objective specifies the rigorous methodology employed—a systematic synthesis of a fragmented, interdisciplinary body of literature, grounding the new framework in a comprehensive evidence base. By framing the goal in this manner, it positions itself not as a passive review of existing work but as an act of theory-building that furnishes the field with a new, more powerful analytical engine for understanding and shaping human-AI collaboration.

Secondary Research Objectives

The primary objective is achieved by completing several secondary objectives, each aligned with a secondary research question.

Objective 1: To systematically define and differentiate the HIL, AI2L, and HI paradigms based on the locus of control, primary goals, human/AI roles, core challenges, and evaluation metrics, codifying these distinctions in a comparative framework (Table 1).

Justification: This objective operationalizes the first secondary research question and represents the core constructive act. It moves beyond high-level critique to the granular, definitional work required to build the new typology. Systematically dissecting the paradigms across multiple dimensions—from the locus of control to evaluation metrics—provides the intellectual rigor necessary for the framework to be a credible analytical tool. Crucially, this objective culminates in creating Table 1, a key scholarly artifact that codifies the research's central theoretical contribution into a concise, accessible, and citable format for researchers and practitioners alike.

Objective 2: To analyze and provide evidence for the "paradigm-domain fit" hypothesis by examining case studies of human-AI collaboration in domains driven by accountability (e.g., healthcare, finance), efficiency (e.g., content moderation, autonomous systems), and creativity (e.g., generative design, software engineering*)*.

Justification: This objective operationalizes the second secondary research question and empirically grounds the theoretical framework. It moves beyond abstract classification to demonstrate its real-world explanatory and predictive power. This is achieved by testing the central **"paradigm-domain fit"** hypothesis, which posits that

the choice of a collaborative model is not arbitrary but is instead strongly correlated with a domain's primary value drivers. By marshaling evidence from case studies across distinct sectors—linking the imperative of **accountability** to the **AI2L** model in healthcare, the drive for **efficiency** to the **HIL** model in content moderation, and the pursuit of **creativity** to the **HI** model in generative design—this objective validates the framework's utility as a powerful analytical tool for making sense of observable patterns of AI adoption in practice.

Objective 3: To critique the ethical insufficiency of the "human in the loop" safeguard and propose "Participatory Governance" as a more robust, systemic model for ensuring fairness and accountability in complex AI systems.

Justification: This objective operationalizes the third secondary research question and constitutes the normative and ethical centerpiece of the research. It moves the argument from the explanatory to the prescriptive by first launching a necessary critique of the "human in the loop" safeguard, which has proven to be a fragile and often misleading ethical backstop. The research argues this concept frequently devolves into "collaboration theatre" or "participation washing," where the performance of oversight provides a veneer of legitimacy without genuine power redistribution, or worse, creates a "scapegoat-in-the-loop" to absorb liability for systemic failures.

Thesis Statement and Proposed Framework

This research introduces a novel tripartite framework, moving beyond the simplistic 'loop' model to offer a nuanced spectrum of human-AI collaboration, differentiated by agency and goals. We demonstrate that this framework offers the necessary granularity to elucidate the conditions under which human-AI synergy is—and is not—achieved, providing a clear path for future research and system design. Our research proposes a new tripartite framework for analyzing and designing human-AI systems to clarify this evolving landscape. This framework categorizes the spectrum of interaction into three distinct and progressively sophisticated paradigms:

- **The HIL/AI2L Dichotomy:** This fundamental distinction classifies systems by their primary locus of control. **Human-in-the-Loop (HIL)** systems are AI-led and human-supervised, whereas **AI-in-the-Loop (AI2L)** systems are human-led and AI-augmented. Researchers like Natarajan et al. (2024) advocate for this clear analytical lens, moving beyond ambiguity by focusing on decision-making authority.

- **Hybrid Intelligence (HI):** This advanced collaborative paradigm moves beyond a simple control dynamic to emphasize human-AI symbiosis. It centers on mutual learning and the co-creation of solutions by human and AI agents, often facilitated by modern generative AI capabilities (Mayer et al., 2024; Rafner et al., 2024). This signifies a shift towards a more holistic, human-centric view of technology and work

(Mayer et al., 2024).

- **Participatory Governance:** This represents the ethical and practical culmination of the field's maturation. For complex, high-stakes systems, the "loop" must extend beyond the immediate user or developer. It requires including a broad range of stakeholders in a structured, ongoing governance process. Griffen and Owens (2024) argue that this ensures systems are effective but also fair, accountable, and aligned with societal values.

The Foundational Dichotomy: Human-in-the-Loop (HIL) versus AI-in-the-Loop (AI2L)

We propose a fundamental distinction rooted in the locus of control to address the current terminological confusion in the field. We identify two primary paradigms: the AI-led, automation-centric **Human-in-the-Loop (HIL)** and the human-led, augmentation-focused **AI- in-the-Loop (AI2L)** (Natarajan et al., 2024). A thorough review of existing literature indicates that the broad term "Human-in-the-Loop" often merges these two distinct modes of interaction (Natarajan et al., 2024). As Natarajan et al. (2024) contend, numerous systems currently labeled as HIL are, in reality, misclassified and more precisely fit the description of AI2L. Recognizing this distinction carries significant ramifications for system design, evaluation, and ethical considerations.

The Human-in-the-Loop (HIL) Paradigm: AI-Led Automation

In the Human-in-the-Loop (HIL) paradigm, the AI system maintains control over the primary process and retains decision-making authority (Natarajan et al., 2024). While fundamentally autonomous, the system strategically incorporates human input for specific tasks. These tasks include error correction, performance supervision, and addressing edge cases outside the AI's operational confidence (Bastani et al., 2017; Natarajan et al., 2024). The primary goal of HIL is to improve the AI model itself—to enhance its accuracy, robustness, and scope of automation by leveraging human intelligence as a refinement tool (Singhal et al., 2023).

In this model, the human plays a specific, often circumscribed, role as an "oracle," a "supervisor," or a "teacher" for the AI (Bastani et al., 2017; Natarajan et al., 2024). This includes the canonical task of data annotation, where humans label vast datasets to train supervised learning models, a process that is often the most significant bottleneck in deploying machine learning systems (Arambepola & Munasinghe, 2021; Savage, 2023). It also encompasses providing evaluative feedback on model outputs and directly correcting model errors to fine-tune performance (Natarajan et al., 2024; Singhal et al., 2023). The focus is squarely on making AI-led automation more effective, with the human inputs used to "guide" the model to a better optimum (Natarajan et al., 2024).

The Human-in-the-Loop (HIL) paradigm is commonly applied in areas demanding large-scale operations and high efficiency. For instance, in social media content moderation, AI systems independently identify potentially harmful content.

Human moderators then assess flagged items, rendering final decisions on complex or nuanced cases that necessitate profound contextual comprehension (Singhal et al., 2023). Likewise, the creation of autonomous vehicles employs HIL processes, wherein humans annotate vast quantities of sensor data.

This teaches the vehicle's perception systems to identify objects and navigate their environment (Jayapradha et al., 2024). These interactions often occur via crowdsourcing platforms, which transform human contributions into a series of distinct micro-tasks, prioritizing cost-effectiveness and productivity (Amershi et al., 2014; Savage, 2023).

The AI-in-the-Loop (AI2L) Paradigm: Human-Led Augmentation

The AI2L paradigm fundamentally differs, positioning the human expert at the core with complete control and final decision-making power (Natarajan et al., 2024). This system's purpose is not to substitute human abilities but to enhance them, thereby amplifying rather than displacing human capabilities (Natarajan et al., 2024). AI functions as an intelligent assistant, a perception aid, or a sophisticated decision-support tool, providing analyses, summaries, and suggestions to inform human judgment (Natarajan et al., 2024). The primary goal of AI2L is to enhance humans' performance, efficiency, and the quality of their decisions. The focus is on empowering the human user, with the overall system supporting a human-led workflow (Natarajan et al., 2024).

AI2L systems are prevalent in high-stakes professional domains where accountability and expert judgment are paramount (Natarajan et al., 2024). In healthcare, AI-powered clinical decision support systems (CDSS) analyze medical images or patient data to highlight potential areas of concern, but the human physician makes the final diagnosis and determines the course of treatment (Arambepola & Munasinghe, 2021; Kumar et al., 2024). In finance, an AI model might recommend portfolio adjustments based on market analysis, but the human trader provides feedback, incorporates their strategic knowledge, and executes the final trades (Arambepola & Munasinghe, 2021). Other examples include interactive tools that use AI to surface distant but relevant scientific papers to augment the creativity of a researcher, or systems that help software developers by suggesting code completions or identifying potential bugs, while the developer retains control over the final codebase (Kang et al., 2022; Medepalli, 2025).

A Comparative Framework of HIL and AI2L Paradigms

Table 1 provides a comparative summary of the HIL and AI2L paradigms across several key dimensions to codify this foundational distinction. This framework distills the complex and emerging discourse in the literature into a clear, concise, and citable format, making the research's central theoretical contribution immediately apparent and providing an accessible analytical tool for researchers and practitioners.

Table 1: A Comparative Framework of HIL and AI2L Paradigms, synthesized from Arambepola & Munasinghe (2021), Bastani et al. (2017), Kang et al. (2022), Natarajan et al. (2024), and Singhal et al. (2023).

Dimension	Human-in-the-Loop (HIL) Paradigm	AI-in-the-Loop (AI2L) Paradigm
Locus of Control	AI-Led: The AI system is autonomous and controls the primary process.	Human-Led: The human expert is at the center and retains final decision-making authority.
Primary Goal	Automation: To improve the AI model's performance, accuracy, and robustness.	Augmentation: To enhance the human expert's performance, efficiency, and decision quality.
Human Role	Supervisor/Oracle/Teacher: Provides labels, feedback, and corrections to the AI.	Decision-Maker/User: Uses AI-generated insights as a tool to inform their judgment.
AI Role	Autonomous Agent: Performs the task and requests human input for complex cases.	Intelligent Assistant/Tool: Provides analysis, suggestions, and decision support to humans.
Core Challenge	Human Input Quality: Managing human bias, inconsistency, and the cost/scalability of annotation.	Human-AI Interaction: Designing effective interfaces, ensuring explainability, and mitigating automation bias.

Primary Evaluation Metrics	AI-Centric: Accuracy, precision, recall, and F1-score of the model.	Human-Centric: Quality of final human decision, user trust, cognitive load, task completion time, and overall system outcome.
Example Application	Content moderation on social media; large-scale data annotation for autonomous driving.	Clinical decision support in medicine, creative assistance for scientific research, and portfolio management in finance.

Hybrid Intelligence: A Synthesis for Symbiotic Collaboration

The evolution of collaborative systems does not culminate in the HIL/AI2L distinction. Propelled by the advent of generative AI, a third paradigm is emerging: **Hybrid Intelligence (HI)**. This is not a mere midpoint but a synthetic paradigm that reconceptualizes the human- AI relationship as a symbiotic, co-creative partnership (Mayer et al., 2024; Rafner et al., 2024). In HI systems, human and AI agents are conceptualized as collaborators working on joint tasks, where the goal is to leverage the complementary strengths of each to achieve a level of performance that surpasses what either could accomplish alone (Mayer et al., 2024).

Core Principles of Hybrid Intelligence

Hybrid Intelligence is characterized by a set of core principles that distinguish it from simpler loop-based models:

- **Co-Construction: A Collaborative Genesis of Solutions**

Central to HI collaboration is the process of **co-construction**, wherein both human and AI partners actively and iteratively engage in developing solutions and articulating problem objectives. This is not a unidirectional process of command and execution; rather, it is a dynamic interplay. Humans typically initiate the process by conveying high- level goals, preferences, constraints, and contextual intricacies that an AI might find challenging to infer independently. The AI then employs its computational power, data processing capabilities, and learned models to generate potential solutions, initial drafts, or conceptual pathways. These AI-generated outputs serve as tangible points for discussion and refinement by the human partner. Interaction frequently occurs through natural language communication, facilitating a more intuitive and flexible exchange of ideas. As noted by Dutta et al. (2024), this continuous cycle of human input, AI generation, and subsequent human critique and refinement ensures that the final solution is technically sound and consonant with human values, intentions, and intricate situational understanding. This iterative back-and-forth ensures the collaborative evolution of the solution, integrating the strengths of both intelligences.

- **Mutual Learning and Adaptation: A Bidirectional Growth Trajectory**

Beyond the simple exchange of information, HI collaboration cultivates a profound environment of **mutual learning and adaptation**. This constitutes a bidirectional learning process where both entities evolve their understanding and capabilities. The AI learns from human feedback, which is a critical data source for enhancing its models, comprehending human preferences, identifying biases, and refining its problem-solving strategies. This learning can be explicit, through direct corrections or ratings, or implicit, by observing human modifications to its outputs. Concurrently, humans learn from the AI's insights, including identifying patterns, exploring novel possibilities, or processing vast quantities of information beyond human cognitive capacity. AI can present alternative perspectives or efficient solutions to humans that might not have occurred,

thereby expanding their mental models and refining their workflows. This "hybrid collaborative learning cycle," as highlighted by Wiethof & Bittner (2022) and Rafner et al. (2024), leads to continuous improvement in both individual and collective performance. It fosters a shared understanding of the task, the solution space, and each other's capabilities, particularly in systems meticulously engineered to augment rather than supplant human-AI interaction. This continuous feedback loop propels an evolving partnership wherein each learns to leverage the other's strengths more effectively.

- **Shared and Dynamic Agency: Fluid Control for Adaptive Performance**

A distinguishing characteristic of effective HI collaboration is **shared and dynamic agency**. In contrast to traditional human-computer systems, where control is often fixed (e.g., the human user explicitly commands the software), HI systems demonstrate a fluid and dynamically allocated control distribution. This implies that leadership over specific sub-tasks can transition between the human and the AI based on the nature of the task, the requisite expertise, and the evolving demands of the situation. For instance, an AI might assume leadership in computationally intensive sub-tasks such as generating extensive code, executing complex simulations, analyzing extensive datasets, or predicting outcomes based on patterns. Conversely, humans consistently retain primary agency and control over strategic direction, the definition of creative objectives, the exercise of ethical judgment, the application of nuanced contextual understanding, and the final evaluation and decision-making. As Mayer et al. (2024) articulated, this flexible sharing of control enables the human-AI team to be highly adaptive, responding efficiently to evolving task demands and unforeseen challenges. This dynamic agency ensures that the strengths of human intuition, creativity, and ethical reasoning, as well as AI's speed, precision, and data processing power, are optimally leveraged throughout the collaborative process, leading to more robust and comprehensive outcomes.

Framgworks and Modgls fior Opgrationalizing HI

Several key frameworks illuminate the evolution of human-AI (HI) collaboration. These frameworks shift the focus from theoretical concepts to actionable design paradigms, emphasizing the creation of systems engineered for deep, symbiotic partnerships with humans.

The Hybrid Intelligence Technology Acceptance Model (HI-TAM)

This model addresses the psychological and practical barriers to HI system adoption, particularly in creative fields where professionals may be apprehensive about AI. HI-TAM posits that successful adoption hinges on two critical elements:

- **Programmable Common Language:** The development of a clear communication channel enabling human experts to convey their goals and constraints to the AI.
- **Human-Centered Continual Training Loop:** The seamless integration of AI training into the expert's natural workflow.

By framing AI as a customizable personal assistant, this approach cultivates a sense of partnership and psychological safety, thereby increasing the expert's willingness to engage with and improve the system (Rafner et al., 2024).

Work System Theory Perspective

This socio-technical approach examines the HI system implementation from an organizational viewpoint. It distinguishes between the roles of the "technical implementer" (AI developer) and the "organizational implementer" (integrator into workflows). This perspective maps challenges and best practices throughout the system's lifecycle, from design to execution and maintenance (Mayer et al., 2024). It underscores that successful HI is not solely a technical endeavor but also an organizational challenge, necessitating careful consideration of workflows, roles, and change management (Mayer et al., 2024).

Thg Homoggnization Risk: A Countgrpoint to thg Crgativg Promisg ofi HI

While promising for enhancing creativity, the paradigm of human-AI (HI) collaboration carries a significant, often overlooked risk: cognitive and cultural homogenization (Agarwal et al., 2024; Rettberg, 2024). A concerning paradox emerges from recent research, indicating that the collective interaction of millions of users with the same foundational generative AI models can result in a convergence of ideas, styles, and solutions (Agarwal et al., 2024; Kumar et al., 2024). Users often face a dilemma: expend effort to articulate unique preferences or readily accept a "good enough" AI-generated output. Rationally, they may gravitate towards the latter (Noy & Zhang, 2023). This can create a "homogenization death spiral": AI-generated content floods the internet, and becomes the training data for the next generation of AI, which in turn produces even more homogenized output, reinforcing mainstream perspectives and marginalizing unique ones (Rettberg, 2024).

A Cross-Domain Analysis ofi Human-AI Collaboration in Practicg

Our framework reveals a powerful explanatory pattern: a precise "paradigm-domain fit" where a domain's primary value driver—efficiency, accountability, or creativity—strongly predicts the dominant human-AI interaction model. An analysis across various sectors demonstrates that the choice of interaction paradigm is not arbitrary but strongly correlated with a given domain's core objectives and constraints. This suggests that as AI becomes more deeply integrated into the economy, we will see an increasing specialization of these interaction paradigms based on industry-specific requirements. This observed 'paradigm- domain fit' provides a strong basis for empirical validation, suggesting that the framework can be used for explanation and prediction, a direction we explore further in our research agenda.

Thg Insufifiicigncy ofi thg "Loop" as an Ethical Safigguard: Collaboration Thgatrg

The notion that human oversight inherently confers ethical legitimacy upon an AI system is a dangerously simplistic assumption. In practice, the "human in the

loop" is often a single individual—a clinician, a content moderator, a manager—who may have a limited understanding of the AI's inner workings, insufficient time to investigate its outputs thoroughly, and their own set of cognitive biases (Griffen & Owens, 2024). This approach can lead to a "scapegoat-in-the-loop" scenario, where the human operator is held responsible for system failures, while the underlying systemic issues in the AI model, its training data, or its organizational deployment go unaddressed (Salloch & Eriksen, 2024).

Furthermore, recent experimental findings suggest that in some cases, the "human-in-the- loop" does not improve decision accuracy but primarily serves to **increase the user's willingness to accept the algorithm's recommendation** (Sele & Chugunova, 2023). One study found that while adding a human monitor increased the uptake of an automated decision support system, it actually *decreased* the quality of the final decisions because humans struggled to appropriately adjust the AI's recommendations, especially the most inaccurate ones (Sele & Chugunova, 2023). This points to the possibility of **"collaboration theatre"**: a performance of oversight that provides psychological comfort and a veneer of legitimacy, making users and organizations more likely to adopt and trust an automated system, even at the cost of accuracy (Rosso, 2024). This "illusion of collaboration" suggests that some systems are designed not for better performance, but for better adoption, using the human's presence as a tool for legitimation rather than for genuine oversight (Jang, 2024).

A Maturity Modgl ofi Human Involvgmgnt in AI Systgms

The technological, interactive, and ethical evolutions discussed throughout this research can be synthesized into a single, cohesive maturity model. This model, visualized in Table 2, provides a narrative arc for the field, offering a clear framework for practitioners and researchers to assess the sophistication of current systems and to guide the design of future

human-AI collaborations. It serves as a diagnostic tool and a conceptual map, linking the paradigms to their corresponding goals, ethical challenges, and mitigation strategies.

Table 2: A Maturity Model of Human Involvement in AI Systems

Stage of Maturity	Primary Paradigm	The goal of Human Involvemen t	Key Ethical Challenge	Ethical Mitigation Strategy
Stage 1: Automation	Human- out- of-	None (Full Automation	"Black Box" opacity;	Post-hoc audits; Impact assessments

	the-loop	)	Algorithmic bias	
Stage 2: Supervision	Human-in-the- Loop (HIL)	Improve AI model performance and accuracy	Biased human input corrupts the model (Garbage-in, Garbage-out)	Data quality control; Annotator diversity; Structured ethical annotation (Savage, 2023; Wang et al., 2023)
Stage 3: Augmentation	AI-in-the-Loop (AI2L)	Enhance human expert decision-making and efficiency	Human over-reliance and automation bias	Explainable AI (XAI); Human-centric evaluation of the socio- technical system; Interface design for critical thinking (Arambepola & Munasinghe, 2021; Salloch & Eriksen, 2024)
Stage 4: Partnership	Hybrid Intelligence (HI)	Co-create novel solutions and achieve synergistic outcomes	Ambiguity of responsibility and accountability for co-created outputs	Clear protocols for shared agency; Dynamic task allocation frameworks
Stage 5: Governance	Participatory System	Ensure long- term alignment with human values, fairness, and safety	Systemic power imbalances; Lack of stakeholder representation	Formal, multi-stakeholder governance bodies; Procedural justice mechanisms (Griffen & Owens, 2024)

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Discussion: A Rgsgarch Aggnda fior thg Futurg ofi Human-AI Collaboration A Structurgd Rgsgarch Aggnda

This research agenda proposes a framework for understanding the evolving paradigms of human-AI collaboration. Drawing on established theories from teamwork and organizational science, it outlines a lifecycle for human-AI teams, structured around four core concepts: (1) Team Formulation and Coordination, (2) Team Maintenance and Training, (3) Empirical Validation and Evaluation, and (4) Governance and Organizational Integration (Lou et al., 2025). This structure aims to ground future work in existing theoretical understanding.

Tgam Formulation and Coordination

This area concerns the initial design and structuring of the human-AI team, including role allocation and communication protocols.

- **Optimizing Role Specification (HIL, AI2L, HI):** Research is needed on frameworks for allocating roles and responsibilities based on the chosen paradigm. For HIL, this involves optimizing the "supervisor" role to mitigate bias and improve feedback quality. For AI2L, it means designing the "intelligent assistant" to avoid cognitive overload and present information actionably. For HI, this extends to managing dynamic task allocation and shared agency.
- **Developing a "Common Language" for Co-Construction (HI):** How can we develop effective and intuitive "common languages" that allow human experts to communicate complex, domain-specific goals to an AI partner? Research should explore grammar- based methods, visual interfaces, and other modalities for diverse creative and technical domains (Rafner et al., 2024).

Tgam Maintgnancg and Training

This area focuses on the ongoing processes that sustain effective collaboration, including trust-building, learning, and adaptation.

- **Managing Trust and Mitigating Automation Bias (AI2L, HI):** Further research is needed to understand the psychological factors that lead to automation bias and to develop interventions—such as confidence scores, explanations of uncertainty, and interactive training modules—that encourage appropriate reliance on AI suggestions and promote critical thinking (Kumar et al., 2024). For HI systems, this includes fostering psychological safety to encourage adoption by experts who may fear replacement.
- **Optimizing Mutual Learning and Feedback (HIL, HI):** Research is needed on more effective methods for active learning, where the system intelligently queries the human for the most informative labels (Kumar et al., 2024). This includes exploring which types of feedback (e.g., personal-centric vs. community-centric) are most effective at maintaining user engagement and improving model performance. For HI, this extends to studying the bidirectional "hybrid collaborative learning cycle" where both humans and

AI adapt over time (Wiethof & Bittner, 2022).

Empirical Validation and Human-Cgntric Evaluation

A critical direction for future work is the empirical validation of this research framework and the development of robust evaluation methodologies.

- **Developing Human-Centric Evaluation Methods (AI2L, HI):** There is a critical need to develop and validate robust, human-centric methodologies for evaluating the efficacy of the entire socio-technical system, not just the standalone AI model. This requires moving beyond lab-based studies with proxy users to real-world deployments with domain experts and measuring outcomes like decision quality, user trust, and overall system performance (Arambepola & Munasinghe, 2021; Natarajan et al., 2024).
- **Conducting Comparative Case Studies:** Future research should conduct in-depth, comparative case studies to empirically test the framework's "paradigm-domain fit" hypothesis. For example, a study could compare two healthcare systems—one using an AI2L diagnostic tool and another using a more HIL-oriented system—measuring differences in clinical outcomes, workflow efficiency, and practitioner satisfaction. This would provide crucial empirical evidence for the framework's predictive power and practical utility.

Govgrnancg and Organizational Intggration

This area addresses the ethical and structural challenges of embedding human-AI systems into real-world contexts.

- **Designing Scalable Governance Models:** What are practical, scalable, and adaptable models for implementing multi-stakeholder governance in different organizational contexts, from large healthcare systems to technology companies? This includes developing charters, protocols, and decision-making procedures that ensure fairness and accountability (Griffen & Owens, 2024).
- **Facilitating Productive Dialogue:** How can we design processes and tools that effectively manage the power imbalances and epistemic asymmetries between diverse stakeholders? Research is needed on facilitation techniques and collaborative platforms that empower non-experts to contribute meaningfully alongside technical experts (Griffen & Owens, 2024).
- **The Economics and Ethics of Crowd Work (HIL):** Investigating the socio-economic impact of HIL systems on the global workforce of data labelers, with a focus on fair wages, working conditions, and the potential for de-skilling or, conversely, opportunities for new forms of skilled labor (Amershi et al., 2014).

Futurg Controvgrsigs: Bgyond thg Currgnt Aggnda

The research agenda must also anticipate the next wave of fundamental challenges as the field matures. The following controversies are likely to define the future of human-AI collaboration:

- **Cognitive Atrophy vs. Cognitive**

Enhancement: A key irony of automation is that mechanizing routine tasks may deprive users of opportunities to practice their judgment, potentially leading to the deterioration of cognitive faculties (Al-Sibai, 2025). Will deep partnership with AI in the HI paradigm lead to a widespread atrophying of core human cognitive skills, such as critical thinking, as we increasingly offload mental effort (Gerlich, 2025; SFI Health, 2024).

- **The AI Identification Problem:** As AI-generated content becomes indistinguishable from human-created work, reliable identification becomes critical for accountability and trust. However, current AI detection tools are notoriously unreliable, often producing false positives that disproportionately affect non-native English speakers and exhibiting high error rates that render them unusable for high-stakes applications like academic integrity (AI Detectors, 2024; I Digital Strategies, 2024). This raises a crucial governance question: How can we develop a standardized, reliable system to label and categorize distinct AI instances, akin to a software license or serial number, to facilitate identification and ethical oversight? (Gao et al., 2024).
- **The Agency-Performance Trade-Off:** In many high-stakes domains, professionals strongly desire to retain final human agency over decisions (Mayer & Karny, 2025). Yet, studies increasingly show that this does not always lead to the best performance, and in some cases, human intervention can decrease accuracy (Mayer & Karny, 2025; Sele & Chugunova, 2023). How will we navigate this fundamental conflict between the human desire for control and the empirical reality of system performance, especially when lives and livelihoods are at stake? (Watkins, 2025).

Conclusion: From Partnership to Stewardship—Navigating the Cognitive Reshaping of the Hybrid Intelligence Era

The conceptualization of human-AI collaboration has matured significantly from its origins in the simple "Human-in-the-Loop" model. The monolithic application of this term has obscured a rich and diverse reality of interaction, creating ambiguity that hinders both scientific progress and responsible implementation. This research has sought to resolve this ambiguity by proposing a more granular tripartite framework—derived from a systematic literature review—that distinguishes between AI-led supervision (HIL), human-led augmentation (AI2L), and symbiotic partnership (Hybrid Intelligence). This framework, grounded in the locus of control and the primary goal of the interaction, provides a powerful lens for analyzing existing systems and designing future ones.

The future of practical and ethical AI lies not in the relentless pursuit of perfect, human- independent autonomous agents but in the thoughtful and deliberate design of more innovative, more collaborative, and more accountable partnerships between humans and machines (Mayer et al., 2024; Rafner et al., 2024). The research

agenda outlined here underscores that the most pressing challenges are no longer purely algorithmic but are deeply intertwined with human-computer interaction, organizational science, and socio- technical ethics (Kirsten et al., 2025; Natarajan et al., 2024). By embracing this interdisciplinary reality, utilizing more precise conceptual frameworks, and confronting emerging controversies head-on, the research community can better guide the development of AI systems that truly augment human potential and align with our most cherished societal values.

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INTERPROFESSIONAL RELATIONS AMONG INDIAN HEALTHCARE PROFESSIONALS: A STUDY OF THE DOCTOR-NURSE RELATION IN THE CONTEXT OF EMERGING 'NURSE PRACTITIONERS.

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ABSTRACT

This study explores interprofessional relationships amongst doctors and nurses in India around the emergent Nurse Practitioner (NP) role. A mixed-method design was employed to study the phenomenon involving a quantitative survey of 218 respondents with a qualitative interview of 20 stakeholder doctors, nurses, NPs, and healthcare administrators. The quantitative study showed that most respondents had a positive attitude toward collaboration, as most of the respondents believed that NPs would reduce doctors' workload (78.4%), provide care with minimal supervision (67.0%), and improve patient outcomes (79.8%). However, the level at which NPs would make independent decisions was questioned. Role clarity emerged as a contested issue, as 45.0% of the respondents agreed that their roles were clearly defined, while 30.3% disagreed. Further analysis revealed that the more clarity there was in the role, the better the quality of collaboration ($\rho = .550$, $p < .001$). There was a strong relationship between awareness and favorable attitudes ($\rho = .614$, $p < .001$). Moreover, Mann–Whitney U tests showed differences in preparedness for NP integration between doctors and nurses ($p < .001$). Open communication, respect, and clear responsibilities facilitated collaboration, whereas hierarchy dominance, cultural barriers, and training gaps hindered cooperation and acceptance of NP, as revealed by the qualitative findings. Doctors maintained ultimate authority for decision-making, whereas nurses saw the NP role as an opportunity for professional empowerment. Integrated insights indicate optimism regarding the benefits of integrating NPs for patient outcomes and workload reduction. However, unprepared organizations, absent policy support, and entrenched hierarchies will be constraints.

Keywords: Nurse Practitioners, Interprofessional Collaboration, Role Clarity, Indian Healthcare

INTRODUCTION

This study aims to investigate interprofessional relations between doctors and nurses in India, particularly in the context of the emerging nurse practitioner (NP) role. A mixed-methods approach is

used to capture both measurable trends and in-depth stakeholder perspectives.

Quantitative Objectives

- To assess the level of awareness among doctors and nurses about the nurse practitioner role in India.
- To evaluate the attitudes of doctors toward collaborating with nurse practitioners in clinical decision-making.
- To analyze the impact of role clarity on interprofessional collaboration between doctors and nurses.

Qualitative Objectives

- To explore the perceptions of nurse practitioners regarding their professional interactions with doctors.
- To identify key barriers—cultural, institutional, or professional—that affect the implementation of the NP role.
- To understand how doctors and nurses interpret power dynamics and professional boundaries in clinical practice.

RESEARCH QUESTIONS

Based on the stated research objectives, the following research questions have been formulated:

Quantitative Research Questions

- What is the current level of awareness among doctors and nurses regarding the role and responsibilities of nurse practitioners in India? (*Aligned with Quantitative Objective 1*)
- What are the attitudes of doctors toward clinical collaboration with nurse practitioners in terms of diagnosis, treatment, and decision-making? (*Aligned with Quantitative Objective 2*)
- How does perceived role clarity influence the effectiveness of interprofessional collaboration between doctors and nurses. (*Aligned with Quantitative Objective 3*)

Qualitative Research Questions

- How do nurse practitioners perceive their professional relationships and interactions with doctors in Indian healthcare settings? (*Aligned with Qualitative Objective 1*)
- What are the key institutional, cultural, or professional barriers to the implementation and acceptance of the nurse practitioner role in India? (*Aligned with Qualitative Objective 2*)
- How do doctors and nurses interpret and respond to existing power dynamics and role boundaries within their interprofessional interactions? (*Aligned with Qualitative Objective 3*)

Research Hypothesis

- **Alternative Hypothesis (H_{11}):** There is a significant difference in awareness and attitudes toward the nurse practitioner role between doctors and nurses in India.
- **Alternative Hypothesis (H_{12}):** There is a significant relationship between role clarity and the quality of interprofessional collaboration between

doctors and nurses.

- **Alternative Hypothesis (H_{13}):** There is a significant difference in stakeholder readiness to integrate nurse practitioners into various healthcare settings based on professional background or prior experience.

LITERATURE REVIEW

Literature review aims to establish the research context, identify scholarly contributions and limitations, and highlight the research gap that the study seeks to address.

Table 1 Literature Review (Summary)

Topic	Major Contributors	Key Finding / Gap
Historical Doctor– Nurse Relationship (India)	Keddy et al., 1986; Nandi, 1977; Paul & Bhatia, 2016; Sarkar, 2022	Persistent gendered hierarchy and medical dominance; collaboration needs structural/cultural change; systemic pressures erode trust.
Nurse as Care Coordinator (DCC)	Ohri et al., 2022	Nurses bridge doctor–patient communication; gap: LMIC adoption pathways and formalization.
Global Evolution of NP/A PN	Thomas & Rowles, 2023; Schober, 2018; Greenberg, 2010; Savrin, 2009; Savard et al., 2023	Education, role clarity, and autonomy improve outcomes; gaps: uneven regulation, physician protectionism, under-recognized NP value.

Topic	Major Contributors	Key Finding / Gap
Emergence of NP in India	Schober, 2023; Kodi, Sharma & Basu, 2022; Stephen & Vijay, 2019; Nanda & Anilkumar, 2021; Jayapal & Arulappan, 2020	Need acknowledged but acceptance mixed; gaps: regulation, role clarity, mentorship, career paths, inclusivity (gender).
Power Dynamics & Boundaries	Pullon, 2008; Salhani & Coulter, 2009; Olson & Dadich, 2019; Molina-Mula et al., 2018; Farrell et al., 2021	Collaboration hinges on competence/respect; gaps: hierarchical constraints on voice, patient advocacy limited when nurses sidelined.
Institutional & Cultural Barriers	Tang et al., 2013; McInnes et al., 2015; Mengstie et al., 2023; Hall, 2005	Communication/role clarity help; gaps: entrenched cultures, weak leadership/resources, siloed professional identities.
Education & Interprofessional Training	Joshi et al., 2022; Hamilton, 2022	TBL/IPE improve teamwork and political literacy; gap: broader curricular integration, especially in LMICs.
Stakeholder Perspectives on NP Collaboration	Schadewaldt et al., 2013; Burgess & Purkis, 2010; Andrews et al., 2021; Casey et al., 2017	Success requires clear NP scope and respect; gaps: autonomy curtailed by medical norms; inconsistent advanced-role deployment.
Patient/Family Experience	Kilpatrick, Jabbour & Fortin, 2016	NPs enhance communication, continuity, trust; gap: make NP roles visible and seamlessly integrated in teams.

The overall research gap in the Indian context lies in the absence of mixed-methods studies that comprehensively examine perceptions, power dynamics, institutional readiness, and socio-cultural barriers, highlighting the need for India-specific evidence to inform policy and education.

RESEARCH DESIGN

This study employs a mixed-methods approach grounded in a pragmatist philosophy to examine the doctor–nurse relationship in India, with a focus on the Nurse Practitioner (NP) role. Based on structured surveys (conducted with 218 doctors and nurses) that assessed awareness, attitudes, role clarity, and readiness, quantitative data were collected. Insights gathered through semi-structured interviews (20 stakeholders (NPs, doctors, admins, and policymakers) on perceptions, power play, and institutional barriers (qualitative). The survey was pilot-tested

and divided into four sections; the interviews followed an open guide. The information was collected over a two-month period through both online and face-to-face methods, with consent. Analysis included statistics like frequency analysis, correlation, and ANOVA with thematic assessment of qualitative responses. The researchers ensured the validity was established through expert opinion and theory-based research. Cronbach's alpha (≥0.7) ensured reliability through member checking. The ethics of anonymity and confidentiality were strictly followed.

Key Findings

Quantitative Findings

High Awareness but Weak Policy Knowledge- Over 80% of respondents were aware of NP roles and education, and 73% knew their clinical responsibilities. However, only 52.8% understood government policies, showing a gap between professional awareness and regulatory knowledge**.**

Positive Attitudes Toward Collaboration-Most respondents supported NP collaboration in diagnosis (72.9%), workload reduction (78.4%), patient care (67%), and improved outcomes (79.8%), though 21.6% remained unsure about NP autonomy.

Mixed Perceptions of Role Clarity- While 45% agreed roles of doctors and NPs are clear, 30.3% disagreed. Lack of clarity was seen as a cause of conflict (84.9%), while clear role assignment was linked to better teamwork (92.7%).

Moderate Institutional Readiness- Only 43.1% felt institutions were ready for NPs, with many neutral or doubtful. Training and cultural support showed mixed responses, but prior exposure improved acceptance (66.6%).

Inferential Findings: Hypothesis Testing

Normality

Table 2 Tests of Normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	Df	Sig.
Awareness	.083	218	.001	.963	218	.000
Attitude	.146	218	.000	.935	218	.000
Role Clarity	.149	218	.000	.949	218	.000
Collaboration Quality	.133	218	.000	.926	218	.000
Readiness	.099	218	.000	.971	218	.000

Table 3 Correlations (Between Awareness & Attitude)

			Awareness	Attitude
Spearman's rho	Awareness	Correlation Coefficient	1.000	.614**
		Sig. (2-tailed)	.	.000
		N	218	218
	Attitude	Correlation Coefficient	.614**	1.000
		Sig. (2-tailed)	.000	.
		N	218	218

**. Correlation is significant at the 0.01 level (2-tailed).

Table 3 Correlations (Between Rale Clarity & Collaboration Quality

			Role Clarity	Collaboration Quality
Spearman's rho	Role Clarity	Correlation Coefficient	1.000	.550**
		Sig. (2-tailed)	.	.000
		N	218	218
	Collaboration Quality	Correlation Coefficient	.550**	1.000
		Sig. (2-tailed)	.000	.
		N	218	218

**. Correlation is significant at the 0.01 level (2-tailed).

Lilliefors Significance Correction

Both the Kolmogorov-Smirnov and the Shapiro-Wilk tests evaluate whether study variables follow a normal distribution. Looking at the table, all p-values are below 0.05. Therefore, all five variables violate normality (they are not normally distributed).

Hypothesis (H_1): There is a significant difference in awareness and attitudes toward the nurse practitioner role between doctors and nurses in India.

The findings support **H_1**, showing a significant relationship between awareness and attitudes toward the NP role ($\rho = .614$, $p < .001$). Higher awareness leads to more positive attitudes, indicating that differences between doctors and nurses in awareness significantly shape their views on NP integration.

The results support **H_2**, confirming a significant positive relationship between role clarity and collaboration quality ($\rho = .550$, $p < .001$). Clearer roles between doctors and nurse practitioners are associated with stronger interprofessional teamwork, highlighting role clarity as a key factor in improving collaboration.

Hypothesis (H_2): A significant relationship exists between role clarity and the quality of interprofessional collaboration between doctors and nurses.

Hypothesis (H_3): There is a significant difference in stakeholder readiness to integrate nurse practitioners into various healthcare settings based on professional background or prior experience.

Table 4 Mann-Whitney Test

Ranks				
	Profession	N	Mean Rank	Sum of Ranks
Readiness	Doctor	76	71.22	5412.50
	Nurse	142	129.99	18458.50
	Total	218		

Test Statistics	
	Readiness
Mann-Whitney U	2486.500
Wilcoxon W	5412.500
Z	-6.585
Asymp. Sig. (2-tailed)	.000

Grouping Variable: Profession

The Mann–Whitney U test confirms **H_3**, showing a significant difference in readiness to integrate NPs based on profession ($U = 2486.500$, $Z = -6.585$, $p < .001$). Nurses (Mean Rank = 129.99) were more ready than doctors (Mean Rank = 71.22), indicating stronger support among nurses for NP integration. This highlights the need to address doctors' reservations while leveraging nurses' acceptance to ensure smoother adoption across healthcare settings.

Qualitative Findings (Summary from Thematic Analysis)

Collaboration Shaped by Communication and Respect- According to the thematic analysis effective collaboration happened in the presence of open communication, respect, and listening. On the other hand, barriers arose because of miscommunication and a lack of freedom to raise concerns.

Role Clarity as the Foundation of Collaboration- The cooperation of various departments was helped by clearly defined responsibilities, job descriptions, and standard operating procedures. Conflicts often arose due to lack of clarity and defined boundaries.

Power Dynamics and Hierarchical Barriers - Whether it be a consultant or HOD, physicians were mostly decision-makers. Nurses' concerns were often ignored or minimized, reflecting deep hierarchies. Obstructionist behavior, an authoritarian attitude and professional prejudice were cited by two.

Competence, Skills, and Training Gaps- Adequate training and professionalism fostering trust and the ability to collaborate on the one hand, but gaps in skills, lack of confidence, and underwhelming training programs undermining NP acceptance on the other.

Operational Pressures and Cultural Barriers- Interprofessional collaboration was strained due to heavy workloads, staff turnover and time pressures. Due to the variety in the hospital, different languages and cultures made matters more complicated.

Barriers to NP Integration - In the healthcare setting, multiple barriers hinder optimal productivity. Weak institutional support, inadequate policies, limited regulations, and financial/resource constraints create systemic challenges. Cultural and professional issues further add to the problem, with overlapping duties and lack of role clarity leading to frequent conflicts. Recognition is another major concern, as many doctors resisted the integration of nurse practitioners, perceiving them as a threat, while the absence of clear career pathways restricted their acceptance.

Integrated Insights

- Both quantitative and qualitative analyses show widespread hope for NP integration in India. Furthermore, there is a strong consensus on NPs' capabilities to improve patient outcomes, reduce burdens and strengthen healthcare.
- However, institutional unreadiness, poor policy acumen and established

hierarchies are major impediments.

- Nurses are always more prepared than doctors whose professional characteristic needs to be considered.
- The success of NP integration depends on clear role definitions, policies, interprofessional education and trainings, and initiatives which contribute to a culture change that reduces hierarchy and enhances collaboration.

IMPLICATIONS

The results have a range of implications for various stakeholders in India's healthcare system.

Policy Makers & Regulators- The development of clear national policy at various levels will define NP role, responsibilities, and scope of practice. Enhance the existing regulatory framework (e.g., NMC, MoHFW) to enable the legal recognition, credentialing and privileging system of NPs. Start campaigns to help people and professionals understand how NP care can help them.

Healthcare Institutions & Administrators Allocate critical resources to develop SOPs, guidelines, collaborative governance structures and more for NP integration. To deal with role clarity, create job descriptions, reporting lines, and conflict resolution. Organize support like mentorship, performance evaluation system, and adequate financial resources for NP programs.

Medical Professionals (Doctors)- Persuade clinicians to see NPs as comrades, not competitors, leading to less ego-based resistance and hierarchy defense. Encouraging joint decision-making models and structured communication (SBAR, clinical huddles) to unite members. It is vital to involve doctors in policy formulation and training design to address their concerns and ensure buy-in.

Nursing Professionals & Nurse Practitioners- Improve clinical skills through training, specialization and continuing professional development. We need to be included in the hospital decision-making and policy forums. Use past exposure and successes NP practice leverage to gain credentials and trust from doctors and patients.

Patients & Communities- Integration of NPs can ensure equitable access to timely, affordable, high quality care in rural and underserved settings. Patient awareness programs need to highlight the competence, autonomy, and outcomes-driven role of NPs to foster confidence and mitigate skepticism. Encourage communities to request collaborative care models whereby physicians and nurse practitioners ensure patient- centred services.

Academia & Training Institutions- Integrate interprofessional education module (IPE) in nursing and medical courses to inculcate team work from training level. NP-specific programs should be expanded using standardized curricula, clinical residency models, and competency-based assessments. Promotion of research and evaluation on the effectiveness of NPs to build local evidence and inform the ongoing enhancement of policy.

RECOMMENDATIONS FOR PRACTICE & FUTURE RESEARCH

Based on the study findings, the following recommendations are proposed to enhance interprofessional collaboration and support the integration of Nurse Practitioners (NPs) in India.

Launch **targeted awareness programs** (seminars, workshops, CME sessions) to improve doctors' and nurses' understanding of NP qualifications, responsibilities, and scope. Develop **public communication campaigns** to increase awareness among patients and communities about NP roles, thereby improving acceptance and trust.

Foster **structured interprofessional training modules** that emphasize mutual respect, communication, and shared decision-making between doctors and NPs.

Create **institutional platforms** (joint ward rounds, collaborative care meetings) where doctors and NPs can engage in real-time teamwork to build confidence and reduce resistance.

Establish **clear role definitions, SOPs, and job descriptions** for NPs and doctors to minimize overlap and prevent conflict.

Incorporate **protocol-driven decision-making frameworks** and escalation guidelines to reduce ambiguity and improve collaboration quality.

Implement **feedback and reporting mechanisms** (e.g., anonymous surveys, interprofessional audits) to continuously assess working relationships.

Provide **conflict-resolution training and mediation systems** to address ego, hierarchy, and communication barriers identified in the study.

Strengthen **policy frameworks and institutional guidelines** to address legal liability, credentialing, and career pathways for NPs.

Promote **organizational change initiatives** (cultural sensitivity training, inclusivity programs) to reduce hierarchical resistance and promote acceptance.

Allocate **financial and human resources** to support NP programs, including training costs, staffing, and infrastructure.

Introduce **interprofessional education (IPE) in medical and nursing curricula** to reduce role stereotyping early in training.

Encourage **shared leadership models** in clinical teams where NPs and doctors participate in collaborative decision-making, reducing dominance and improving equity.

FUTURE STUDY

This study helps understand the awareness, opinion, role clarification, collaboration, and readiness for integrating Nurse Practitioners (NPs) in India. However, there are gaps that future research can fill.

Longitudinal Studies on NP Implementation: Future studies should take on longitudinal designs to check how perceptions, collaboration, and outcomes change after the introduction of NPs into Indian healthcare institutions. This would help to track the real-world performance of NP models over time.

Comparative Multi-Regional Studies: This study involved a limited pool of respondents. Future studies should compare the perceptions of respondents across

diverse locations in India (urban vs rural, private vs public hospitals) to get a bigger picture and understand acceptance and readiness in context.

Patient and Community Perspectives: Future research must involve patients and caregivers as stakeholders in evaluating how NP roles are perceived by and received by the public. The trust and perception are vital for successful NP integration.

Impact Assessment of NP Role on Healthcare Outcomes: Research to measure the impact of NPs on satisfaction, access, clinical outcomes and doctors' workload Should be done in the Indian context. This evidence could strengthen policy advocacy.

Exploring Power Dynamics in Depth: Qualitative studies could further investigate doctor–nurse–NP power relations, resistance, and negotiation of professional boundaries. This work could focus on how hierarchy norms could be reshaped for collaborative working.

Interventional and Policy-Oriented Research: Research that involves interventions and/or can influence policies should evaluate pilot studies of organized interventions (e.g. interprofessional training modules, institutional SOPs of the NP role, credentialing frameworks, etc.) for impact. Results can guide reforms of national policies and nursing education.

Cross-Professional Training and Education Research: Future research should focus on how interprofessional education (IPE) may shape early attitude of medical and nursing students towards NP role. Nurturing Cultural Change in Higher Education Through Embedding NP Concepts

LIMITATIONS OF THE STUDY

- Sample Composition: The sample was taken from doctors and nurses only, thus excluding other important stakeholders such as patients, policymakers and hospital administrators. This may lead to a restricted range of views on NP integration.
- Geographical Scope: The data was collected from few institutions. Most of the respondent institutions were private hospitals. The generalizability of results may be affected by these factors, especially in rural and government hospital settings.
- Self-Reported Data: As responses were based on self-reported perceptions, there is a possibility of social desirability bias, personal attitudes, or institution culture influencing the accuracy of reported awareness and attitudes.
- Cross-Sectional Design: The research used a cross-sectional design in which perceptions were collected at one point in time. As policies and practices change over time, this limits the ability to observe changes in awareness, attitudes, or readiness.
- Limited Measurement of Outcomes: There was very limited measurement of outcomes in study. Researchers measured perceptions only (awareness, attitudes, readiness, role clarity). Measurement of patient outcomes, clinical effectiveness or institutional

efficiencies could have provided stronger evidence of impact of NP integration.

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INFRASTRUCTURE GAPS, CAPITAL FORMATION AND SUSTAINABLE DEVELOPMENT GOAL (SDG) SCORES IN SOUTH ASIA

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ABSTRACT

Infrastructure indicators for South Asia reveal huge gaps in access and usage despite rising investments. Maldives, Sri Lanka have fewer gaps while Pakistan, Afghanistan have the largest gaps. The persisting infrastructure gaps despite stable growth and rising investment does have impact on sustainable growth. The paper analyzes the relationship between Infrastructure investment and sustainable development scores. The panel regression approach with random effects assesses the impact of gross fixed capital formation, government capital expenditure, per capita GDP growth, bank credit allocation and tax revenues on sustainable development scores from 2000 to 2022. The results show that improvements in the sustainable development goal scores are negatively impacted by gross fixed capital formation, bank credit allocation and growth in gross domestic product. However, per capita GDP growth, government capital expenditure and tax revenues creates a positive impact. The demand of infrastructure is expected to increase with urbanisation and GDP growth. Mobilisation of domestic savings into infrastructure investment is still very rigid in Asian countries and at the same time capital market imperfections depressed the return for foreign capital or foreign currency accumulation. Government expenditure remains the key financing option. The study argues for the government's funding of infrastructure provisioning than promoting public-private partnerships.

Keywords: Infrastructure gaps, infrastructure investment, panel regression, SDGs, South Asia.

INTRODUCTION:

Development policies have increasingly focused on achieving enhancing infrastructure provision for achieving the Sustainable Development Agenda 2030 in recent years (Kumar, 2019) (Filho et al, 2022), measured through 169 indicators. The Sustainable Development Goals (SDG) encompasses three important pillars: economy, environment and society, with infrastructure being the core strength of these pillars. SDG 9 focuses on building resilient infrastructure for inclusive and sustainable industrialisation. SDG 11 targets

inclusive, sustainable, safe, and resilient human settlements and cities. Moreover, SDG 5 (Gender Equality), SDG 6 (Clean Water & Sanitation), SDG 7 (Affordable & Clean Energy), and SDG 17 (Partnerships for the Goals), revolve directly around infrastructure availability and adequacy. Lower SDG scores for South Asian Countries reflect upon the infrastructure gaps.

There is an urgent need to step up infrastructure investment of $3.7 trillion (4.1 percent of global annual GDP) between 2017-2035. 54 percent of this investment is required for Asia (IMF, 2020). It has further projected an investment shortfall of $5.5 trillion. The highest investment gaps are for water supply and energy in South Asia, dominated by India and Bangladesh. Infrastructure is a significant determinant for Asian economy's growth but at the same time consistent economic growth created enormous pressure on Asia's transport, energy, and communications infrastructure. Gradually, it becomes the biggest bottleneck for growth, competitiveness, and poverty reduction. Infrastructure[1] is a prerequisite (as an explicit goal and an implicit means) for attaining SDGs. However, infrastructure is highly dependent on investment, or the capital allocated for the infrastructure provisions. Along with infrastructure provisions, per capita availability, accessibility, and affordability of infrastructure services are equally critical for developing regions like South Asia, given the low per capita income levels and incomplete markets. Governments, therefore, are the essential source for infrastructure financing and provisioning (Kumar, 2019) (GI Hub, 2020). Public expenditure to GDP (GE/GDP) ratio is considered as the most suitable proxy for government demand for infrastructure (Aschauer, 1993). So, the countries with a higher ratio of GE/GDP will have a higher demand for infrastructure. With increasing government expenditure and international lending, infrastructure has gradually improved in South Asia. For instance, South Asia has one of the highest irrigated farmland (40 percent of the total cultivated area) in Asia. More than 70 percent of the intra-regional trade takes place through land transport. Similarly, electricity, ports, and railways have experienced phenomenal changes during the last two decades. This has resulted in a considerable rise in agricultural and industrial output and income and consumption levels. Further, expanding schools, hospitals, communication and financial infrastructure have resulted in increased productivity and improved living standards. Expansion of the banking institutions and communication has promoted economic activities and induced innovation and investment in these economies. Digitalization, mobile penetration, and internet connectivity are the recent additions to infrastructural facilities, enabling faster inclusion and higher productivity. Consistent enhancement of infrastructure is visible via increasing

real GDP and business sale revenues. Per capita availability is another indicator for increased investment in infrastructure, such as railways, roads, electricity, commercial and residential buildings, water supply and sanitation. Broadly, production, productivity and living standards are accelerating gradually across South Asian countries. Nevertheless, regional differences are wide due to infrastructure gaps. Therefore, infrastructure is the key determinant for inclusive and stable growth in South Asia.

In the last three decades public and private sector investments have significantly contributed toward infrastructure provision and availability. For instance, infrastructure investment increased from 4.7 per cent to 6.9 per cent of gross domestic product from 1973 to 2009 for South Asia. This increase, though, fluctuated but still managed to register a 47 percent increase. The infrastructure investment was dominated by investments in electricity and transport-related provisions. Consequently, private sector investment crowded in and rose upto 2.34 percent of gross domestic product during 2007-2012 for South Asia. Private sector infrastructure investments were again concentrated in the energy sector, indicating the crowing in effect of public investment as well as commercial and non-commercial energy demand in the South Asian region. The improvement in infrastructure can be explained in two ways. One is the increase in gross value added in real terms and business activities. The second is per capital availability in terms of railways, roads, electricity, houses, commercial and noncommercial buildings, basic amenities and many more. Production, productivity and living standards are broadly accelerating across countries and within. Because of the limited capacity of investment financing in these countries, international SDG funding has gained significance for the region. Given the marginal improvements in SDG indicators in South Asia, international funding agencies are increasing their investment commitments. South Asia needs an additional 11.3 percent of GDP as an investment in infrastructure to move successfully towards the SDG Agenda 2030. The empirical literature survey on the relationship between infrastructure growth and development can be categorized into four different but interrelated dimensions.

Theoretical Framework for infrastructure as exogeneous and endogenous factor:

The provision of infrastructure is regarded critical for development by policymakers as well as academics. There available literature can be classified into three groups. First, the stock of physical infrastructure is explained as the major determinant for growth and productivity. Second, the stock of gross fixed capital formation is considered more significant and a proxy for the stock of physical infrastructure. Third where annual

flows of investment and government capital expenditure is taken as the major determinant for infrastructure. The endogenous growth theory framework is used to explain the relationship between infrastructure and growth (Canning & Pedroni, 2004) (Straub, 2008) (Calderón & Servén, 2014). The simple model is explained as gi=αyi0+βKIi+Ziγ+vi, where g is the per capita real GDP growth of country I, K is the infrastructure stock or investment, Z is the vector of covariates or other explanatory variables and v is the random error term (Straub, 2008). The model used in the other two studies is Yt=At+Ktα+Gtβ+Lt1-α-β where K is the infrastructure capital stock and G is the non-infrastructure capital stock. The researchers have established the long-term significant growth effect but with a reduced welfare effect and less significant short-term effects. In the empirical estimations, all studies have used a large panel data set with 20-30 years of timeframe. It also includes regressors for controlling the infrastructure quantity and quality. GMM estimators are used to account for the endogeneity. The two important results from the studies include a robust impact of stock of infrastructure assets on growth along with a reduction in inequality. extended Barro's Model has been extended to include public and private capital. For infrastructure investment, current consumption is sacrificed for future consumption because public investment takes time to become productive. Moreover, infrastructure development needs both capital and repetitive (current) expenditure, for instance, to build and maintain roads respectively (Tsoukis & Miller, 2003) (Ghosh & Mourmouras, 2004). The above framework has been examined by considering the stock of public capital and the flow of non-investment spending simultaneously. The previous results prevail; the growth maximization level of public investment is greater than the welfare maximizing level of capital expenditure. Stock of infrastructure assets as well as flow of infrastructure expenditure have been alternatively used in the models. It has been established that availability of infrastructure is more closely related to the stock of assets rather than flow of infrastructure related expenditure. For instance, the stock of public highways has a more pronounced relation to road transport (availability of transport infrastructure) in contrast to the effect of annual spending on road construction. Multiple approaches have been employed to assess the impact like cross- country and time-series regression using macroeconomic data to micro-level studies analyzing the effect of infrastructure provision on incomes of the poor of the rural areas. Meta analysis of 123 meta-observations, have been conducted to examine the robustness of the evidence regarding the impact of fiscal policy on growth (Nijkamp & Poot, 2003). Five fiscal policy areas are considered: general government consumption, tax rates, education expenditure, defence, and public infrastructure. Several

meta-analytical techniques are applied, including descriptive statistics, contingency table analysis and rough set analysis. On balance, the evidence for a positive impact of conventional fiscal policy on growth is rather weak, but the commonly identified importance of education and infrastructure is confirmed. These mentioned studies provide an extensive literature review of the available empirical estimations in different settings. Further, use an ordered probit model have been performed for investigating changes in the probability of finding negative, positive, and insignificant impacts (Elburz et al., 2016). The total data base consists of 912 observations from 42 studies conducted between 1995 and 2014. The meta-analytical results show that study characteristics do matter for the magnitude and sign of the variables concerned. The study finds that type of infrastructure, research methodology, time span, type of infrastructure measure, and geographical scale affect the outcomes of the primary studies. Studies that take into account interregional, interstate and interprovincial relations have a higher chance of finding negative effects, which gives an idea about the spillover effects of these investments. In contrast, some characteristics like output measure and selection of a particular sector appear to have no effect on obtaining positive, negative or insignificant outcomes. The findings of this study offer new insights to policy makers on the variation in empirical results regarding the relationship between public investment infrastructure and regional growth.

Infrastructure, government expenditure and inequality:

There have been attempts to assess the impact of public investment on inequality. Income inequality proves to be an obstruction in growth, and enhanced provision of productive public services contributes to growth. If these services are provisioned in a heterogenous fashion across individual households then it influences the income distribution further, impacting growth positively indirectly. Due to lesser access to private alternatives, provision of public infrastructure is more advantageous to the poor. Private sector participation in infrastructure not only impacts employment status, but also affects public revenues and expenditures. It tends to abolish the subsidies provided to infrastructure services and generation of revenues. Thereafter, the impact on inequality depends on management of increased fiscal resources. If the enhanced fiscal space is utilized in bringing about an improvement in the efficiency and coverage of public service provision, be it infrastructure or non-infrastructure then income inequality might decline. It has also been argued that elimination of subsidies on infrastructure utilisation might lead to higher prices with the increased participation of the private sector, these providers may charge higher connection fees than public providers, and they may even be sceptical about functioning in poorer

areas (Estache et al., 2002). Therefore, handing over infrastructure services to private sector makes it unaffordable to lower income groups. Although such an outcome depends on the complete design of the reforms and private participation might also lead to enhanced access by the poor (Calderon & Servén, 2014). According to an estimate by World Economic Forum, about 14% of GDP is invested in infrastructure, even then with rising world population, increased pace of urbanization and development and emergence of outdated infrastructure, this level of investment is not enough (WEF, 2020) (WEF, 2022). This rate of investment is going to exacerbate the gap between projected infrastructure spending and the actual amount of investment required to suffice the infrastructure needs of the world. The estimated gap would be reaching the figures of $15 trillion by 2040.

Infrastructure investments generate either positive or negative externalities or even both and it depends on the affected party. This makes exclusion of the non-payers difficult. Not only this, the determination of a single price which showcases the economic effects of the service provided becomes tough. Also, there is difficulty in collection of payments that are proportional to the usage of services. These features prove that infrastructure services have properties of public goods and therefore these are required to be provided by the public sector. These services turn out to be advantageous to the poor and therefore generates positive externalities and strengthens the role of public sector. These externalities and the poverty of consumers of the service make operative user fees a distant dream. This necessitates the involvement of public sector, but poor countries lack infrastructure revenue raising capacity and are characterized with less developed financial markets. The public infrastructure policy cannot be assigned a decisive role due to network effects and coverage characteristics. The feature atypical of infrastructure projects such as scale and long-time horizon also point towards involvement of public sector. These features highlight the concerns in financing infrastructure investments and the crucial role of development of well-functioning financial market to support infrastructure investment. Specifically, bond market with long-term bonds in local currency tend to facilitate international financial intermediation by easing risks involved in foreign exchange. Restrained public sector budget outline the importance of crowding in the private sector. This is easier in infrastructure sectors such as telecommunication than in others. Infrastructure is associated with market failures. The construction and operation of infrastructure facilities is associated with significant economies of scale. Larger infrastructure facilities are cheaper on a per unit of output basis than the analogous smaller infrastructural facilities. Also, infrastructure facilities are capital intensive as a massive amount of investment as compared to their annual output and/or to the amount of labour needed for their operation. This capital

intensity generally is responsible for the economies of scale of such facilities. The provision of infrastructure once made, lasts for generations, although this very feature is possessed by several residential and commercial facilities as well. These services tend to serve broad public goals. In some cases, these services are purely public goods and as such are characterized with positive externalities. Therefore, increased number of individuals can be benefitted at a very low or even no additional resource cost. This availing of services by greater number of individuals doesn't contribute to reduction in the benefit expropriated by others. It is not even possible to exclude anyone from availing the benefit of these services (Walter, 2016).

Recent Literature on Infrastructure gaps, efficiency and financing:

The effects of infrastructure development on growth and income distribution has been the recent focus in theoretical literature (Straub, 2008) (Claderon and Servén, 2014) The theoretical literature has employed a variety of analytical settings regarding the drivers of income growth, the degree to which infrastructure represents a public or a private good, and the extent of market distortions, notably in capital markets. In turn, the empirical literature has used various econometric methodologies on time-series and cross-section macro and microeconomic data to test for the effects of infrastructure development. However, these empirical tests face challenging issues of measurement, identification, and heterogeneity. Overall, the literature finds positive effects of infrastructure development on income growth and, more tentatively, on distributive equity. Still, the precise mechanisms through which these effects accrue, and their full impact on welfare, remain relatively unexplored. The positive and negative effects of infrastructure and the interdependencies between infrastructure sectors is another important aspect of investigation (Thacker et.al., 2019). Because infrastructure either directly or indirectly influences the attainment of all of the Sustainable Development Goals (SDGs), including 72% of the targets, policymakers need to establish long-term visions for sustainable national infrastructure systems, informed by the SDGs. Investment in infrastructure is at an all- time high globally, thus an ever-increasing number of decisions are being made now that will lock-in patterns of development for future generations. Although for the developing countries these investments are motivated by the desire to increase economic productivity and employment (IMF, 2020). More importantly, efficiency and productivity impact of public investment on growth conditional upon the infrastructure governance has been emphasized by several authors. Even if the level of public spending is similar, the availability of physical

infrastructure differs because of the efficiency differences of per unit expenditures. Further, with the accumulation of physical infrastructure productivity outcomes can differ because of the quality.

Empirical studies investigating the impact of public expenditure on infrastructure, its adequacy and efficiency is extremely sparse, mainly due to the lack of information on patterns of infrastructure expenditures (Foster et.al., 2023). Using the World Bank's BOOST database (it only includes Afghanistan from South Asia), this study attempts to disaggregate infrastructure spending trends and patterns for a large sample of more than 70 developing countries covering 2010-18. It further explores expenditure by sector for roads as well as electricity, into two categories of operating and capital expenditure. The study finds that on-budget expenditure on infrastructure has been low both in absolute and relative terms, as well as declining over time. There is evidence that low-income countries, despite lower spending envelopes, attach greater priority to public investment and infrastructure spending than their middle-income counterparts. Econometric analysis suggests that infrastructure spending in low- and middle- income countries has been historically procyclical, although to a lesser degree than total expenditure. In the transport sector, road funds are shown to play a substantial role in funding road maintenance, appearing to improve the adequacy of funding, while attenuating pronounced capital biases in road sector spending, but there is little evidence of efficiency improvement over time.

Developing Countries, Asia and Infrastructure Gaps:

A survey of studies on the economics of infrastructure in developing countries highlight huge gaps and investment shortfalls (Stone, 2008). Energy, transport, telecommunications, water and sanitation are considered. The survey covers two main set of issues: the linkages between infrastructure and economic growth (at the economy-wide, regional and sectoral level) and the composition, sequencing and efficiency of alternative infrastructure investments, including the arbitrage between new investments and maintenance expenditures; OPEX and CAPEX, and public versus private investment. Infrastructure provision has been shown to aid in reducing time, improving productivity, reducing inequality and poverty and improving employment prospects. The developing region is characterized with low level growth, dense population, poor performance in education and health parameters. Therefore, to tap the potential of this region there is a requirement to give an impetus for infrastructure investment. The demand of infrastructure is expected to get spurred in this region as majority of the population resides in rural areas, and with passage of time there will be urbanization which in turn would be highlighting the requirement of

increased public expenditure on infrastructure. Infrastructure is significantly related to per capita GDP. The divergence in quality and availability of infrastructure among different countries is responsible for their different levels of productivity. Lack of infrastructure causes productivity inefficiency. It is evident from several instances, as improper facilitation of transport and telecommunication hamper access to markets and interactions with clients thereby increasing input costs, similarly unavailability of proper electricity networks makes investments subject to volatility of voltage and frequent power-cuts, which further force manufacturers to invest in support system like power-generators. Therefore, to tap the potential of this region there is a requirement to give an impetus of infrastructure investment (Straub and Akiko, 2011). The efficacy of transport infrastructure in facilitating economic prosperity stems from Adam Smith's Wealth of Nations. The development of infrastructure enables in easier access of productive opportunities to poor and raises the value of their assets. Their human capital can also be enhanced by improving their health and education parameters with the help of infrastructure provision. Overall, it plays a key role in integration of individuals and households into social and economic life, through the access to infrastructure services like electricity, roads, safe water, and sanitation (World Bank, 2012) (ADB, 2009) (ADB, 2017). Infrastructure development utilized a high share of the fiscal stimulus granted during global crisis of 2007-08, the developing and emerging economies deployed 40% of the stimulus to infrastructure spending, while advanced economies deployed 21% of the package to infrastructure (TEIUL, 2021). During the Covid-19 pandemic, the fiscal stimulus was initially diverted more towards health but gradually shifted back to energy and digitalisation.

South Asian Region faces significant challenges, including uneven economic growth, slow urbanization, rapid population expansion, and severe infrastructure gaps (Biller et al., 2013) (Andrés, et al, 2014) (Biller et al., 2014). Despite high economic growth rates, the region lags in urban development, with many South Asian countries ranking poorly in living standards. Addressing the infrastructure deficit in South Asia requires substantial investments, ranging from 6.6% to 9.9% of the GDP of 2010 annually. However, given limited financial resources, countries in the region must prioritize whether to focus on immediate needs or medium-term goals. They can seek external assistance and consider restructuring their current infrastructure approaches. Assessing the infrastructure deficit involves evaluating the quality and efficiency of existing infrastructure, determining access rates, and establishing targets in line with sustainable development goals. Infrastructure demand is dynamic and varies across South Asian and East

Pacific regions. Access to infrastructure exhibits significant disparities, with some South Asian nations performing well in certain sectors while others lag. Even within countries, there are discrepancies in infrastructure provision among districts. Prioritizing infrastructure investments is crucial, given the limited funding sources. These investments can be categorized as public, private, or public-private partnerships (PPPs). Infrastructure investment in South Asia has varied over time, with fluctuations in sectors like electricity and more stable investments in transport, water, sanitation, and irrigation. India plays a dominant role in infrastructure investment in the region, particularly in the energy sector. Energy, telecom, and transport sectors have attracted substantial private and foreign investment. A set of panel regressions for South Asia reveal that tax financing, concessional lending, or private sector financing through public private partnerships (PPPs) are more advantageous than government borrowing through financial markets because they support growth while containing the impact on public debt (Bizimina et.al., 2021). South Asia needs large infrastructure investments to achieve its development goals, and public investment can also support the Covid-19 recovery. At the same time quantity and quality of investment both needs careful management. Infrastructure investment has a strong (at least 1.5 times greater) multiplier impact on economic growth (Andres, et al 2014). Infrastructure investment can play a key role in supporting economic recovery and stability, however simply investing in infrastructure is insufficient. It needs to be the right kind of infrastructure that has transformative outcomes for the people and the planet (GI Hub, 2020). The recent literature and empirical estimations on infrastructure impact and financing with reference to the SDG goals confirms the positive relationship between the two (Filho et al., 2020) (Filho, et al, 2022). These studies highlight the need to study the region-specific impact of infrastructure investment impact on SDG goals progress in order to assess the future financing needs.

The brief literature review reveals that despite the advocacy of higher public investment for sustainable development goals, there are a smaller number of studies exploring the effect of

fixed investment and government capital expenditure flows on the SDG scores. Moreover, the studies analyzing South Asia have focused more on the poverty and income inequality challenges as compared to infrastructure gaps and infrastructure financing. This paper aims to investigate the impact of gross fixed capital formation (as a proxy of infrastructure investment) on SDG scores for eight South Asian countries. To analyze the impact, the paper first presents a discussion on infrastructure gaps in south Asia and the disparities in terms of selected development indicators. This paper hypothesizes a

positive relationship impact of public investment (gross fixed capital formation and government capital expenditures as proxies for infrastructure investment) on SDG scores for South Asian countries. Further this results in a positive impact of GDP growth and per capita GDP growth on SDG scores. This paper would be an important contribution to the scarce literature available on infrastructure and sustainable development financing gaps in South Asia. Firstly, it presents a status of infrastructure gaps measured through eight important parameters of infrastructure which affect the sustainable development goals excluding climate change and environmental damage. Secondly, It estimates the impact of fixed capital formation and GDP growth on SDG scores for South Asia.

RESEARCH METHODS:

The variables selected for the paper are for two purposes. One, to analyze the development gaps and infrastructure gaps in eight south Asian countries. Second, to estimate the impact of capital formation and GDP growth on sustainable development scores during 2000-2022. Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka. The development gaps are analyzed through three indices, viz, human development index, multidimensional poverty index and sustainable development index. For the first two indices' values have been used while for the third index, composite scores are used. The Human development index (HDI) is a geometric mean-based summary measure of achievement in three major dimensions of human development, viz, per capita gross national income, life expectancy and mean years of schooling. Multidimensional Poverty index (MPI) is related to measurement of deprivations across 12 major indicators based on poverty, education, health and basic amenities. In case of HDI higher values (closer to 1.00) reflect higher level of human development, while in case of MPI lower values (closer to 0.0000) reflects lower poverty. The sustainable development index scores range between 0-100, higher score indicating higher development. The countries included in the SDG ranking are 193 UN member countries. Rankings and scores are inversely related for SDGs. These indicators capture various aspects of development and governance and reveal the standard of living for the countries along with the GDP per capita. Per capita GDP has been taken in current dollars to understand the effect of absolute income differences, while GDP at purchasing power parity reveal relative income differences. Moreover, per capita GDP growth and GDP growth are the two variables that help to understand the responsiveness of economic growth towards development status and living standards in the selected countries.

The infrastructure gaps have been explained by using eight indicators capturing the economic, social,

financial, and digital infrastructure gaps. Gross Fixed capital formation has been used as a proxy for infrastructure investment. This is due to insufficient infrastructure investment data for selected South Asian countries. Bank credit for infrastructure-related activities is also chosen to understand private sector investment. The share of urban population and GDP growth are the two major demand side variables for infrastructure. The major data source is the World Bank open data bank. Energy use per person in kilowatt/hour and Paved Roads (Density) Km/1002 km are representations of economic infrastructure. Safely managed Sanitation, Safely managed Drinking water, and Hospital beds per lakh population is taken as the representation of social infrastructure. Commercial Bank Branches per one lakh adults and the number of ATMs per lakh population are the representation of financial infrastructure. Lastly mobile density per 100 persons and the percentage of the population accessing Internet usage are the representation for digital infrastructure. The relationship between SDG scores (SDG) as a dependent variable and selected independent variables has been estimated by using the Panel regression approach. The independent variables are real GDP growth (GDPGR), per capita GDP growth (PCGDPGR), government capital expenditure (GCapex), gross fixed capital formation (LnGFCF) in constant $, rate of urbanisation (Urban) gross fixed capital formation as percent of GDP (GFCF/GDP) and Tax revenue as percent of GDP (Tax/GDP). log values of the variables are taken for the estimations. All the selected independent variables are found to be stationary at the first difference. The following Panel regression has been estimated in the paper:

$$SDG\ Score_{it} = GDPGR_{it} + PCGDPGR_{it} + GCapex_{it} + GFCF_{it} + Urban_{it} + GFCF/GDP_{it} + Tax/GDP_{it} + e_{it}.$$

e represents the error term. 'i' indicates the country and t indicates the time.

RESULTS:

South Asia is one of the regions with huge development gaps and the highest infrastructure gaps (UNESCAP, 2019) (TEIUL, 2019) (Asadullah et al., 2020). Moreover, rapid urbanization and migration have created a lot of pressure on the existing infrastructure leading to a decline in the quality of available infrastructure. In the last three decades, absolute poverty has been declining, and per capita income is rising along with per capita consumption across major categories, such as food, non-food, and services. However, development gaps in South Asia are visible through the rankings of the Human Development Index (HDI), Multi-dimensional Poverty Index (MPI) and Sustainable Development Goals (SDG) rankings. Two important observations in the case of South Asian countries are noteworthy. First, there is a similar pattern of human development index values and GDP growth. Second,

the increasing disparities in terms of gross fixed capital formation (the primary proxy variable for Infrastructure investment) and multidimensional poverty. The empirical evidence is increasingly indicating dissatisfactory quality and efficiency in the expanding infrastructure provisions in South Asia (UNESCAP, 2023). Figure 1 shows the growth in real GDP and gross fixed capital formation. Both values are expressed at constant prices. The growth rates are shown on the left Y axis. The right y axis presents the gross fixed capital formation as ratio to gross domestic product. In 2007 this ratio reached the highest level of 33.7 percent and gradually declined to 26.52 in 2019. Movements in gross fixed capital formation have been more volatile compared to GDP growth. The GDP growth ranged between two to 7 percent whereas gross fixed capital formation varied between
-13 percent to 25.81 percent but largely they are positively correlated. Volatile fixed investment, as a proxy for infrastructure investment, has its implications for larger infrastructure gaps in South Asia (Andres et al, 2014b).

Table-1 & 2 exhibits the pattern of development and infrastructure gaps in South Asia. Sri Lanka and Maldives have achieved the human Development index value higher than the Asia average. Maldives due to the higher income levels and Sri Lanka due to higher levels of educational attainments and life expectancy rates. Then Bhutan, Bangladesh, India, and Nepal remain below the Asia average with wide inter-country and intra-country differences. Maldives in South Asia is an exceptional case with low development gaps and low infrastructure gaps because tourism is the engine of growth creating all positive externalities for development and infrastructure. However, in the last 10 years, the country has had a higher burden of child mortality, malnutrition, debt liabilities, inflation, and corruption. Sri Lanka is the second country in the South Asian region with the lowest levels of deprivation and development gaps again mainly due to the second highest per capita income levels. Since the onset of the COVID-19 pandemic crisis, Nepal, India, and Sri Lanka have experienced a gradual increase in multidimensional poverty mainly because of increasing malnutrition, and decreasing availability of housing, water, sanitation and cooking fuel. For these three countries, macroeconomic stability challenges act as a compromising factor for the development agenda. The biggest challenge for Bhutan and Bangladesh in terms of multidimensional poverty is the years of schooling and housing. Pakistan and Afghanistan have the highest poverty in terms of malnutrition, schooling, and housing. however, there is an emphasis on the shift in poverty gravity center from South Asia to Africa, but the challenges have increased (Luo and Xu, 2018) (Kumar, 2019) (Cheraghlou et al, 2024). The need for a resilient and sustainable povertyreduction is

propagated because of the growth shocks as well as intra-country risks

Table1
Development gaps in South Asia

Countries/ Regions	HDI in 2021	Population Density per sq km	GDP per capita in current $	Per capita GDP in PPP $	Per capita GDP in PPP $	Per capita GDP growth
Afghanistan	0.478	0.272 63.06	390	1673.96	-22.9	na
Bangladesh	0.661	0.101 1315.1	2820	6958.82	6.0	7.19
Bhutan	0.666	-- 20.52	3040	12036.36	3.4	4.08
India	0.633	0.069 476.65	2380	7873.53	6.3	7.00
Maldives	0.747	0.003 1745.99	11030	22739.18	11.8	41.75
Nepal	0.602	0.074 213.1	1340	4488.71	3.8	5.61
Pakistan	0.544	0.198 305.92	1580	6105.31	4.2	6.19
Sri Lanka	0.782	0.011 352.93	3610	11405.42	-7.9	-7.82
Asia	0.749	0.091 150.30	9952.2	18818.8	3.1	na

	Mobile density per 100	Energy use per person kw/hour	Safely managed Sanitation	Safely managed Drinking water	Paved Roads (Density) Km/100^2 km	Banks Branch per 1lakh adults	Hospital Beds per 10000	Internet usage
AFG	57	677	56	30	51 (5)	1.9	3.9	na
BANG	105	2912	59 (31)	59	30 (250)	9	7.95	6.10
BHT	95	27785	78 (51)	73	62	20.9	17.4	0.41
IND	81	7143	78 (51)	na	67 (204)	14.6	5.3	1.66
MALD	137	17669	100	na	na	13.8	na	11.78
NPL	127	1608	80 (52)	16	31 (54)	22.3	3	4.35
PAK	82	4243	71	51	70 (30)	10.4	6.3	1.14
SLK	143	4348	95	47	15 (174)	17.4	41.5	8.31
South Asia	83.82	565.32	75.46	93.08	na	14.58	0.58	2.75
East Asia	129.81	2124.82	93.53	96.54	na	9.65	4.51	31.75
World	108.02	1905.85	80.6	91.15	na	11.18	2.88	18.42

Table: 3 Panel Regression Results for SDG Score determinants in South Asia

Independent Variables	Coefficient	Std. Error	t-stats
C	3.440978*	0.109912	31.30666
GDPGR	-0.066746**	0.035798	-1.864493
PCGDPGR	0.062055*	0.023243	2.669819
GCapex	0.055812*	0.020360	2.741336
Ln GFCF	-0.062402*	0.019747	-3.160024
Urban	0.172599*	0.030120	5.730447
GFCF/GDP	-0.044444	0.029816	-1.490597
Tax/GDP	0.219189*	0.022225	9.862074
Adjusted R^2	0.700308		
No. of observations	100		
Log likelihood	133.9343		
F-statistic	26.70431		
Prob(F-statistic)	0.000000		
Durbin Watson stat	3.223064		

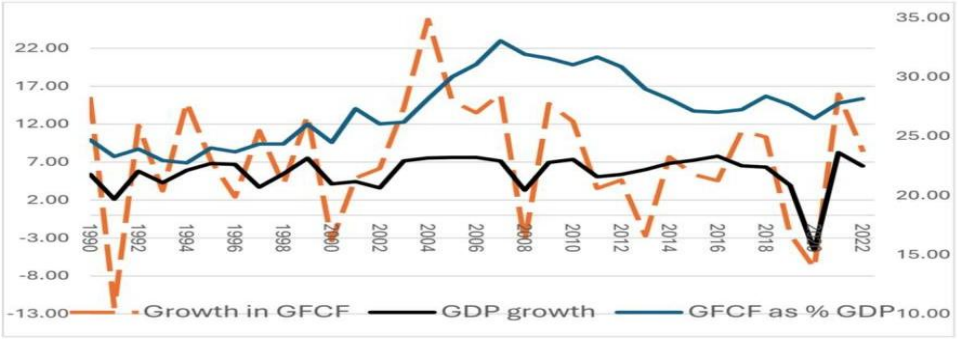


Figure-1: Fixed Capital Formation and GDP Growth in South Asia

Figure 1: Fixed Capital Formation and GDP Growth in South Asia

Table-3 presents the results of the panel regression. The relationship between SDG scores as a dependent variable and selected independent variables has been estimated by using the Panel regression approach. The independent variables

are GDP growth, per capita GDP growth, government capital expenditure (capex), gross fixed capital formation in constant $, rate of urbanisation gross fixed capital formation as percent of GDP and Tax revenue as percent of GDP. All the selected independent variables are found to be stationary at the first difference. The Variance Inflation Factor test shows that all independent variables have a value lesser than 1 (VIF<1) that is no multicollinearity. The model is significant and provides robust results. The Hausman Test indicates that the random effect model is significant. In contrast to the hypothesis, we find a significant negative impact of GDP growth and fixed capital formation on SDG scores in South Asia. The probable reason of this negative impact is the instability in growth and stagnant gross fixed capital formation. One of the positive and significant relationship emerged in the model is between government capital expenditures and SDG scores. In the South Asian countries more than 50 percent of the infrastructure financing as well as SDG financing is done by the Government. Similarly, tax revenues show a significant and positive impact on SDG scores indicating the need for larger fiscal reforms in these countries on the revenue side.

DISCUSSION:

South Asia is one of the regions with huge development gaps and the highest infrastructure gaps (UNESCAP, 2019) (TEIUL, 2019) (Asadullah et al., 2020). Moreover, rapid urbanization and migration have created a lot of pressure on the existing infrastructure leading to a decline in the quality of available infrastructure. In the last three decades, absolute poverty has been declining, and per capita income is rising along with per capita consumption across major categories, such as food, non-food, and services. However, development gaps in South Asia are visible through the rankings of the Human Development Index (HDI), Multi-dimensional Poverty Index (MPI) and Sustainable Development Goals (SDG) rankings. Two important observations in the case of South Asian countries are noteworthy. First, there is a similar pattern

of human development index values and GDP growth. Second, the increasing disparities in terms of gross fixed capital formation (the primary proxy variable for Infrastructure investment) and multidimensional poverty. The empirical evidence is increasingly indicating dissatisfactory quality and efficiency in the expanding infrastructure provisions in South Asia (UNESCAP , 2023).

Infrastructure financing or investment gap has increased from 2.5 trillion USD to 4.5 trillion USD per year since 2014 estimates. The growing infrastructure and its financing gap are also explained as a “global capital flows paradox” (Summers, 2006) (Sungsup & Zhigang, 2018). This paradox has two dimensions, the first related to domestic capital outflows given low returns on

foreign exchange reserves and second related to shrinking fiscal space. Mobilisation of domestic savings into infrastructure investment is still very rigid in Asian countries and at the same time capital market imperfections depressed the return for foreign capital or foreign currency accumulation. Though in the recent years, there has been larger flows of international development fundings for projects related to water, electricity, roads, health and education but the inefficiencies and quality of infrastructure spending and infrastructure provisions is the biggest challenge for the South Asian countries.

Public expenditure on infrastructure is fundamental to crowd in private and foreign investment along with employment generation. Consistent public investment in infrastructure ensures significant social returns, accelerate productivity growth, and strengthen resilience to economic, social and environmental shocks. There have been various estimations regarding the infrastructure investment for SDGs. After the Covid-19 pandemic the required infrastructure investment has risen to $4 trillion per year (around 4% of world GDP) from the previous estimate of $ 2.5 trillion per year (UNCTAD, 2014) (UNCTAD, 2022). Further according to the International Renewable Energy Agency $5.7 trillion (6% of global GDP) of investments are required at the global level by 2030, to control the greenhouse gases effect. Empirical research finding establish that aggregate investment and development spending on health, education, sustainable infrastructure, agriculture, food and land use practices, and biodiversity would need to increase from 11.3 per cent of GDP in 2019 to 15.1 per cent in 2025 and 18.2 per cent in 2030 to reach the relevant SDGs. This amounts to additional spending of $1.3 trillion by 2025 and $3.5 trillion by 2030. While most new and additional investments are expected to come from the private sector, public funding would need to increase significantly from its current level to stimulate and crowd in private investment in the SDGs. Fiscal adjustments and expenditure cuts to fight inflation and improve debt sustainability could severely undermine the ability of developing countries to achieve the SDGs by 2030. The positive effects of public investment on long-term growth are particularly strong when there is a crowding in of private investment and when sectors with large infrastructure gaps and positive externalities, like education, digitalization and the green economy, are prioritized. Furthermore, in times of elevated uncertainty, strategic public investment plans may have even larger effects on output and private investment. By one estimate a total of US$ 57 trillion is needed by 2030, or US$
3.4 trillion per year, for infrastructure investment. Yet there is currently a finance gap to meet
this demand of US$ 500 billion per year. Governments are therefore increasingly looking for mechanisms to close this gap, crowd-in private finance,

and improve efficiency and effectiveness of infrastructure projects. Innovative approaches to infrastructure finance and sustainable public procurement will be critical to their success.

According to the Mckinsey Global Institute Report, during 2016 - 2030, the world needs to invest about 3.8 percent of GDP, or an average of $3.3 trillion a year, in economic infrastructure just to support expected rates of growth. Emerging economies account for some

60 percent of that need. But if the current trajectory of underinvestment continues, the world will fall short by roughly 11 percent, or $350 billion a year. The size of the gap triples if we consider the additional investment required to meet the new UN Sustainable Development Goals. The highest investment gaps are for water supply and energy in South Asia, dominated by India and Bangladesh. Infrastructure is a significant determinant for Asian economy's growth but at the same time consistent economic growth created enormous pressure on Asia's transport, energy, and communications infrastructure. Gradually, it becomes the biggest bottleneck for growth, competitiveness, and poverty reduction. Greater regional collaborations for developing seamless connectivity among Asian countries with environmentally sustainable and greener infrastructure development remains remains an unfinished task (ADB, 2009). Given South Asia's diversity in terms of size, income levels, population, natural resources, and access to both regional and global markets yet common development challenges, sub-regional infrastructure programs can help improve the SDG progress. McKinsey Global Institute's analysis suggests that increasing infrastructure investment by 1% of GDP could create substantial employment opportunities. According to the Boston Consulting group, infrastructure is a powerful vector for social and economic development, and its industry accounts for 6% of the global GDP and workforce. Government investment in infrastructure has an annual multiplier effect of 0.4 to 2.2 times GDP. Infrastructure can help create at least 10,000 total jobs for every $1 billion invested. With these numbers in mind, governments can support the infrastructure industry not just for its own sake, but also as part of the larger pandemic recovery effort. Stimulus packages could be transformational even beyond the immediate crisis; they could address long-term infrastructure challenges (Castagnino et al., 2020). McKinsey Global Institute also estimates that enhancing infrastructure productivity can reduce spending requirements by 40%. While governments continue to stimulate infrastructure investments, there continues to be a multi-trillion-dollar financing gap due to the lack of bankable projects. Particularly in Asia-Pacific, demand far outweighs supply. The private sector will likely play a crucial role in filling these gaps, and multilateral banks should work together

to help create a suitable enabling environment by working with governments to scale up operations, streamline procedures, and deepen capital markets. Public procurement is instrumental in creating demand for innovative and sustainable infrastructure provisions. Because the public expenditure to GDP (GE/GDP) ratio is a proxy for government demand for infrastructure. So, the countries with a higher ratio of GE/GDP will have a higher demand for infrastructure. Consequently, this government expenditure-led demand will incentivise the industries and the private sector to make the production pattern efficient, sustainable, and cost-effective for infrastructure utilisation. In this framework, public infrastructure provisions take place through a predominantly PPP model. Regarding the SDGs, it is not only the allocation of infrastructure investment but the quality and efficiency along with the governance of infrastructure which creates significant progress for countries with higher population density. Therefore, this paper argues for integrated infrastructure development projects in South Asia.

CONCLUSION:

To sum up the paper it is emphasized that, in contrast to the proposed hypothesis, GDP growth and fixed capital formation have a significant negative impact on SDG scores in South Asia. One percent increase in GDP growth results in -6.6 percent change in the SDG scores. On the contrary one percent increase in per capita GDP growth has a significant 6.2 percent positive impact on SDG scores. One percent increase in government capital expenditure and tax GDP ratio results in significant positive increase of 5.58 and 21.9 percent respectively. Similarly, the urbanisation ratio is positively impacting the SDG scores. The probable reason of the negative impact is the instability in GDP growth and stagnant gross fixed capital formation.

On the contrary, in South Asian countries more than 50 percent of the infrastructure financing as well as SDG financing is done by the Government. Further, positive impact of tax revenues indicate the need for larger fiscal reforms in these countries on the revenue side. The growing infrastructure and its financing gap are also explained as a “global capital flows paradox” (Summers, 2006) (Sungsup & Zhigang, 2018). The World Bank’s definition of infrastructure includes utilities (gas and electricity, water supply, telecommunications, sewerage, and waste collection and disposal), public works (roads and major dam and canal works for irrigation and drainage), and other transport sectors (railways, ports, waterways, and airports). OECD includes public works in a country, state or region, including roads, utility lines, and public buildings. The broadest definition includes real estate, oil and gas, and mining. In the recent decade real estate is becoming the highest investment sector. As the definition of infrastructure is expanding

the need for investment is rising but with weakening impact of development outcomes

The South Asian region is characterized with low level growth, dense population, lagging performance in education and health parameters. The demand of infrastructure is expected to increase with urbanisation and GDP growth. Mobilisation of domestic savings into infrastructure investment is still very rigid in Asian countries and at the same time capital market imperfections depressed the return for foreign capital or foreign currency accumulation. Though in the recent years, there has been larger flows of international development fundings for projects related to water, electricity, roads, health and education but the inefficiencies and quality of infrastructure spending and infrastructure provisions is the biggest challenge for the South Asian countries. In South Asia, the highest investment gaps are for water supply, roads and energy, dominated by India and Bangladesh (Cheraghlou, 2024). Infrastructure is a significant determinant for Asian economy's growth but at the same time consistent economic growth created enormous pressure on Asia's transport, energy, and communications infrastructure. Lack of Infrastructure is the biggest bottleneck for growth, competitiveness, and poverty reduction for South Asian countries. Given the South Asia's diversity, in terms of size, income levels, population, natural resources, and access to both regional and global markets yet common development challenges, sub-regional infrastructure programs can help improve the SDG progress.

Conflict of Interest & Funding: The paper has no conflict of interest and no funding has been used for the paper.

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THE PROSPECTIVE OF ARTIFICIAL INTELLIGENCE FOR NET ZERO SUSTAINABILITY: A COMPREHENSIVE REVIEW OF CURRENT EVIDENCE AND FUTURE PROSPECTS

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DOI: https://doi.org/10.64558/bllp/855752bfupgb

ABSTRACT

The worldwide limitation to achieve net-zero levels of greenhouse gas emissions by mid-century requires a radical increase in the pace of decarbonization of all sectors of the economy. Machine learning, deep learning, and advanced data analytics, also known as Artificial Intelligence (AI) are becoming an enabling technology that is central and cross-cutting in this transition. The current evidence and future of AI use in achieving net-zero sustainability is comprehensively evaluated in the paper to understand the perspectives on the matter. We summarize and discuss an expanding body of literature and practical case studies of optimisation of energy systems (including grid management and integration into renewable systems), increased industrial efficiency, smart and low-carbon mobility, and transformative climate sciences, carbon capture, and monitoring. The aggregate evidence suggests that AI can greatly decrease emissions, decrease expenditures and speed up innovation in the following important areas. Nevertheless, AI integration is not totally free of serious challenges, such as its own carbon footprint, data accessibility and quality, algorithmic bias, and the necessity to tackle them with a powerful governance and policy system. We conclude that, although AI is not a panacea, it is necessary to implement it strategically and responsibly because it is becoming an indispensable element of timely and efficient and equitable transition to a net-zero future. In order to achieve its potential, it will imply certain research and development priority, better data infrastructure, and cross-disciplinary collaboration between policymakers, industry leaders, and the AI research community to ensure that these powerful tools will be aligned to the greater goal of climate stability at the global level.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has been right in its expression of scientific orthodoxy; to ensure that global warming does not exceed 1.5degC above the pre- industrial era, the globe must become net-zero on carbon dioxide (CO2) emissions by around 2050 [1]. This mammoth project demands a systemic restructuring of our energy system, transport system, industrial system, and agriculture, never done before and in such a brief period. Despite the very simple technologies of this transition, which are solar photovoltaics, wind turbines, and batteries are under development, the sheer complexity, scale, and interdependence of the problem brings out a requirement to have more complex instruments to

streamline, regulate, to accelerate the process.

Brand into Artificial Intelligence (AI). Artificial intelligence (AI), a broad field of computer science, which entails the creation of intelligent computers that may perform tasks which would have required human cognition, has demonstrated some remarkable abilities insofar as pattern recognition, predictive analytics, optimization of multifaceted systems and autonomous decision-making systems are concerned. The most important sub-field in this regard would be the Machine Learning (ML) that allows systems to learn and improve, and this is not designed to address all the possible situations.

OBJECTIVE

The present paper will contend that AI is a high-priority, cross-cutting facilitator to the achievement of net-zero ambitions, providing a significant tool of efficiency, faster innovation, and handling complexity. The main aim of this review is to generalize the existing evidence of AI implementation into the main industries, predict its future, and new applications, and present a critical analysis of challenges and threats related to it. This paper will enlighten stakeholders in the policymaking process, the industry and scholars on the strategic role of AI in combating the climate and the conditions required to ensure its responsible use. This paper is structured in the following way: Section 2 presents the existing evidence concerning the use of AI in energy, industry, transport, and carbon management. Part 3 is an exploration of future opportunities and new horizons. In section 4, the challenges are critically analyzed such as the footprint of AI itself, as well as the ethical issues.

Lastly, a conclusion and important policy implications are given in Section 5.

METHODOLOGY

Current Evidence: AI in Action for Net Zero

The practical usefulness of AI is being confirmed through more and more real world applications in high-impact domains. The sections below outline the situation of evidence.

Grids and the Management of Energy.

The shift to non-centralized, non-dispatchable, and weather-dependent renewable energy (solar power, wind power) makes the management of electrical grids immensely complex. AI is emerging as one of the most important tools to maintain stability, reliability of the grid and efficiency.

Renewable Energy Forecasting: Renewable intermittency is a significant problem to grid operators that have to balance emerging demand and supply on a real-time basis. The AI models, in particular, deep learning networks, deploy historic weather data, satellite data, and real-time weather prediction to predict solar irradiance and wind energy generation with great accuracy. The most notable of the listed is the DeepMind project of Google that developed an ML model that can estimate the output of a wind farm power 36 hours in advance. This will allow the grid operators to plan energy with less effort and more confidence, reducing the reliance on fossil fuel to supply backup energy. Google argued that such a step raised the value of their wind power by about 20 percent [2].

Smart Grid and Demand-Side Management: The conventional grid is changing to a two- way smart grid. This transformation is centered on AI. The AI algorithms will be able to use smart meter data and IoT data to implement dynamic pricing and demand-response initiatives by analyzing real-time data. As an example, when renewable production is higher and demand is lower, AI can instruct smart appliances (e.g., water heaters, electric vehicle chargers) to use energy, which will absorb surplus clean energy. On the other hand it can encourage low consumption when there is a peak demand. This flattens the demand curve, increases the resilience of the grid and postpones the expensive upgrades of grid infrastructure.

Grid Maintenance and Operations: Predictive maintenance is an AI-based tool that anticipates grid failures in transformers, transmission lines, etc., before they happen taking the sensor data. This will avoid expensive blackouts and enhance safety. In addition, the lines are also controlled by AI optimization algorithms in voltage control and topology optimization to reduce line losses and enhance the overall efficiency of electricity transmission and distribution systems.

Industrial Decarbonization

Industrial sector contributes to the world emissions about a quarter of all the emissions and is regarded as being incredibly hard to decarbonize with the heat demands and the complicated chemical reactions.

- **Process Optimization:** Cement, steel, and chemicals are the energy-intensive industries that apply AI to optimize their production processes. Firms such as Siemens and Bosch have AI applications that adjust the variables of temperature, pressure, and flow rates in real-time. Through constant learning based on the operational data, these systems will be able to determine the best setpoints that will produce the same or even better output using much less energy consumption and reduced greenhouse gas emissions. Using AI to optimise the kiln in a cement plant, as an example, can save the plant 2-5 in fuel consumption, which at scale can equate to significant cost and emission savings.
- **Predictive and Prescriptive Maintenance:** Off of the grid, equipment failure in the industrial domain is predicted by AI-based sensors and analytics. Understanding the anomaly in vibration, temperature, and acoustic data, AI shall be able to strategize the maintenance exactly in time before the sudden unforeseen downtime shall come by and ensure that the specified motors, pumps, and compressors are operating to the full capacity. This will end up destroying the energy wastage and the emissions produced and bring about more productivity.
- **Supply Chain and Logistics Optimization:** AI will be able to optimize complex industrial supply chains, such as the sourcing of raw materials to the final product delivery. This will entail selecting the most effective transportation channels,

minimum inventory to reduce wastes and selecting suppliers with reduced carbon footprint to reduce total emissions of the industrial activities in Scope 3.

Transportation and Mobility.

The transport sector in the world is one of the major contributors to the emission. One of the pillar technologies is AI, which makes its processes electrified, automated, and optimized.

- EV Integration: EV Mass adoption of EVs is a two-sided issue: there is a need to consider the impacts of EVs on the electricity grid and maximize the degree to which they can be helpful to the environment. AI is used to coordinate intelligent charging systems, scheduling charging events to avoid grid overload and to be in sync with periods of high renewable energy generation (i.e. midday with solar). Besides, EVs have their battery management optimized by the use of AI software to extend the battery life and performance, which is another important consideration of the total vehicle lifecycle emissions.
- **Smart Traffic Control:** Traffic congestion is one of the issues that contribute to huge emissions of cars stalling in traffic. Traffic signals control systems based on AI have been implemented in such cities as Pittsburgh and Beijing (e.g., Surtrac). These systems utilize real-time camera and radar information and are dynamically adjusted to change the timing of traffic lights, minimize idling, stop and go traffic and travel time. The independent research of these systems has revealed 25% to 21% reduction in travel duration and 25% to 21% decrease in vehicle emissions [3].
- **Logistics and Fleet Management:** The shipping industry (Maersk), the road delivery industry (UPS and Amazon) involve utilizing AI through complex route and network optimization. The AI algorithms take into account the traffic, weather, topography, and delivery window to decide on the most fuel-efficient routes to be used by their fleets. They also maximize containerization and reduce the amount of empty miles (moving vehicles without a load), which saves a lot of fuel and contributes to a significant decrease in emissions.

Carbon Capture, Utilization, and Storage (CCUS) and Climate Science

CCUS is viewed as an essential technology in hard-to-abate industries, such as heavy industry and aviation. Nonetheless, it is now power-consuming and costly. Artificial intelligence is contributing to the elimination of these challenges.

- **Sorbent Material Discovery:** The most important part of many CCUS technologies is the sorbent material that captures CO 2. It is a lengthy and expensive process to come across new materials, more efficient and less energy-intensive. This is being drastically accelerated by AI and especially by generative models and reinforcement learning. Scientists at colleges such as MIT and Carnegie Mellon have utilized AI to filter

through millions of possible metal-organic structures (MOFs) and other nanoporous substances in a few days, which would have required centuries by employing conventional experimental techniques [4]. This AI-in-science is finding very promising sources of capturing CO2 in the air or the industrial flue gases.

- **Climate Modeling and Monitoring:** The dynamic nature of climatic conditions in the earth can only be predicted and understood to mitigate and adjust. AI is increasing the quality of the high-resolution climatic models making them more precise and quicker. In addition, AI applications process satellite data (e.g. ESA Sentinel missions, NASA OCO-2) to measure greenhouse gas emissions, identify methane escapes of oil and gas infrastructure, and trace deforestation with an unprecedented high level of accuracy. This facilitates improved responsibility and specific corrective measures.

Future Prospects and Emerging Applications

There is more potential of AI applications in the future. There are a number of new frontiers that are likely to open up new disruptive ways of reaching net zero.

- **Independent Technology to Climate:** The idea of the self-driving laboratories is emerging. They are AI-controlled robotic platforms that are capable of formulating, designing, and executing experiments on their own and interpreting the findings to guide the following process. The cycle will bring the basic technology innovations such as next-generation perovskite solar cells or other advanced geothermal systems to orders of magnitude faster, as well as new battery electrolytes or green hydrogen catalysts.
- **System-Level Integration and Energy System Planning:** The future net-zero energy system will be a very complex network of electricity, hydrogen, synthetic fuels, and heat. AI will play a key role in managing this complicated system in real-time where it will choose the most cost effective and low-carbon streams of energy conversion, storage, and transfer. Moreover, at a strategic planning level, AI models can enable a policymaker and an investor to simulate thousands of scenarios to find the best paths of investing in the energy infrastructure in the face of deep uncertainty.
- **Precision Agriculture and Land Use Management**: Agriculture, forestry, and other land use are also major contributors to emissions (e.g. m methane form livestock, nitrous oxide form fertilizers, CO2 form deforestation). Precision agriculture is possible with the help of AI, satellite imagery, drones, and IoT sensors. This enables the use of water, fertilizers, and pesticides which are highly calized and this significantly reduces the amount of input used and the emissions created. The optimization of the reforestation projects can also be done through AI, which will help to find the best planting sites and the type of plants that will capture carbon the most.
- **Circular Economy and Waste**

Management: AI can be used to optimize the flow of waste to the recycling plant by improving waste sorting using computer vision, to discover the best way of disassembling products and remaking them, and anticipate the quality of materials to recycle. This conserves on the production of virgin materials which is energy intensive.

- **More Flexible Climate Risk Assessment:** In the case of adaptation finance, and resilience planning, AI can be applied to create hyper-localized climate risk models to assess the physical risk of climate change (flooding, wildfires, droughts) to particular assets, supply chains, and communities and make more targeted and effective investments in adaptation.

Challenges and Risks

Challenges

The use of AI to the net-zero journey is not a panacea. There are a number of major challenges and risks that should be proactively handled so that benefits of the same can be achieved in a fair and sustainable manner.

- **Auto Carbon Footprint of AI:** It is a big number of computational resources to run and train large AI models. It was estimated that training a single large natural language processing model such as GPT-3 to use hundreds of megawatt-hours of electricity which could produce hundreds of tons of CO2 equivalent depending on the source of the data center data [5]. This poses a possible paradox in the fight against climate change in which AI may be used to fight climate change. This needs mitigation on a multi-pronged basis; by designing AI algorithms that are more computationally efficient (e.g., TinyML), hardware that is specialized and energy-efficient, and data centers powered by 100 percent renewable energy. The idea of green AI is becoming quite popular, with the focus on creating the models that are highly-performing with reduced computational overhead. [6]
- **Data Quality and Availability:** accessibility and quality of data are the main precondition of the successful work of AI. In most of the industries that are very essential in terms of net-zero transition like heavy industry, built environment, and supply chains, data is typically isolated, confidential, inconsistent, or even non-existent. The absence of standardized forms and the fear of commercial privacy also contribute to the inability to build the large and high-quality datasets required to use to train an effective AI model. It is necessary to initiate the development of open-data systems of non-sensitive climate- related information.
- **Algorithms Bias and Equity Concerns:** AI algorithms have the potential to reproduce and increase the existing biases in the society when they are trained on faulty or unrepresentative information. This may cause unfair results in a climatic context. To take a specific example, an AI model to optimize EV charging infrastructure may give priority to the affluent neighborhoods that have a large number of cars, which will

increase transport inequalities. Equally, climate risk models may fail to recognize vulnerable communities in the underserved population because of insufficient information. Fairness, transparency, and equity in climate AI applications is an essential ethical concern demanding a variety of data and multidisciplinary teams.

Risks

Governance, Trust, and Explainability: It is a barrier to adoption because the logic behind a decision is not as easy to understand with certain complex AI models, sometimes known as the black box. Operators find it difficult to lose control to an inexplicable system. Training the explainable AI (XAI) methods and ensuring proper accountability and regulatory frameworks of the AI-assisted or autonomous decisions is an essential step to gaining trust and its safe operation.

Cost and the Digital Divide: The first investment, AI infrastructure and software, and special talent may be prohibitive, especially on small and medium-sized enterprises (SMEs) and in developing countries. This may lead to the development of a so-called digital divide in climate action in which the richest entities will be able to purchase the AI tools that reduce the price and increase the speed of decarbonization. These transformative technologies should be provided to the world through international cooperation and capacity-building programs.

POLICY IMPLICATIONS

The overall evidence that has been combined in this review is a strong argument: Artificial Intelligence has the potential to be transformative in the world making a faster switch towards a net-zero economy. It is a strong lever, both in maximizing the effectiveness of already existing systems and infrastructures, and in finding and implementing breakthrough clean technologies by leaps and bounds. The existing uses in energy, industry and transport are already providing quantifiable results in terms of emission cuts and cost savings and the future perspectives in climate science and material discovery are expected to establish new frontiers in combating climate change.

It is, however, most important to note that AI is not a solution, but a tool. Its effect is determined by the motive of its human makers and paradigms in which it is implemented. The problems are not easy- the AI computational foot print, data gaps, risks of bias, and governance gaps have to be treated in a serious and immediate manner. [7]

CONCLUSION

To effectively and ethically tap the potential of AI in a net-zero future, the multi-stakeholder effort must be coordinated. Our recommendations of policies and action plans are as follows:

- **Focused R&D and Public Investment:** Governments, collaborating with the non- government sector, must massively augment the financing of R&D of the "Climate AI. This involves studies on energy efficient AI (Green AI), solutions to sectors difficult to abate, and open source tools and benchmarking to the community.
- **Develop Data Ecosystems:** The

creation of secure and standardized platforms to share climate-relevant information (anonymized energy data, material properties, satellite data) should be incentivized or compelled by policymakers. This will create innovation and the equalizing of the playing field to smaller players.

- **Establish Standards, Rules and Ethics:** The international regulatory bodies and those in the country should establish standards to gauge and report the environmental impact of AI systems. Moreover, ethical, fair, and transparent recommendations regarding the utilization of AI in climate-critical applications are to be set to develop the trust of the population and avoid any harm.
- **Build Capacity and Bridge Digital divide:** Invest to create education and training programs to create a workforce with skills in the sustainability and AI disciplines. The international support and knowledge-sharing initiatives should be strengthened such that the developing nations would be able to use AI to their benefit to pursue climate- resilience and clean developmental paths.
- **Encourage Cross-Sectoral Cooperation:** Organize forums and innovation competitions that include AI specialists, climate scientists, engineers, industry leaders, policymakers and civil society. To deal with the climate crisis, it is necessary to disintegrate the classic silos. [8]

To sum up, the way towards having a net zero is not easy, but the supporting, accountable, and fair process of integrating Artificial Intelligence offers a vital and possibly essential tool to have this change more streamlined, more affordable, and quicker. It is within our capability to manage the most potent general-purpose technology of our generation to support the most urgent mission of our time: to ensure the future generations live in a sustainable and habitable planet.

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INTEGRATING ALTERNATIVE MEDICAL PRACTICES FOR BUILDING A SUSTAINABLE HEALTHCARE SYSTEM: A PATHWAY TO HOLISTIC AND RESILIENT PATIENT CARE

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ABSTRACT

Global healthcare systems can no longer bear the burden of chronic illnesses, high costs, and environmental challenges. Although biomedical models have become more advanced, they still overlook preventive, holistic, and person-centered approaches to health. Incorporating alternative medical practices—known as Traditional, Complementary, and Integrative Medicine (TCIM) is a step toward sustainable and resilient healthcare. The study seeks alternatives to sustainability that boost prevention, empower patients, and are environmentally friendly. According to a qualitative review and thematic analysis of recent literature (2020– 2025), mechanisms, barriers, and policy implications of integration are identified. Studies reveal that the most frequently cited topics were person-centered care, prevention/self-care, interprofessional collaboration, evidence-based regulation, and system sustainability. Integrative models enhance health system resilience, equity, and resource utilization, the study concludes. Theoretical implications involve reconceptualizing health care through a maltogenic lens, whereas practical implications emphasize the need for policy transformation, workforce education, and empirical evaluation in India.

Keywords Integrative Medicine, Traditional and Complementary Medicine, Sustainable Healthcare, Holistic Care, Healthcare Resilience

Abbreviation

AYUSH- Ayurveda, Yoga, Unani, Siddha, and Homeopathy
TCIM- Traditional, Complementary, and Integrative Medicine
UHC- Universal Health Coverage
SDGs-Sustainable Development Goals
GDP- Gross Domestic Product
LMICs-Low- and Middle-Income Countries
WHO- World Health Organization
TCM- Traditional Chinese Medicine
PMC- PubMed Central

INTRODUCTION

The pressure on healthcare systems across the world today is unprecedented due to the burden of chronic disease, the demographic and epidemiological transition, the increasing cost of treatment, and environmental damage. Even when technology is integrated, illness-focused models are alienated and proactive rather than prevention-focused. For this reason, they frequently overlook the psychosocial, behavioral, and environmental determinants of health that are essential for sustainability over time. India's Ayushman Bharat launch and the institutionalization of AYUSH (Ayurveda, Yoga, Unani, Siddha, and Homeopathy) are landmark events in the history of India's traditional medical systems.

In India, the Ayushman Bharat initiative and the institutionalization of AYUSH mark critical milestones in recognizing traditional medical systems as integral to national health policy. The World Health Organization (WHO, 2023) calls for all countries to include Traditional, Complementary, and Integrative Medicine (TCIM) in their formal health systems to support Universal Health Coverage (UHC) and the Sustainable Development Goals (SDGs). The focus is shifting from curative hospital-based care to prevention and wellness care in community models (Hoenders et al., 2024; Wątróbski et al., 2023).

With the launch of the Ayushman Bharat scheme, the advantages of Indian traditional medicine have been recognized as the first-ever policy of the Government of India. By institutionalizing AYUSH — Ayurveda, Yoga, and related products and services —India's health care system will have a place for them. According to WHO (2023), TCIM should be more formally integrated into health systems worldwide to facilitate Universal Health Coverage (UHC) and the Sustainable Development Goals (SDGs). There is a movement towards prevention, wellness, and community-based models from curative, hospital-based care (Hoenders et al., 2024; Wątróbski et al., 2023).

Background of Study

The study's background focuses on sustainability principles as they make their way into the health care system. Most economists agree that health expenditures have exceeded GDP growth, imposing a significant fiscal burden on governments and health institutions (Badanta et al., 2025). In India, inequities in healthcare access—especially between urban and rural populations—lifestyle-related diseases such as diabetes, hypertension, and cardiovascular disease are increasing fast. There is a need to reorient the health system for prevention and holistic wellbeing (Seetharaman, 2021). According to the report (2024), the alternative systems, i.e., ayurveda, yoga, and naturopathy, have considerable potential in preventive health, chronic disease management, and psychosocial support (Locke et al, 2024 ; Open Access Journals, n.d.).

Across the world, research suggests that integrating these practices into standard medicine not only complements treatment but also improves the cost-effectiveness,

satisfaction, and community involvement of patients (Northwestern Health Sciences University, n.d.). The use of different practices along with modern ones can be seen as a growing response to the difficulty of creating sustainable health systems that can deal with biological and environmental determinants of health.

The rationale to explore integrative models as pathways to a resilient, equitable, and sustainable healthcare ecosystem is provided in the background.

OBJECTIVE

This paper aims to examine how integrating alternative medical practices contributes to building sustainable healthcare systems by enhancing resilience, equity, and holistic patient care.

Research Questions

- How can alternative medical practices contribute to healthcare sustainability across economic, social, and environmental dimensions?
- What mechanisms and models support effective integration of alternative practices into mainstream healthcare?
- What barriers and enablers influence the integration of alternative practices in healthcare systems?
- What are the observed impacts of such integration on patient outcomes, equity, and system resilience?

LITERATURE REVIEW

Concept of Alternative and Integrative Medicine

Various systems are included under the umbrella of alternative medical practices. These include, for example, Ayurveda, Traditional Chinese Medicine (TCM), naturopathy, diet, acupuncture, and mind-body therapies. Balance, prevention, and harmony form the basis of practice (Hoenders et al., 2024). Integrative medicine is the integration of conventional biomedical treatment with complementary approaches in an evidence-informed and patient-centered manner to promote health as a whole-person concept encompassing the physical, mental, social, and spiritual aspects of health (Locke et al., 2024). Research on integrated care systems continues to confirm their effectiveness in improving clinical outcomes, patient experience of care, and the value of care (Jonas et al., 2021). Recent studies also align integrative health with social and environmental justice, establishing holistic medicine as a way for medical practice to become equity- focused, ecologically responsible, and a wholly sustainable community. (Agarwal, 2024). All of these viewpoints, then, point to integrative medicine not merely as an adjunct to standard care but as a change in approach towards more holistic, sustainable, and human-oriented care.

Sustainability in Healthcare Systems

The capability of a health system to deliver fair, effective, and environmentally friendly care sustainably over time, with adequate budgets and operations, is termed health system sustainability (Padget et al., 2024). A sustainable healthcare system relies on the economy, society, and the environment.

More precisely, the efficiency of expenditure ensures the accessibility, acceptability and affordability of service delivery. In turn, the equity of healthcare services ensures minimization of emissions, waste, and energy use.

Integrative medicine contributes to the sustainability of health care by promoting preventive care, self- management, and community-oriented wellness initiatives that yield significant reductions in hospitalizations and long-term treatment costs (Seetharaman, 2021). According to a systems perspective, sustainability depends on adaptive capacity and resilience. These positive aspects benefit from the co-existence of therapeutic models. It reinforces patient autonomy (Wątróbski et al., 2023). Through careful alignment with preventive and person-centered care philosophies, integrative medical systems enhance the responsiveness and efficiency of the health sector while ensuring ecological responsiveness, which strengthens the sustainability agenda.

Empirical and Policy Developments

Research and analysis done in the last decade show the positive and negative aspects of integrating Traditional, Complementary and Integrative Medicine (TCIM) into national health systems. The World Health Organization (2023), through its TCIM Global Strategy 2025-2034, highlighted the importance of appropriate policies and funding dedicated to the regulation and strengthening of research infrastructure to promote the safe and effective use of TCIM. The strategy calls for TCIM to be included in Universal Health Coverage (UHC) frameworks and for the development of evidence-based policy instruments within global health equity.

In India, several steps taken up by the Government of India through the Ministry of AYUSH are speeding up the mainstreaming of TCIM. This is done through the setting up of integrative health centers, AYUSH colleges, as well as cross-referral networks between modern and traditional practitioners (PMC, 2024). India's acknowledgement of the importance of holistic and preventive medicine for its population's health has been on the rise. Data collected through observation shows that AYUSH services are being more increasingly used with biomedical treatments by patients suffering from chronic and lifestyle-related diseases particularly in primary health care in rural areas (Maghrabi et al., 2023).

Nevertheless, challenges persist pertaining to regulatory oversight, credentialing of practitioners, and quality of clinical evidence related to TCIM. The implementation science literature suggests that fragmented governance, inconsistent research funding, and the lack of compatible quality assurance criteria for TCIM impede many national systems from engaging with TCIM (Chung, 2023). Practitioner collaboration and public trust were hindered by these issues.

To conclude, there is growing policy momentum and grassroots adoption of integrative health. However, the institutionalization would require stronger regulation, better generation of evidence, and more sustained policy consistency.

Synchronizing research evidence and national policies is critical to activating TCIM's potential capacity to foster sustainable and equitable health systems.

RESEARCH GAPS

There is considerable development in policy and arising recognition of integrative healthcare, but there continue to be critical research gaps. Current evidence-based, long-term studies examining the link between integrative care practices and measurable sustainability outcomes (e.g. cost, environmental impact, and resilience of the healthcare system) are lacking. Few studies have thoroughly investigated the cost- effectiveness, ecological benefits of these treatments.

Furthermore, poor inter-professional education, diverging regulatory frameworks, and inadequate research capacity in LMICs, pose challenges to the effective implementation of integrative models. Organizations need stronger empirical research, context-specific frameworks, and cross-sectoral collaboration to support the case for integration as a sustainable health care strategy.

Methodology

This study adopts a **qualitative integrative review and thematic analysis** approach. Secondary data were sourced from peer-reviewed journals, WHO reports, and open-access policy papers published between 2020 and 2025. Databases research included Scopus, PubMed, and SpringerLink using the keywords *integrative medicine*, *sustainable healthcare*, and *TCIM*. Extracted data were coded thematically based on recurring patterns regarding integration mechanisms, barriers, and sustainability outcomes. Themes were refined through iterative reading and comparison, producing the five dimensions summarized in Table 1.

Findings and Thematic Analysis

According to the Table below, a thematic synthesis of the relevant literature (2020–2025) on the use of alternative medicine in sustainable health care has been conducted. The analysis identifies five main themes emerging from 20 peer-reviewed studies, highlighting the multifaceted nature of integrative medicine. The themes include person-centered and whole-person care, preventive and self-care, interprofessional collaboration, evidence-informed regulation, and a resilience-oriented system. Overall, the evidence shows that complementary medicine can improve the health and safety of patients and the health care system when properly integrated, and is superior to treatments that are not properly integrated.

Table 1: Thematic Analysis of Literature on Integrating Alternative Medical Practices for Sustainable Healthcare

Theme	Key Description	Supporting Evidence
Person-centered, whole-person care	Focuses on treating individuals holistically, considering physical, emotional, and social factors rather than focusing solely on disease symptoms.	Locke et al. (2024). Seetharaman (2021)
Prevention and self-care	Emphasizes lifestyle modification, self-management, and early intervention, reducing dependence on acute care.	Open Access Journals (n.d.); Padget et al. (2024)
Interprofessional collaboration	Promotes cooperation between biomedical and alternative practitioners through referral networks or joint clinics.	Hoenders et al.(2024); WHO (2023)
Evidence-based regulation and quality assurance	Requires safety validation, practitioner licensing, and research to build credibility and trust.	WHO (2023); Badanta et al. (2025)
System resilience and sustainability	Enhances healthcare adaptability, reduces costs, and aligns with ecological and social sustainability goals.	Northwestern Health Sciences University (n.d.); Wątróbski et al. (2023)

DISCUSSION

RQ1: Contribution to Healthcare Sustainability

By moving away from disease treatment and focusing on health creation, alternative medical practices encourage sustainability. Preventive, low-cost interventions lessen hospital admissions and other energy-demanding treatments, indirectly decreasing the carbon footprint of the sector (Padget et al., 2024). Furthermore, community-based wellness programs empower patients, decentralize care, and increase accessibility in rural areas—a major concern in the Indian context. By applying the above methods, healthcare deals that have an enhanced population health outcome as well as enhanced system efficiency over the long-term system.

RQ2: Mechanisms and Models of Integration

Integration takes place via collaborative care models, public policy frameworks, and academic partnerships. Interprofessional education assists doctors and traditional practitioners in sharing competencies. According to WHO (2023), we encourage the use of co-located integrative clinics that combine biomedical diagnostics with Ayurvedic or naturopathic therapies under evidence-based supervision. Sustainable implementation requires institutional

leadership, training and systemic incentives for individuals involved (Zurynski et al., 2023). Mechanisms that integrate promote working together and respect for each other across the medical field and this allows for a more patient-centered and sustainable approach.

RQ3: Barriers and Enablers

Barriers include insufficient evidence on cost-effectiveness, fragmented policy, lack of insurance coverage, and professional skepticism. Additionally, weak regulatory oversight undermines product quality and patient safety.

Enablers involve policy recognition of AYUSH systems, consumer demand for holistic care, government funding for integrative research, and the growing emphasis on sustainable public health strategies. Implementation science suggests that leadership continuity, funding, and contextual adaptation are critical to maintaining long-term integration (Zurynski et al., 2023).

RQ4: Impacts on Patient-centeredness and System Resilience

Models that integrate systems work on patient satisfaction. They also improve adherence and trust. According to Northwestern Health Science University, there might be a little benefit of diversification in care modalities and decreasing burnout in workforce rot mechanisms. More data will be needed to provide conclusive quantitative evidence, but the qualitative data indicates improved continuity of care, patient empowerment and lower dependency on medicines. All of these lead to the sustainability of the system. Furthermore, integrative approaches contribute to a more robust health system by enhancing resilience, cultivating a preventive culture among providers and patients, and facilitating coherence in practices with social and environmental sustainability.

Implications

Theoretical Implications

The salutogenic model of health care shifts attention from pathology to the origin of health. Integrative systems represent a systems-thinking approach whereby social determinants, prevention, and environmental externalities are dealt with at the same time especially (Locke et al., 2024). Findings that bridge integrative medicine with sustainability science and resilience theory may inform a holistic concept for 21st-century healthcare.

Practical Implications

- **Policy Frameworks:** Integrate TCIM formally into healthcare regulation, ensuring safety, research funding, and professional accreditation.
- **Institutional Leadership:** Hospitals should develop integrative departments and sustainability offices to track preventive impact and energy efficiency.
- **Workforce Development:** Introduce cross-disciplinary curricula combining modern medical sciences with evidence-based traditional therapies.
- **Patient Engagement:** Empower

communities through wellness education, yoga, nutrition, and mental health awareness.

- **Research Infrastructure:** Create national centers for integrative medicine evaluation focusing on environmental and cost metrics.

Recommendations and Future Research Recommendations

- Policymakers need to create a health policy framework that deals with TCI, which formally includes TCIM in healthcare regulation, practitioner accreditation, and allocation of funds for cost-effectiveness and sustainability outcomes.
- Healthcare institutions should establish integrative care units merging modern and traditional practices while monitoring impact of preventive activity and energy efficiency.
- Educational and research institutions should create cross-disciplinary curricula and strengthen evidence generation through special centers for integrative medicine.
- Healthcare professionals should participate in interprofessional training and implement person- centered approaches based on evidence-based standards to enhance the trust of these patients.
- To ensure sustainable health for all, patients and community members must be empowered with wellness education, knowledge of self-care, and participation in shared decision-making.

Future work should:

- Conduct **longitudinal studies** assessing cost savings, emissions reduction, and clinical outcomes of integrative models.
- Develop **context-specific frameworks** for LMICs like India, emphasizing community-driven preventive health.
- Evaluate **training and credentialing systems** for alternative practitioners to ensure safety and consistency.
- Apply **implementation science approaches** to identify success factors in long-term integration.
- Establish **metrics and indicators** for measuring sustainability performance in integrative healthcare (economic, ecological, and social).

CONCLUSION

The alternative medicine integration into mainstream healthcare represents not just a complementary movement, but a transformative shift towards holistic, equitable and sustainable health systems. Integrating this way improves prevention, engages patients, and ensures stewardship of the environment. Yet there are still institutional barriers, regulatory uncertainty and uneven evidence. AYUSH and other systems offer a unique opportunity to increase resilience, lower costs and realize universal and sustainable health in India and similar countries.

Future development will rely upon multidisciplinary collaborations, policies with frameworks and measurable standards for sustainability. An authentic sustainable

healthcare ecosystem that values healing over mere treatment is possible through a judicious mixture of traditional wisdom and modern science.

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PROFESSION TO PASSION
EXPLORING ENTREPRENEURSHIP FROM THE PERSPECTIVES OF DOCTORS, ENGINEERS, LAWYERS AND CHARTERED ACCOUNTANTS.

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ABSTRACT

Entrepreneurship serves as a dynamic force that drives innovation and economic growth, assuming unique dimensions when observed through the diverse professional perspectives of doctors, lawyers, engineers, and chartered accountants. Customarily associated to sectors characterized by specialized expertise, these professions are now experiencing a prominent surge of entrepreneurial spirit. Against the background of evolving societal and economic settings, professionals in medicine, law, engineering, and finance are exploring into entrepreneurial pursuits that leverage their expert skills to address evolving needs and capitalize on pristine opportunities.

This study aims to explore the unique entrepreneurial journeys embarked upon by individuals within these well-regarded fields.

It seeks to understand how doctors, lawyers, engineers, and chartered accountants navigate the connection of their professional expertise with the ever-changing world of business. Whether establishing healthcare startups, engineering-focused innovation hubs, legal tech firms, or financial consultancy enterprises, these professionals are extending beyond traditional career paths, actively shaping their fates within the entrepreneurial realm.

By exploring the experiences of doctors, lawyers, engineers, and chartered accountants turned entrepreneurs, our goal is to uncover valuable insights revealing the evolving setting of entrepreneurship within traditionally structured professions. Through an analysis of problems encountered, and strategies employed, we aim to contribute to a comprehension of how entrepreneurship is enduring transformation and gaining acceptance across varied professional spheres. This study not only promises to uncover individual tales of entrepreneurial success but also aims to determine broader trends that hold the potential to redefine the future of entrepreneurship within these specialized fields.

The present study aims to identify the problems encountered by professionals in the entrepreneurial endeavor and how their business practices help them to overcome those problems. To carry out this research, a sample of 124 professionals operating in

Belagavi district were selected. A simple random sampling technique was opted and a well-structured questionnaire was used to collect the responses. Frequency, Mean, Standard deviation, Correlation and Regression were used to analyze the data. It was found that there existed a positive correlation between their problems and practices suggesting that as entrepreneurs adopt practices to address business related problems, there is a moderate and positive association with improvements in these problems. Furthermore, practices were regressed with problems and it was revealed that business practices have a significant impact on overcoming the problems.

Keywords*:* Entrepreneurship, Professionals, Problems, and Practices.

INTRODUCTION

Entrepreneurship may be defined as the capacity to recognize, develop, organize, and promote an enterprise with a willingness to take risks and turn an original idea into a reality.

Entrepreneurship serves as a dynamic force that drives innovation and economic growth, assuming unique dimensions when observed through the diverse professional perspectives of doctors, lawyers, engineers, and chartered accountants. Customarily associated to sectors characterized by specialized expertise, these professions are now experiencing a prominent surge of entrepreneurial spirit. Against the background of evolving societal and economic settings, professionals in medicine, law, engineering, and finance are exploring into entrepreneurial pursuits that leverage their expert skills to address evolving needs and capitalize on pristine opportunities.

This study aims to explore the unique entrepreneurial journeys embarked upon by individuals within these well-regarded fields. It seeks to understand how doctors, lawyers, engineers, and chartered accountants navigate the connection of their professional expertise with the ever-changing world of business. Whether establishing healthcare startups, engineering-focused innovation hubs, legal tech firms, or financial consultancy enterprises, these professionals are extending beyond traditional career paths, actively shaping their fates within the entrepreneurial realm.

By exploring the experiences of doctors, lawyers, engineers, and chartered accountants turned entrepreneurs, our goal is to uncover valuable insights revealing the evolving setting of entrepreneurship within traditionally structured professions. Through an analysis of problems encountered, and strategies employed, we aim to contribute to a comprehension of how entrepreneurship is enduring transformation and gaining acceptance across varied professional spheres. This study not only promises to uncover individual tales of entrepreneurial success but also aims to determine broader trends that hold the potential to redefine the future of entrepreneurship within these specialized fields.

The overall expansion of the economy and the GDP in particular is greatly aided by entrepreneurs. The main goal of entrepreneurship is to create value.

Compared to the native population of a particular nation, a large number of self-employed professionals in urban areas demonstrate that they undoubtedly have a big potential for entrepreneurship. Following a review of the literature on entrepreneurship, it became clear that very few studies are conducted to evaluate entrepreneurship among professionals with very little attention paid to the challenges faced by professionals in the fields of engineering, finance, medicine, and law as they embark on their entrepreneurial journey. Thus, the purpose of this article is to highlight the issues that professionals turned entrepreneurs in the Belagavi District encounter and to what extent the strategies adopted by them, help them to overcome those problems.

REVIEW OF LITERATURE

- **(Supriya & Kuttalam, 2019) :** The authors posited that entrepreneurs need a combination of strength, expertise, support, infrastructure, and, most importantly, a strong resilient entrepreneurial spirit and dedication in order to address various operational problems of business.
- **(Ahmed, 2017) :** The author posits that addressing the identified difficulties requires sustained efforts and strategic interventions to foster an environment conducive to entrepreneurial success in the region
- **(Raj, 2016) :** Financial difficulties centered on the heavy burden of high-interest rates. The study recommended the establishment of transparent and simplified policy procedures by policymakers to foster entrepreneurial growth and development in the country.
- **(Noorinasab et al., 2016):** The study comprehensively addressed financial concerns, managerial challenges, legal formalities, recruitment of suitable staff, marketing issues, and bureaucratic impediments.
- **(Nishantha & Pathirana, 2014):** The findings unveiled that the foremost challenge confronting small business proprietors in Sri Lanka pertains to the scarcity of reliable employees. Amidst a sluggish economy, the incapacity to secure long-term financing and heightened competition were identified as significant impediments.

OBJECTIVES OF THE STUDY

- To study the demographic characteristics of Entrepreneurs with professional knowledge.
- To assess how problems faced by Entrepreneurs with professional knowledge impact their practices

SCOPE OF THE STUDY:

A total of 124 entrepreneurs with expertise knowledge, registered with prestigious institutes, were identified. These respondents included 33 doctors, 51 lawyers, 33 engineers, and 7 chartered accountants. The study focuses exclusively on professionals who registered with these institutes or associations within the specified research period, spanning from 2016– 17 to 2020–21. This category comprises individuals who, post-professional qualification, did not opt for traditional employment but rather expressed an interest in utilizing their professional

expertise by establishing independent ventures. The study specifically includes professionals who own firms, or clinics, or are involved in partnership associations, emphasizing their entrepreneurial orientation and preference for independent ventures over traditional employment. The survey was conducted over a three-month period from September to November 2022, providing a comprehensive and timely picture of the entrepreneurial setting among professionals.

RESEARCH METHODOLOGY

Type of research: This research is descriptive cum analytical research as it describes the problems encountered by the respondents, and whether practices help to reduce them or not, are analyzed to conclude.

Data collection: Both Primary data and secondary data was used to carry out the study. **Primary data:** It was collected from the selected entrepreneurs with professional expertise of Belagavi district.

Secondary data: Various scholarly journals, articles and sites covering a wide area of academic literature on the topic were referred for extensive literature review. Available secondary data was substantially used.

Sampling: A simple random sampling technique was adopted to identify sample respondents for the study. The study extends to those registered with prestigious institutions such as the Institute of Chartered Accountants of India (Belagavi branch), the District Bar Association, the Indian Medical Association Belagavi, and the Institute of Engineers (IEI) Belagavi for the period of five years spanning from 2016-17 to 2020-21.

Traditional Statistical tools such as mean, and standard deviation, and inferential statistical tools such as correlation and regression are used to analyze the data. The data were analyzed with the help of SPSS software, version 28.

RESULTS

Out of 124 respondents approached, 52 (41.90%) were located in both urban and semi-urban area. 93 respondents (75%) were males and out of the total respondents, 59.67% (74) respondents were possessing a degree. 82 respondents (i.e. 66.10%) were married and the rest were unmarried. Most of the respondents (29.80%) belonged to 35 - 45 age group. Around 76.60 % of respondents belong to nuclear type family structure.

Table No. 1 Demographic Profile

Distribution of demographic profile of respondents		
Characteristics	**Frequencies**	**Percentages (%)**
Location		
Urban	52	41.90
Semi Urban	52	41.90
Rural	20	16.10
Gender		
Male	93	75.00
Female	31	25.00
Level of Education		
Degree	74	59.67
PG Degree	19	15.33
Technical Degree	31	25.00
Marital Status		
Married	82	66.10
Unmarried	42	33.90
Age Group		
Below 25	21	16.90
25-35	30	24.20
35-45	37	29.80
Above 45	36	29.00
Type of family		
Nuclear family	95	76.60
Joint family	29	23.40
Total	124	100

Source: Field survey

DISCUSSIONS AND ANALYSIS

In this study, the following hypothesis is tested.

H0: The problems encountered by entrepreneurs do not impact their practices.

H1: The problems encountered by entrepreneurs does impact their practices

Table No. 2 Correlation Matrix

		Operational Problems
Practices	Pearson Correlation	0.293**
**** Correlation is significant at the 0.01 level (2-tailed)**		

Source: Primary data

The Pearson correlation coefficients indicate the strength and direction of relationships between practices adopted to overcome problems. The double asterisks indicate statistical significance for all relationships at the 0.01 level (two-tailed). The following are the correlation coefficients for operational problems, $r=0.293$, $p < 0.01$. These positive correlations suggest that as entrepreneurs adopt practices to address business related problems, there is a moderate and positive association with improvements in these problems. The correlation coefficients quantify the strength of these associations, highlighting the potential effectiveness of adopted practices in mitigating diverse problem areas within the enterprise.

Table No. 3 Perception of Entrepreneurs with professional knowledge on operational problems

Perception of Entrepreneurs on Operational Problems	N	Min.	Max.	Mean	Std. Deviation	C.V
Getting new clients or patients	124	1	5	3.56	1.308	37%
Retaining existing clients / patients	124	1	5	3.68	1.137	31%
Non availability of qualified / skilled staff for assistance	124	1	5	3.67	1.110	30%
Adopting technological changes	124	1	5	3.75	1.194	32%
Constantly updating to new regulations	124	1	5	3.72	1.116	30%
No fixed working hours	124	1	5	3.75	1.109	30%

N (list wise) = 124

Source: Primary data

Table No. 3 presents the perceptions of entrepreneurs with professional knowledge regarding operational problems faced by them. The mean scores range from 3.56 to 3.75 on a 5-point scale, indicating a high level of agreement among respondents. Specifically, problems such as "Adopting technological changes" ($M = 3.75$, $SD = 1.194$) and "No fixed working hours" ($M = 3.75$, $SD = 1.109$) receive higher mean scores, suggesting greater concern among entrepreneurs. Conversely, "Getting new clients or patients" ($M = 3.56$, $SD = 1.308$) demonstrates a relatively lower mean score. Standard deviations, ranging from 1.110 to 1.308, signify a moderate degree of variability in perceptions. The coefficient of variation (C.V.) values, ranging from 30% to 37%, highlight a moderate level of diversity in responses across the operational challenges.

Table No. 4 Perception of Entrepreneurs on Business practices followed to overcome the problems

Perception Business practices followed to face the challenges	N	Min.	Max.	Mean	Std. Deviation	C.V
Adopted strategies of the existing firms	124	1	5	3.22	1.227	38%
Took the assistance from consultants or agents	124	1	5	3.41	1.344	39%
Received guidance from previous entrepreneurs	124	1	5	3.44	1.321	38%
Assistance was taken from friends and family members	124	1	5	3.31	1.327	40%

N (list wise) = 124

Source: Primary data

Table 5.3.4.7 elucidates the perspectives of entrepreneurs regarding the business practices adopted to tackle challenges. Mean scores, falling within the range of 3.22 to 3.44 on a 5-point scale, suggest a moderate level of engagement in various strategies. Specific practices encompass "Adopted strategies of the existing firms" (M = 3.22, SD = 1.227), "Took assistance from consultants or agents" (M = 3.41, SD = 1.344), "Received guidance from previous entrepreneurs" (M = 3.44, SD = 1.321), and "Assistance was taken from friends and family members" (M = 3.31, SD = 1.327). The standard deviations, ranging from 1.227 to 1.344, indicate a moderate degree of variation in responses. The coefficient of variation (C.V.) percentages, between 38% and 40%, underscore a notable relative variability in perceptions. This emphasizes the diverse business practices employed by entrepreneurs, encompassing strategies from existing firms, consulting with agents, seeking guidance from previous entrepreneurs, and obtaining support from friends and family members to address challenges. **Regression Analysis**

H1: There is a significantly positive impact of operational problems on practices

Table No. 5 Hypotheses Results

Hypotheses		Regression Weights	B	T	P-value	Results
H1	Operational Problems→Practices	Operational →Practices	0.333	2.956	0.004	Supported
R		0.143				
F (2,121)		10.079				

Source: Primary data

Note: *p < 0.05.

The dependent variable labelled as Practices was regressed on predicting variable labelled as Operational problems. The independent variable significantly predicts Practices to overcome business problems, $F(2,121) = 10.079$, $p < 0.001$, which indicates that the factor under study have a significant impact on business practices to overcome problems. Moreover, the $R^2 = 0.143$ depicts that the model explains 14.3% of the variance in practices. Additionally, co-efficient were further assessed to ascertain the influence of the factor on the criterion variable (practices). H1 evaluates whether operational problems significantly and positively affect practices. The results revealed that operational problems have a significant and positive impact on practices. Operational Problems ($b=0.333$, $t=2.956$, $p < 0.05$). Hence, H1 was supported.

Findings and Conclusion

The findings from the study underlines the significance of addressing operational problems among entrepreneurs with professional knowledge. The positive correlations between adopted practices and improvements in operational problems suggest a moderate association, emphasizing the potential efficacy of implemented strategies. Entrepreneurs express notable concerns about issues such as "Adopting technological changes" and "No fixed working hours," indicating areas that may require focused attention. The study also reveals a moderate level of engagement in diverse business practices, including strategies from existing firms, consulting with agents, seeking guidance from previous entrepreneurs, and obtaining support from friends and family members. Importantly, the regression analysis confirms that operational problems significantly and positively influence the adoption of practices to overcome business challenges. In conclusion, the study highlights the relevance of tailored strategies in addressing specific operational hurdles faced by professional turned entrepreneurs, emphasizing the need for targeted support and guidance in navigating these problems effectively.

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COLLABORATION BETWEEN PUBLIC AND PRIVATE SECTORS TO DEVELOP SEAPORT INFRASTRUCTURE PROJECTS WITH SUSTAINABILITY DIMENSIONS.

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ABSTRACT

Post COVID 19, as countries are focusing on revival of their economies, seaport development, particularly in emerging economies is gaining importance. Also, it is of relevance that the development process is inclusive with due consideration to sustainability aspects. To wholistically analyze the sustainability aspects that can strongly contribute to conservation of marine ecosystem and the Sustainability Development Goals (SDGs), the paper analyses environmental, social, economic, technological and institutional sustainability as the key elements where there is opportunity for the public sector and the private sector to collaborate in the process of development of seaport infrastructure. In addition to the seaport authority and private operators which are the principal partners in the Public Private partnership (PPP) arrangement, the authors consider Policy Makers, Financing Institutions and Local community at the seaport as relevant stakeholders in sustainable development of seaport infrastructures. The paper is divided into three sections. The first section is centered on knowing the nuances of infrastructure development and the importance of sustainability adoption in seaports. The second section connects infrastructure development in seaports with principal partners in the PPP set up and key stakeholders that can majorly contribute to the infrastructure development of seaports with due sustainability considerations. The third section elaborates on key sustainability dimensions -environmental, economic, social, technological and institutional that can be adopted in seaports through collaboration among key public and private partners.

Keywords- Public Private Partnership, Principal Partners, Key Stakeholders, Sustainability Elements, Collaboration, Marine ecosystem, Seaport infrastructure projects.

INTRODUCTION

Infrastructure development at seaports facilitates trade and commerce between countries thereby boosting their economy. However, in the process the ecological system gets impacted if the development ignores sustainability dimensions in and around the seaports. As the pace of infrastructure development increases, there is growing need to adopt sustainability to minimize the harmful impact on the marine ecosystem. Developing economies face a dual challenge of catering to increase demand for adequate seaport infrastructure on the one hand and the need to responsibly develop this infrastructure in

line with the goals outlined in UNSDG. Consequently, governments are seeking enhanced participation of private sector and exploring concessional investment opportunities not just for development of infrastructure projects in seaport but also to have it developed with due consideration on sustainability aspects.

According to the port reform toolkit published by the Public–Private Infrastructure Advisory Facility (PPIAF) of World Bank, different port management structures are used worldwide but in the majority of large and medium sized ports the landlord port model is used.[1] The landlord port model bifurcates responsibilities between Seaport Authority and the Service Provider, the two principal partners in the PPP set up. The Seaport Authority is primarily responsible for planning, design and regulatory functions while the private sector Service Providers operators are generally entrusted to develop and operate specific terminals dedicated to handling particular types of goods. The private sector need to have the technical capabilities in developing such structures and in generally responsible for arranging financing requirements for its development. This sort of formalized relationship between the public seaport authority and the private operator defining the roles and responsibilities of each of the actors is termed as Public Private Partnership (PPP) . There is a spectrum of possible contractual arrangements between these entities. These range from relatively short-term service contracts to long-term joint venture arrangements called concession agreement. The concession agreement are thus a binding mechanism involving key stakeholders associated with infrastructure development in seaports.

INFRASTRUCTURE DEVELOPMENT AND SUSTAINABILITY

Seaport being the essence of maritime trade requires Infrastructures to facilitate the process of cargoes handling, transportation and storage. According to London Maritime academy [2], Port infrastructure is a mixture of facilities and equipment, including breakwaters, docks, cranes and other equipment. To ensure all these elements work optimally, seaports must keep them well- maintained and functional. Seaport being the essence of maritime trade requires Infrastructures to facilitate the process of cargoes handling, transportation and storage. Countries having access to seaports consider it as a very critical infrastructure for economic reasons. As defined by America's Cyber Defense Agency [3]: "Critical Infrastructure are those assets, systems, and networks that provide functions necessary for our way of life. There are 16 critical infrastructure sectors that are part of a complex, interconnected ecosystem and any threat to these sectors could have potentially debilitating national security, economic and public health or safety consequences." Seaports are part of the Marine Transportation system and are part of the 16 critical infrastructures. Therefore, the development of the infrastructure at the seaports and upkeep of the infrastructure developed can assume much significance. Infrastructure development at seaports primarily is carried out for three major reasons , which are as follows :-

- Development of new seaports – Development of new seaports have

been a constant phenomenon since the industrial revolution. Developed countries with maritime resources have witnessed rapid growth in development of seaports in the 19th century. In the current century, developing economies having access to sea are constantly exploring opportunities for development of new seaports to cater to the need emanating out of economic and demographic growth . The investment for creation of new seaport complexes at project level is usually termed as greenfield project investments . These green field projects are very capital intensive and gestation time for completion is long . New seaport development from scratch can provide opportunities to develop the infrastructure with the latest technologies and sustainability criteria can be easily integrated in the process of development . However, this is dependent on the seaport authority to specify such requirements in the concession agreement , competencies of private sector to develop it and capacity of private sector service providers to raise the needed financing for its development. Private Sector Service Providers also ensures environmental clearance from the concerned authorities for the development of a new seaport . Environmental clearance from the regulators will enable the SPV with support from its parent company to approach lenders to the projects. Financing Institutions evaluates the economic feasibility of developing the new seaport and also minutely examines the sustainability aspects particularly to ensure that the project does not negatively impact the ecosystem and adversely affect the livelihood of the local population.

- Revamping existing seaport capacities- Seaports need to continuously develop and augment their cargo handling capacity to remain competitive . Therefore, to facilitate handling of larger volume of cargo and greater number of vessels visiting the seaports, development of infrastructures at seaport becomes essential . The investment in increasing the berth and cargo handling capacity at seaports is generally referred to as brown field investment projects . To enable the visit of larger ships to the coast, capital dredging initiatives are carried out by the seaport authorities. Also, necessary modification related to the increase in cargo has to be in place . The stock yard needs to be revamped to accommodate the increased cargo, and the material handling system should be accordingly designed to handle all of the cargo. To remain competitive seaports, need to have an efficient system of providing electricity to ships while the ships are berthed, which requires the related electrification infrastructure . To improve efficiency, seaports also upgrades their manual cargo handling system to automated mechanized systems. This not only improves efficiency but also contributes to a decrease in pollution because of improved cargo handling. Therefore, any infrastructure development activities in the seaport complex has to be well planned and coordinated among

all stakeholders particularly the public Seaport Authorities and the private Service Providers. Revamping existing infrastructures with proper coordination and including sustainable elements help all the stakeholders-the Seaport Authorities, the private sector Service Providers as well as the local communities who benefit from reduction of pollution.

- Making seaport resilient to climate hazard-Seaports are increasingly being exposed to climate hazards like floods, tsunamis, hurricanes etc. With rise in sea level many of the infrastructure in the seaport are at risk of submergence. Many of the studies have predicted alarming climate events that can impact many seaports across the globe. Therefore, seaports have to continuously climate proof the infrastructure and focus on climate resilient development of infrastructures . Climate resilient measures can be having a robust early warning system, exploring nature-based solution measures to check flooding and innovative designing of new infrastructure that are planned to be developed. Other adaptation actions that seaport can adopt in engineering ,technology ,insurance , planning design and development area are as follows[4].
- Prioritizing the development of resilient structures that can withstand potential climate events like floods, tsunamis and cyclones. Exploring nature-based solutions as an alternative to conventional civil structures, that can be a full proof remedy to counter such challenges in the medium to long term.
- Long term planning to consider the future climatic threats should be made while procuring material handling equipment and systems. The likelihood period of usability of such equipment and systems can be determined through application of stress testing models.
- Climate proofing and making necessary upgradation if required to the places of storage.
- Using innovative systems to determine dredging requirement particularly capital dredging which are mostly carried out by seaports. Proper scheduling of such activity in predetermined intervals with room for accommodating exigencies can be part of the monitoring system.
- Exploring mechanization of processes where there is possibility of environmental benefits as an alternative to manual processes to increase efficiency. Systems can be improved in the areas of material handling, storage , energy generation and in cooling systems. If required existing systems can be revamped.
- Having an adequate risk mitigation strategy to counter unforeseeable accidents. Routine inspection of existing systems and having risk coverage by way of insurance if not already existing can be beneficial.
- Inhouse development of capacities of existing personnel and familiarization on sustainable aspects through trainings and workshops also are the areas seaport authorities can focus on.

The above three requirements for infrastructure development in seaports also brings forth the necessity to develop the infrastructure that will serve the purpose for a long time . The developed infrastructure should withstand the climatic hazards the occurrence of which have increased in recent times because of climate change. With the growing importance of seaports striving to be climate resilient there is increasing focus on adoption of sustainability in development of infrastructures . It has been gaining considerable importance, particularly in emerging countries . Emerging countries need to continuously invest in infrastructure developments at seaport to meet the rising demand in domestic and international trade. However, the countries cannot lose sight of the long-term consequence if sustainability is delinked from infrastructure development . Seaport Authorities to improve their corporate governance are understanding the importance of engaging with environmental and social groups and are prioritizing complying with regulatory norms of the country. The best practices available internationally and the guidelines issued by international organizations like IMO relevant in the area of infrastructure development are being taken seriously by all stakeholders. Seaport Authorities and Service Providers have now an increasing responsibility to jointly develop the infrastructure meeting all the sustainability criteria. Financing Institutions are also guided by Responsible financing guidelines and are looking for investments that meet their internal guidelines on environmental and social frameworks which also considers equal gender representation in policy formulation and decision-making particularly in relation to involvement of local communities in and around seaport complexes. Thus, the role of these key stakeholders in addition to the principal partners in the PPP set up have been gaining importance. The engagement of all stakeholders enable the sustainability elements to be captured in its entirety during the infrastructure development process in the seaports thereby benefiting the whole marine ecosystem.

PRINCIPAL PARTNERS IN PPP AND KEY STAKEHOLDERS

The primary responsibility of infrastructure creation and development in the seaports lies with the seaport authorities as they own the seaports. The seaport is managed either through public corporations or public trusts. Although public authorities own the ports, the infrastructure investments and operations are generally outsourced to private players. Private service providers have to comply with the policies laid down from time to time by policy makers and develop the entire seaport or a particular terminal as per the concession agreement . Therefore, the role of Policy makers is crucial in the infrastructure development in seaports. Private service providers also have to continuously engage with the local communities during the development stage . Financing Institutions provide bulk of the financing required by the service providers to develop the infrastructure. Considering the above, the main stakeholders identified in this paper who are associated with infrastructure development in seaports under PPP arrangements are the Seaport

Authority , Seaport Service Providers , Policy Makers , Financial Institutions and the Local Communities. A brief on each of these partners and stakeholders is as follows.

Seaport Authorities

Seaport Authorities are mostly from the public sector, and they are responsible for every infrastructure development that are carried out in the seaport domain. Based on the needs of the seaport, they make development plans . They may outsource consultants that help them design the project for development . It would be useful if the seaport authorities at this stage involve relevant stakeholders and through consultation process make investment planning . Involving prospective private sector service providers and specialists in social and environmental domain helps in due consideration of sustainability factors during the planning process. The private sector actors who finally wins the bid and executes the contracts benefits from the initial consultation phase. Seaport Authorities can have a common platform for exchanging information and knowledge among stakeholders. Seaport authorities are presently focusing on using technology and systems to improve efficiency and engagement with stakeholders. To remain competitive, numerous seaports have begun to implement Port Community Systems (PCS), where all port information is centralized and data exchange between port stakeholders is safer and faster. Desired outcomes from the implementation of PCS, apart from increasing the quality of data are minimizing paperwork, supporting data connections between different stakeholders, enhancing and facilitating activities across the entire transport and logistics chain to stakeholders, etc. Port authorities act as initiators and creators of the sustainable port development strategy on behalf of the whole port community. By developing and implementing PCS, port authorities are becoming real digital hubs, where available data is gathered and exchanged between various stakeholders. One of the reasons for creating PCSs is that port service users and customers need an increasing amount of information every day to innovate and optimize their own processes. Such innovations in trade, logistics, transportation, and port sectors should not only address the internal needs of each individual company, but also those of the companies and other entities that make up the entire supply chain[5]

Seaport Service Providers

The seaport service providers are the private players engaged by the port authorities to carry one or more activities within the seaport premises as per the PPP arrangement. The bid process starts with the Seaport Authority issuing Request for Proposal (RFP) documents which are generally published on the seaport website and in the newspapers of the country. These documents contain details of the project development requirements and the details of the bid process which may have a separate technical and financial stage. The private sector bidder is selected through a competitive process as per the criteria mentioned in the RFP document. Quite often , the private sector players form a separate entity called Special Purpose Vehicle that participates in the bidding process. SPVs are created for the particular

project and after the completion of the development and operation , the SPV existence ends. They have separate legal obligation from that of the parent company and are considered bankruptcy remote . The SPVs as per the concession agreement are entrusted generally responsible to design , build and operate the infrastructure. Maintenance responsibilities lie with the SPV for the agreed years of operations and the SPV may sub contact the maintenance activities to any specialised entities. In most of the concession agreement , the SPV is responsible for arranging finance for the project . This sort of arrangement with seaport authorities is popularly termed as DBOF (Design , Build, Operate and Finance) contracts. Sometimes as agreed upon in the concession agreement the SPV may be assigned only responsibility to Design , Build and Finance the infrastructure with the operations of the terminals managed by Seaport Authority . In either of the above scenario, the SPV depends on its principal sponsor the parent company that arranges debt and equity financing from public and private financial institutions. The parent company generally based on its competencies and experience build over the years have sound credit rating assigned by independent Credit issuing entities. The sound credit ratings of the parent company enable them to raise debt from Financing Institutions. Equity in the SPV is contributed by the parent out of its own fund or sometimes it raises fund from the market . To arrange financing from the financing institutions at a concessional pricing , SPV sometimes offer corporate guarantee of the parent company. However, according to Y. Ke, X. Liu and S. Wang ,Lenders should be strongly involved in the project to ensure the project's feasibility instead of requiring more guarantees from the sponsors which creates more barriers for project implementation when the financial conditions are not very attractive.[6]

Policy Makers

In most of the seaports most of the policies and regulations are made either by the Seaport authorities or by the national governments or jointly through different commitees. Many international organizations like International Maritime Organization (IMO), European Sea Ports Organisation (ESPO), International Association of Ports and Harbors (IAPH) provide guidelines which are helpful for Port trusts and national governments in framing policies related to compliance and seaport operations. With respect to seaport infrastructure development there is plenty of opportunity for the policy makers to act as facilitators to enhance seaport sustainability . Policy makers can frame guidelines on inclusion of nature-based solutions wherever possible . There can be policies on usage of renewable energy systems in seaports and replacing conventional polluting energy applications in staggered manner. Policy makers can spearhead in creation of enabling environment wherein all sorts of support including financial are available to private players so that they can prioritize including sustainable components while designing seaport infrastructure projects. Policy makers can also explore ways to design regulatory schemes to integrate pollution

mitigation mechanisms with long term climate change adaptation goals to develop seaport infrastructure which is resilient to climate change [7]. Policy and legal frameworks that facilitate, support and accelerate effective action on adaptation and resilience- building for ports and other critical transport infrastructure have a particularly vital role to play in strengthening risk governance and increasing resilience on the ground. Policies, strategies and plans establish agreed objectives, priorities and commitments which, among others, inform the provision and use of resources as well as institutional frameworks, and can provide important incentives for advancing port resilience. Legal frameworks are both powerful and vital tools to facilitate and advance implementation, along with accountability[8]. Policy makers can coordinate and integrate their efforts in internal negotiations such as the annual Conference of the Parties (COP) meetings . These meetings under the United Nations Framework Convention on Climate Change (UNFCCC) are held annually to chalk out strategy for sustainability adoption in the marine transport domain.

Financing Institutions

Both Public and Private Financing Institutions are key stakeholders involved in the development of seaport infrastructure. Development Finance Institutions (DFIs) , Climate Funds and the Sovereign governments are the Public Finance Institutions that are active in the seaport infrastructure development space. Commercial Banks, Insurance companies, Pension funds, Infrastructure Funds and some private equity funds look for opportunities in the infrastructure space where the risk in investment is low to moderate. Of these private entities, infrastructure funds and pension funds are the only entities that are in a position to provide debt with long tenor that are best suited for infrastructure development at seaports

Private Financing Institutions

Pension funds and Insurance companies are the prominent private sector financing entities that look for long-term investments projects to match their long-term deposit base . They prefer steady cash flow over a long period of time and a great level of certainty and generally are ok with low returns on investments. In the case of infrastructure development at seaports they prefer investing in existing set up where the risk is perceived less compared to an investment area where there is the adoption of new technology . Therefore, the private entity or the SPV that executes the PPP contract can reach out to these long-term investors provided they infrastructure development activities that are attempted are considered to have proven cash flow generating potential and tested in the past . The Pension funds and insurance companies active in infrastructure financing are generally strong international players and have a strong appetite to fund long tenor projects . Many of the entities over time strengthened their in-house capacity to evaluate sustainable oriented projects and would prefer such investment to build a sound reputation among its shareholders . These entities can classify such investment in sustainable infrastructure in seaports depending on the very nature of investments as Socially

Responsible Investments (SRI), ethical finance, impact investing or social investment.

Public Financing Institutions

Development Finance Institutions (DFIs) , Climate Funds and the Sovereign governments are the Public Finance Institutions that are active in the seaport infrastructure development space . These Public Finance entities support PPP and fund projects with a strong sustainability angle. These institutions, through a range of financial instruments which include concessional loans, guarantees and technical assistance on select projects, can create an enabling environment for private sector investments. DFIs are able to provide finance with very attractive terms because of their shareholder capital and their strong credit rating which allows them to borrow large amounts of money at attractive interest rates on international capital markets. The DFIs look for a positive return on investment over a long tenor which suits most marine infrastructure development projects . Prominent among the DFIs that are active in funding marine infrastructure projects are the International Finance Corporation, World Bank and the Asian Development Bank . Prominent bilateral DFIs that are active in the infrastructure financing space are Kreditanstalt für Wiederaufbau (KfW), Agence Française de Développement(AFD) and the Japan International Cooperation Agency (JICA). There are National DFIs like Brazilian Development Bank (BNDES) and Development Bank of Southern Africa (DBSA) which also funds long term marine infrastructure projects.

Climate Funds (CFs)

There are also another set of public long-term investors that can play an instrumental role in sustainability adoption during infrastructure development processes. These funds are provided with resources from mostly developed countries to focus on financing climate projects in developing and underdeveloped countries. Green Climate Fund(GCF), Global Environmental Facility (GEF) and the Adaptation Fund (AF) are CFs which are active in providing concessional funding to projects that tries to diminish carbon footprints and oriented toward strengthening climate adaptation. These CFs prioritize sustainability inclusions and have stringent criteria for investing in projects with strong climate rationale. These CFs are mandated by their governing Boards to extend long term loans and selectively invest in equity of companies to catalyze private capital. Underdeveloped countries and developing countries particularly vulnerable to impacts of climate change are particularly benefited by these institutions.

Local Communities :

Local communities are a key stakeholder in the seaport infrastructure development process . Seaport Authorities are specifying clauses to consider the social aspects of local communities in the concession agreement . SPVs, which executes the infrastructure development contracts, is responsible to ensure proper safety and employment conditions for the local community . According to World Bank [9] PPPs can graduate from being a pure public

private partnership to a people-oriented PPP strongly considering and implementing policies in the PPP design that are people centric and considers due importance to sustainable elements. The people centric PPP called People First PPP (PfPPPs) can be identified by outcomes which are beyond the normal
techniques that are used in project evaluation. These outcomes which projects can focus on are as follows

- Outcomes aiming to enhance social aspects including due consideration on essential services aspects.
- Outcomes designed to consider economic sustainability
- Outcomes that are oriented towards prioritizing environmental sustainability
- Outcomes are easy and replicable across geographies
- Outcomes that aims to enhance with all relevant stakeholders.

ELEMENTS OF SUSTAINABILITY AND COLLABORATION BETWEEN STAKEHOLDERS

Private sectors are inherently guided by profit considerations and to expect seaport Service Providers to embed sustainability elements in marine infrastructure development on their own appears farfetched. Seaport Authorities are primary responsible for development of infrastructure at seaports. However, Seaport authorities need support from other principal partners in the PPP set up and other stakeholders to have sustainability-oriented considerations during the process of planning and designing of infrastructures. Since many of the aspects are technical in nature, collaboration between Public Seaport authorities, Private sector operators, Financing institutions and community in the seaport is very crucial to develop marine infrastructures with sustainability considerations.

Environmental Sustainability

Seaport Authorities and Seaport Service providers have a common goal to develop seaport infrastructures that serves their respective interests in terms of timeliness of completion of the project and the project generating the envisaged returns on investments. In the whole process of project development unless there is a clear specification of ways to include sustainable elements in the concessional agreement there is a little motivation for the private sector to initiate measure to protect marine ecosystem. To develop a robust marine infrastructure in a sustainable way, the first essential step for the public sector port authority is to initiate a consultation process during the planning stage with prominent experts in the marine environmental field to examine the feasibility of incorporating nature-based solutions and sustainable elements in the concessional agreement clauses. The role of Seaport Authority in prioritising environmental sustainability is immense. Through carefully laid policies and effective planning , measures that are environmentally friendly can be included in the project design. Consultation with environmental specialists and prospective private sector service providers will help all stakeholders to align on the best technologies and measures. More weightages can be accorded to sustainable criteria in the technical bid evaluation process. Some of the areas where

environmental measures can be specified by the public sector in the concession agreements enabling private sector to sustainably develop infrastructure with due considerations to conserving the fragile ecosystem are as follows.

Measures to protect the coastline

Seaport coastline can be protected through different measures. Instead of the traditional civil structures, nature-based solutions can be explored wherever feasible to protect the coast. Normally the Nature-based Solutions once developed are long lasting and requires less maintenance compared to civil structures which are to be regularly maintained and periodically upgraded, . Conservation and afforestation of mangrove forests and sand breakwaters are few nature-based solutions that have been attempted . Other innovative environmentally friendly measures can be explored .

Measures to protect aquatic life

Aquatic life including coral reef should be considered while infrastructures are developed . Aquatic flora and fauna can be a vital source of livelihood for local communities and they are also found to be diminishing the water pollutants. Public sector in collaboration with private sector can explore possibility of creating eco-tourism infrastructure near the seaport. Ecotourism, defined as “environmentally responsible travel and visitation to relatively undisturbed natural areas”, to enjoy and appreciate nature, is often used to enhance the natural capital, while protecting and promoting protected areas. Ecological benefits can translate into economic benefits, and this includes market benefits (goods or services observed through a market transaction; example: the increase in tourism) and non-market benefits (not achieved by a market transaction; example: the benefit to people from knowing that a threatened species is protected)[10]. Seaport authority can explore allocating a separate land parcel for eco-tourism with the private sector being responsible to develop it.

Measures to contain water Pollution

Marine Infrastructure development has been going on since ages and many of the development have ignored ecological considerations. This has resulted in damage to the coastline and the natural way to combat climate change phenomena like sudden flood and tsunamis. Aquatic creates and fragile plantations have been impacted by infrastructure developments across seaports. Water pollution can be diminished if the efluents reaching the water are properly treated. Proper wastewater discharge system and treatment plants are beneficial sustainable measures that can be integral part of seaport infrastructure development and can be seriously considered.

Measures to check air pollution

Major air pollutants near the seaport complexes are the oxides of Sulphur and Nitrogen and small dust particles caused by shipping liners and port operations that include the handling of dirty (coal and iron ore) cargoes. Increase in global trade and shipping volumes will likely exacerbate shipping-sourced emissions and attributable health burdens in the near future, and in light of the International Maritime Organization (IMO)'s goal to reduce GHG emissions by 50% by 2050 compared to

2008, even more ambitious emission control efforts are needed to not fail this climate goal. Therefore, significant shipowner investment and commitment to improved and more efficient ship design and operational performance, wide adoption of LNG and biofuel use, wind power and electrification are needed, as well as improved IMO oversight and enforcement of established rules[11]. Steps can be initiated by private sector service providers in collaboration
with public sector Port Authorities to implement measures that substantially reduce air pollution. Seaport authorities can collaborate with private project developers during planning of the infrastructure development to explore installation of dust suppression technologies. Innovation in material handling systems and conversion of conventional energy sources to renewable ones can be very useful in checking air pollution.

Social Sustainability

It is very essential that Seaport Authorities and private Service Providers consult with the local communities during the planning stage of infrastructure development in seaports and the local communities remain engaged throughout the project implementation and operation stages. Public Sector port authorities can specify clauses to incorporate sustainable elements which holistically considers the social aspects in the project design and development. Private Sector while making design for the infrastructure development can include measures that contribute to wellbeing of the societal ecosystem. Thus, through coordination and collaboration between the principal public and private stakeholder, social aspects can be duly taken into consideration through the process of development of seaport infrastructure. Few suggestions that can enhance social sustainability with the collaboration of public and private sector are as follows.

Measures to address livelihood issues

Aquatic creatures are sensitive to the construction work in and around seaports . The normal breeding cycle can be impacted resulting in less catch effecting livelihood of communities dependent on these marine resources. Therefore, these factors should be taken into consideration and suitable measures that protects local population livelihood can be part of the infrastructure development process. To foster positive relationships with local communities, industry stakeholders should engage in transparent communication, support community development projects, and mitigate the negative impacts of shipping activities on coastal habitats and livelihoods[12].

Safety, Health and Well-being measures

Local communities and workers at the site are exposed to safety and health risks during construction stage of the infrastructure development in seaports. Safety aspects are an essential element in infrastructure development and should be focused on by all stakeholders. Adequate measures to prevent any accident should be in place. Relevant safety guidelines, training and operations manuals should be made available to all those who are exposed to such risks. Well- being measures like schools and hospitals near

the seaport vicinity managed by the Seaport Authorities in collaboration with Private Service Providers are essential features of social sustainability measures. By demonstrating a commitment to the well-being of the community, seaports can enhance their reputation and gain a social license to operate, which fosters trust and positive relationships with stakeholders[13].

- Measures to improve and develop skills

Seaport staff, workers and local communities can be imparted regular skill upgradation knowledge through workshops and training. Vocational training institutions can be established either within or in close proximity of seaport complex. Public and private sector can work together to impart professional training to employees in the seaports. Seaport Authorities and private Service Providers can jointly take initiative to set up learning facilities and develop training centres in tie up with specialised institution and universities . These initiatives will help the employees, staff and temporary workers to gain knowledge. The training can also include module on sustainability and its adoption in seaports thereby making the trainees well aware of the sustainability dimension . The training can help in the professional career development and the organisation can benefit from the new perspectives from the trained employees on sustainability and its implementation during infrastructure development in seaports. The employees well trained in their respective domain and on sustainability issues can help in fine tuning existing norms and having new ones for ultimately benefiting all stakeholders .

- Economic Sustainability

Infrastructure development in seaports are capital intensive projects wherein there is a strong need for collaboration between public and private sector. The public sector attaches utmost importance to the development of the infrastructure with clear economic goals in tune with the economic benefit for the country. Infrastructure investment yields positive, enduring, and often immeasurable returns to people, communities, and society and is thus affordable to society at sufficient levels of fiscal support [14]. The private sector expects a commensurate return to its risk while developing seaport infrastructures which is very technical and capital intensive project. The private sector service providers are generally responsible to arrange for debt to finance the infrastructure . Equity infusion in the SPV created is done primarily by the parent sponsor. The return on investment increases for the equity investors if the debt arranged is concessional in nature. Incorporating measures related to sustainability while designing seaport infrastructure projects, may increase the project cost and consequent requirement of additional financing. To address the issue public sector Seaport Authorities can actively consult with the private Service Providers to segregate the cost that are budgeted for sustainability inclusions. Concessional financing from developmental financial institutions and climate funds can be tapped by the private sector with a performance guarantee from the port authority ensuring that the envisaged sustainable components are incorporated in the project development contributing to the holistic development of the marine ecosystem. With strong collaboration between the public and private sectors and continuous engagement with the financing institution economic sustainability aspects can be prioritised. Financial concessions that can come into play to facilitate economic sustainability are as follows.

- Concessional finance

Arranging concessional finance from non-commercial financing sources. Multilateral Development Banks (MDB)/Developmental

Financial Institutions and Climate Funds provide funding to mainstream sustainable projects. The financing instruments are very concessional in nature including grants and reimbursable grants. Special incentives can be initiated by Seaport Authorities to stimulate private sector include more sustainable elements while developing seaport infrastructures. The public authority can create a separate technology upgradation fund
that the private sector can draw upon in concessional finance terms to upgrade or adopt modern technologies that are efficient and environmentally friendly .

- Long Loan Tenor

Developing infrastructure projects incorporating sustainable elements require long gestation period. A long tenor loan and adequate moratorium in servicing of loan helps the private sector to efficiently develop and operate the project. An important task of public policy should be to create favourable conditions for intensifying long-term lending, which is especially important for the maritime industry. [15]

Cash flow in the initial period are less and it gradually stabilizes over the period of concession. Considering this a structured repayment schedule for loan servicing and long tenor of the loan is always beneficial for the project and all the stakeholders associated with it.

- Innovative financing

Issuance of blue bonds can be used to incorporate sustainable elements in the infrastructure project development. A blue bond is a debt security issued to raise capital specifically to finance the implementation of the SDGs related to the ocean, the seas and marine resources, as well as the transition towards a sustainable ocean economy. There are a number of SDGs which a blue bond can relate to given the diversity of factors relevant to a sustainable ocean based economy. Corporates, financial institutions, governments, and municipalities can issue blue bonds to fund ocean-related assets and to deliver initiatives that support the SDGs [16].

- Technological Sustainability

Use of advance technology during the development of seaports not only brings efficiency in the operations but also has a positive impact on the marine ecosystem. To attain technological sustainability collaboration between private and public sector is very crucial. Private sector can be incentivised to make the best use of the state-of-the-art technology available in the marine infrastructure domain. Public sector can ensure that the best technology is used through clear specifications in the concession agreement. A separate fund can be earmarked for technology upgradation that will be concessional in nature. Few measures that can be adopted in the infrastructure development related to technology are as follows.

- Process Mechanization

Usage of mechanized material handling equipment not only brings efficiency but also diminishes the chances of pollution that is associated with manual operations. There are different dust suppression technologies available to control pollution emanating from dust particles during material handling process and in the storage yard. Many of the technologies applications are automated and there is minimal manual interventions thereby keeping the employees less exposed to the pollution emanating from dust particles. The roads within the seaport complexes can be paved using nature-based solutions thereby providing double benefits of reducing pollution as well as making the roads resilient to heat and storm water.

- Application of energy efficient technologies

According to K-L.A.Yau, et al., recent research on smart ports have revolved around the

application of Internet of Things, cold ironing, renewable energy generation and storage, energy management, locating systems and code recognition for containers, the use of AIS data for trajectory estimation, and resource management. Future investigations could be made to explore, design, and develop new smart port applications, collaboration platform among different ports, enhanced terminal operating system, collaboration with smart ships, completely digitized autonomous smart ports, as well as big data analytics, blockchain, and cyber security solutions [17]. The electrification of ports and their transformation into smart energy infrastructures represent one of the most promising solutions toward the decarbonization of the maritime industry. [18].

- Application of advanced information technologies

Staying abreast of the new technologies can help seaports improve operational efficiencies and improve overall safety . Modern remote sensing technologies, such as RFID for identification and location, cameras and built-in computer vision algorithms, could contribute to safer and shorter handling time in comparison to classic container terminals[19]. Seaport Service Providers can embrace new Information and Technologies (ICT) to bring in efficiency in operations . Cloud computing and 5G technology can also be explored to improve development of infrastructures at seaports.

- Institutional Sustainability

While social, environmental , economic and technological sustainability have been focused a lot, institutional sustainability is gradually being stressed upon . Port authorities and Private sector players being the key stakeholders, can work together to improve institutional sustainability . Few dimensions of institutional sustainability are :-

- Regulatory compliance

Complying with regulatory norms of the country is a paramount requirement of the seaport authority as well as the private sector involved in the development of seaports . There are many international and national guidelines that can be adopted while developing infrastructures in seaports that will contribute to adoption of UNSDGs. There is a need to periodically revisit the local policies and regulations to accommodate the latest technology assimilation within the seaport complexes. According to R. Canessa et al., local regulations need to be developed to promote the implementation of optimal microgrid designs with cold ironing technologies and to address the problem of requiring substantial investment to carry out this type of project [21]. Development of regulatory frameworks in tune with technology advancement and prioritizing sustainable criteria will benefit all stakeholders in the long run.

- Process improvement

Seaport Authorities and private Service Providers can engage to set up a platform to exchange relevant information and knowledge and also to settle issues if any . Since the infrastructure development at seaports takes a long time for development and the concession for operations are usually set for 20 to 30 years there can be occasions where change in process or improvement of existing mechanisms may be required . Therefore, having a mechanism to discuss among stakeholders help all stakeholders to be more involved and facilitate decision making which are mostly on a consensus basis. Many of the seaports have introduced single window clearance mechanisms to ease approval processes. Single window approval ensures a timely and effective way of getting things fixed while the infrastructure is being developed. Since the gestation time for the development of the seaport infrastructures are long, single window clearance mechanism helps remove bottleneck midway in project implementation.

Development of infrastructure in a timely manner is a benefit to all stakeholders. According to M. Sadiq *et al*., policy development and incentives can be provided to have smart technologies that can improve energy efficiencies and reduce GHG emissions [21]

- Monitoring and Supervision

Monitoring and Supervision of projects while on implementation is very crucial in achievement of institution sustainability . Public sector in collaboration with the Private sector can design a framework to have effective monitoring and supervision of the activities . Periodic impact assessment after closure of the development phase always benefits the stakeholders to understand how well the project is benefiting the ecosystem.

CONCLUSION

Most ports have emphasized the identification, mitigation, and monitoring of impacts, as well as improved energy management, and stakeholder engagement–particularly linked to environmental policy development[22]. Enhancing environmental sustainability through additional clauses in port concession agreements, beyond existing regulations, also raises concerns about impacting port competitiveness, potentially disadvantaging concessionaires, particularly in markets where ports compete for the same market share and clientele. Such measures may increase demand for a level playing field across the port sector. However, environmental sustainability is an urgent, collective priority that should not be viewed solely through a competitive lens among enterprises or port authorities. At the same time, market dynamics and realities must be acknowledged. Achieving sustainability requires a balanced approach, integrating economic, social, and environmental objectives rather than prioritizing one over the others. Effective governance is essential in this context: it involves setting clear goals and priorities, addressing challenges and finding adequate solutions, accommodating diverse interests, making thoughtful compromises at the highest level, and seeking consensus wherever possible [23]. While each port is unique, there is some scope for joint action and convergence among seaports with respect to these aspects. Port authorities and terminal operators are only able to fully benefit from initiatives toward the greening of concession procedures if these actions are embedded in a chain approach toward the environment (ship, port, terminal, warehouse, and inland transport). Green concession agreements miss their effect when treated in isolation. Any green concession policy should give incentives to firms to integrate environmental issues into their management practices, while avoiding making terminal operators victim of any unfair or ineffective green policies. Eventually, such an approach will benefit both the port authority and the terminal operating companies [24].

Infrastructure development in seaports is a capital-intensive activity with involvement of number of stakeholders and alignment of diverse interests among stakeholders is not easy. Seaports are considered very vital for the country’s economy and are subject to rules and regulations. infrastructure development with sustainability adoption is a challenging activity for all stakeholders and especially for the private sector service

providers. However, strong collaboration between the principal partners that is the public Seaport Authority and the private Service provider in the PPP set up and with all key stakeholders identified in the paper can help adoption of sustainability with all its dimension that include environmental, economic, social, technological and institutional. It is essential to consider resilient infrastructure development and sustainability are interrelated and can be considered both sides of the same coin. It would be beneficial if all the principal partners in PPP and relevant stakeholders engage with each other at the planning stage of infrastructure development at seaports exchange ideas and collaborating to maximise sustainability adoption during the development process. A common forum ensuring due consultation among the stakeholders from the planning to the execution will have maximum positive impact on the overall sustainability and on the planned execution of the infrastructure development in the seaports.

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SUSTAINABILITY INITIATIVES: CASE STUDY OF GOOGLE AND MICROSOFT

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ABSTRACT

This study discusses the sustainability practices of Google and Microsoft, two of the top technology companies. By conducting a literature review and reviewing company reports, the study identifies best practices and policy implementations that may be used in future sustainability practices in the technology industry. The results imply that ambitious goal-
setting, stakeholder involvement, and investment in renewable energy, sustainable operations, and the use of the principles of the circular economy are the strategies that help encourage sustainability. This study adds to the existing literature on sustainability in the technology sector and gives insights to companies that are interested in minimizing their impact on the environment.
Keywords: sustainability, technology industry, Google, Microsoft, renewable energy, and circular economy.

INTRODUCTION

Technology has become one of the major causes of environmental degradation, and the production, consumption, and disposal of technological devices and infrastructure have
become major contributors to greenhouse gas emissions, e-waste, and depletion of resources (Bibri, 2018). Sustainability is, however, an issue that is being acknowledged more by technology firms as they make efforts to lessen their impact on the environment (Hart and Milstein, 2003). This study will analyse sustainability initiatives used at Google and Microsoft, two major technology firms that have gone a long way in ensuring their reduced environmental footprint. The case study explores their sustainability activities, obstacles, and lessons learned.

The sustainability initiatives at Google.

- **Renewable Energy:** Google is hoping to run 100% on renewable energy. The company has contracted to buy 3 gigawatts of renewable energy as of 2022.
- **Carbon Neutrality:** Since 2007 Google has been carbon neutral and hopes to be running on 24/7 carbon-free power by 2030.
- **Sustainable Data Centres:** Google data centres rely on sophisticated cooling and machine learning in order to maximize the efficiency of energy consumption.

Microsoft's Sustainability Effort.

- **Net-Zero Emissions:** Microsoft intends to be carbon negative in 2030.
- **Renewable Energy:** By 2025, Microsoft intends to run 100 percent of its operations on renewable energy.
- **Sustainable Technologies:** Microsoft is creating AI-based products to aid in

sustainability.

Challenges and Lessons Learned.

- **Scalability:** The two firms have the problem of scaling down the sustainability initiatives without compromising the speed of growth.
- **Limitations to technology:** The companies will be forced to keep on innovating and investing in new technologies in order to meet their sustainability objectives.
- **Collaboration:** Google and Microsoft understand the need to collaborate with governments and non-governmental organizations and other stakeholders in order to spur industry-wide sustainability.

The sustainability efforts of Google and Microsoft are a sign that technology firms can be used to transform the environment. Investing in renewable energy, sustainable technologies, and new solutions will help these companies decrease their carbon footprint and help create a more sustainable future.

Research Gap

The paper reveals a gap in the current body of knowledge regarding sustainability within the technological industry, specifically among the Indian technology companies. Nevertheless, the analysis is based on worldwide corporations such as Google and Microsoft. The gap could be further bridged by a more specific analysis of sustainability initiatives of Indian technology companies.

Significance of the Study:

The paper has stated the significance of sustainability in the technology sector, which contributes notably towards the degradation of the environment. The paper offers insights to other technology companies in adopting sustainable practices and lowering their impact on the environment by studying the best practice of Google and Microsoft.

RESEARCH QUESTIONS

- What are the major sustainability interventions adopted by Google and Microsoft?
- To what extent do these interventions help decrease carbon footprint and environmental sustainability?
- What are the challenges that Google and Microsoft encounter in the implementation of the sustainability initiatives?
- What can other companies take away from the Google and Microsoft experiences and use for the sustainability initiatives?

OBJECTIVES

- To examine the sustainability initiatives of Google and Microsoft.
- To explore how technology can be used to develop sustainability efforts and reduce environmental impact.
- To examine the effects of the initiatives in reducing carbon footprint and environmental sustainability.

Literature Review

Sustainability has become a very popular concept in the recent years, as organizations and industries have realized the need to minimize their environmental

impact (Hart and Milstein, 2003). Technology, in its turn, has been cited as a major cause of environmental degradation, as the production, usage, and disposal of the technological gadgets and infrastructure have been known to contribute heavily to the release of greenhouse gases, e-waste, and resource depletion (Bibri, 2018).

Technological Industry Sustainability

Studies have indicated that technology firms are becoming more sustainable, revealing itself through investing in renewable energy, introducing sustainable operations, and embracing the principle of the circular economy (Geissdoerfer et al., 2017). An example is Google and Microsoft, both of which have pledged serious investments in minimizing their environmental impact, and Google has committed to using renewable energy to power 100% of its operations and Microsoft working to be carbon-neutral by 2030 (Google, 2022; Microsoft, 2022).

Benefits of Sustainability

The benefits associated with sustainability to businesses includes, improve brand image, customer loyalty as well as lower costs (Porter and Kramer, 2006). Moreover, the sustainability interventions may lead to innovation and the development of new business opportunities as well (Hart and Milstein, 2003).

Challenges and Opportunities

Challenges in implementing sustainability initiatives, including increased initial expenses and requiring a lot of change in the organization (Seuring and Muller, 2008). Nevertheless, many technology firms that are increasingly becoming aware of the value of sustainability, and are making efforts to lower their carbon footprint.

Systematic Initiatives of Google and Microsoft

Google and Microsoft are on the forefront of sustainability efforts in technology industry. The two companies have greatly invested in minimizing the effects they have on the environment. **Carbon Neutrality and Renewable Energy**

- **Google:** By 2030, strives to operate on 24/7 carbon-free energy on any grid to which it has access. At present, two-thirds of its energy consumption is non-carbon based.
- **Microsoft:** Has a commitment to utilize 100 percent carbon pollution-free electricity and wants to be carbon-negative by 2030.

Sustainability Initiatives Google:

- Spends on alternative energy sources such as solar and wind power.
- Uses machine learning to optimize data centres.
- Provides Google Cloud platform to assist businesses in better hardware and energy consumption.

Microsoft:

- Invests in its carbon removal projects where it contracts above 1.4 million tons of carbon removal.
- Invents AI so as to measure and abide by emissions.
- Gives emphasis to recyclable materials in its activities.

Emissions Reduction

Google: The emissions have grown in

2018 by 48 percent, primarily due to the energy consumption of data centers and the supply chain operations.

Microsoft: Emissions have increased by 30 percent since 2019 even after the company has been working on lowering its carbon footprint.

Innovation and Partnerships.

Google: Collaborates with businesses providing solutions that are sustainability oriented and invests in climate change startups.

Microsoft: Co-operates with the suppliers to minimize emissions and invest in climate innovation fund.

Industry Background: The Environmental Impact of the Technology Industry and the Significance of Sustainability Initiatives.

Technology is a life changer, as it has become an indispensable component of our modern lives that has transformed the way we live, work, and communicate. But due to the booming industry and its rise and development, there have also been several environmental issues.

Use, disposal, and production of technology products and services have led to massive releases of greenhouse gases, creation of e-waste, and depletion of resources.

Environmental Impact of the Technology Industry

- **Greenhouse Gas Emissions**: The technology industry is one of the biggest contributors to greenhouse gas emissions, majorly through the use of energy in the data centres, manufacturing process, and transportation. The report by the International Energy Agency (IEA) showed the estimated carbon footprint of the ICT sector was approximately 1.4% of the global emissions in 2020 (IEA, 2020).
- **E-Waste Generation:** High obsolescence of the technology products has resulted in an explosion in the generation of electronic waste (e-waste) that is very dangerous to both the environment and health unless it is disposed of appropriately. According to the World Economic Forum, 50 million metric tons of e-waste were produced in the world in 2018, and only 20 percent could be recycled (World Economic Forum, 2019).
- **Resource Depletion:** Rare earth minerals, metals, and other resources are needed to create technology products and hence might be harmful to the environment and may result in resource depletion. In one study, the European Commission discovered that the mining of rare earths may cause serious environmental effects such as land degradation and water contamination (European Commission, 2020).

Significance of Sustainability Initiatives

- **Minimizing Carbon Footprint:** Sustainability can be made to enable technology firms to minimize their carbon footprint, to curb global warming, and even to meet tighter environmental laws that are set to be enforced. According to a report by the Carbon Disclosure Project, companies that make sustainability their priority have more chances of minimizing their greenhouse gas emissions and realizing cost savings (CDP, 2020).
- **Resource Conservation:**

Sustainability can be used to reduce waste, conserve resources, and encourage the use of renewable energy. The United Nations Environment Programme says that sustainable practices can be adopted to minimize waste and pollution and increase economic growth and employment (UNEP, 2020).

- **Strengthening Brand Reputation:** A company that values sustainability will have a better chance of attracting customers, investors, and employees who are environmentally conscious, which brings improvement to their brand reputation. Nielsen conducted a study that found 81 percent of consumers believe firmly that businesses have a responsibility to contribute to bettering the environment, and 73 percent will feel more inclined to purchase from companies that take sustainability into account (Nielsen, 2019).

Advantages of Sustainability Efforts in the Technology Industry**.**

- **Cost Savings:** Sustainable practices would be able to create a great deal of cost savings by cutting on energy usage, wastage, and enhanced use of resources. The National Resources Defence Council report revealed that by moving toward sustainable practices in the data centre, their consumption of energy can be minimized by up to 30 percent (NRDC, 2020).

- **Innovation and Competitiveness:** Sustainability initiatives can also develop new business, improve competitiveness, and be innovative. A report by the World Business Council on Sustainable Development reveals that sustainability can be the source of innovation, growth, lowering costs, and enhancing brand reputation (WBCSD, 2020).
- **Compliance with Regulations:** With sustainability, technology companies will be able to comply with environmental regulations and prevent possible fines and image losses. The Environmental Defence Fund report revealed that firms with a sustainability focus are better placed to adhere to environmental regulations and decrease their chances of going noncompliant (EDF, 2020).

The environment is highly affected by the technology industry, and sustainability initiatives play a significant role in minimizing the effect on the environment. By employing sustainability, the technological companies can minimize their carbon footprint, save resources, and improve the brand image. With the industry still developing and changing, the companies have to be more sustainable and encourage environmental sustainability.

METHODOLOGY

The sustainability initiatives of the Google and Microsoft case study involved qualitative research, whereby a mix of primary and secondary data was used to collect information. The qualitative approach was used in the case study, which provided the opportunity to conduct a thorough analysis of the initiatives of sustainability in Google and Microsoft. This strategy allowed us to obtain more specific information regarding the sustainability strategies, problems, and

results of the companies.

Data Collection Methods

The data collection methods used in the case study include:

Document Analysis: The publicly available documents, in the form of annual reports, sustainability reports, and press releases, were reviewed to provide information regarding Google and Microsoft and sustainability initiatives.

Case Study Analysis: Preexisting case studies and research articles on sustainability activities of Google and Microsoft were reviewed to have more insight on how these two companies handle sustainability.

Industry Reports: Industry reports and research studies about the sustainability of the technology industry were examined to give the context and insight about the challenges and opportunities of sustainability in the technology industry.

Data Analysis

The analysis of the data in this case study was conducted through a thematic analysis methodology, according to which the themes and patterns of the data were identified and
coded. Such a strategy allowed the researcher to find the main findings and insights regarding the sustainability initiatives of Google and Microsoft.

Stakeholder Analysis: Progressing the Sustainability Programs.

The stakeholders are important in the sustainability initiatives within the organizations. The study focuses on the role of employees, customers, and investors in enhancing sustainability.

Employees

- **Internal Champions:** Workers who will propagate sustainability efforts and motivate other colleagues to engage in environmentally conscious behaviors (Benn et al., 2014).
- **Innovation and Idea Generation:** Employees are able to make contributions in the development of the sustainable products and services, which will become the source of the innovation and competitiveness (Hart, 1995).
- **Cultural Transformation:** The workers have the ability to shape the culture within the organization and encourage the shift to sustainability and environmental responsibility (Linnenluecke and Griffiths, 2010).

Customers

- **Market Demand:** Sustainable products and services can be demanded by customers, and this forces the companies to embrace the environmentally friendly practices (Kotler, 2011).
- **Brand Loyalty:** Environmentally responsible consumers would tend to be loyal to companies that prioritize environmental responsibility (Cone, 2017).
- **Feedback and Insights:** Customers are able to give good feedback and insights, and this will assist firms to enhance their sustainability performance (Fraj-Andres et al., 2015).

Investors

- **Financial Help:** Sustainability can be financially assisted by the investors who will help companies invest in eco-friendly technologies and practices (Sparkes, 2002).

- **Risk Management:** Shareholders can inspire companies to handle sustainability- related risks, including climate change and resource depletion (KPMG, 2020).
- **Long-term Value Creation:** Investors have an opportunity to focus on long-term value creation, and they understand that long-term sustainability efforts bring positive results to the financial performance and image of the companies (World Economic Forum, 2020).

Employees, customers, and investors are all significant in the execution of sustainability initiatives in organizations. Through the insight of the needs and expectations of these stakeholders, the companies can create viable sustainability strategies.

Financial Analysis: Financial Implications of Sustainability Initiatives on the Bottom Line of Google and Microsoft.

Google and Microsoft have adopted several sustainability initiatives to lessen their effects on the environment. The economic cost of such initiatives.

Cost Savings

- **Energy Efficiency:** Google has made efforts to make its data centers efficient, which has seen it save a lot of costs. In the environmental report published by Google, data centers consume half the amount of energy as the industry average (Google, 2022).
- **Green Energy:** Microsoft has made investments in renewable energy, which has enabled them to save the cost of energy. By 2025, Microsoft has several goals, such as to switch all its activities to renewable energy (Microsoft, 2022).

Revenue Growth

- **Sustainable Products:** The sustainable products at Google, including the carbon footprint calculator of Google Cloud, have had a substantial increase in revenue (Google Cloud, 2022).
- **Green Services:** Green services offered by Microsoft, like Microsoft Cloud for Sustainability, have helped the company increase revenues (Microsoft, 2022).

Investment and Returns

- **Sustainability Investments:** Google and Microsoft have been practicing high levels of sustainability investments such as renewable energy and energy efficiency programs (Google, 2022; Microsoft, 2022).
- **Returns on Investment:** Research has indicated that sustainability efforts have had very high returns on investment in the form of cost savings and increases in revenue (Harvard Business Review, 2020).

Financial Performance

- **Google's Financial Performance:** The financial performance of Google parent company, Alphabet, has shown good financial performance in recent years, with revenues increasing partly as a result of sustainability efforts (Alphabet, 2022).
- **Microsoft's Financial Performance:** Microsoft has also announced a very good financial performance, as revenue increased due to its cloud business and sustainability programs (Microsoft, 2022).

The sustainability efforts of Google and Microsoft have positively influenced their bottom line and created cost savings, revenue growth, and payback. As sustainability becomes a priority among companies, it is probable that these efforts will improve the financial performance.

Operational Analysis: Sustainability Initiatives Operational Changes.

Google and Microsoft have carried out several changes in their operations to support sustainability initiatives. This discussion looks at the changes in the operations made by these companies.

Operational Changes of Google.

- **Efficiency in Data Centres:** Google has streamlined its data centre processes to minimize its energy use, and some of its methods comprise machine learning to anticipate its energy demand (Google, 2022).
- **Renewable Energy:** Google has invested in renewable sources of energy, including solar and wind, to energize its data centres and operations (Google, 2022).
- **Sustainable Supply Chain:** Google has introduced a sustainability supply chain program, collaborating with its suppliers to eliminate waste and emissions (Google, 2022).

Operational Changes of Microsoft.

- **Carbon Neutrality:** Microsoft is set to become carbon neutral by 2030 and is investing in renewable energy projects and energy efficiency projects (Microsoft, 2022).
- **Sustainable Operations:** Microsoft has been enforcing sustainable means of operation, which includes minimizing water usage and waste in its facilities and data centres (Microsoft, 2022).
- **Circular Economy:** Microsoft is pursuing the concept of a circular economy, creating products and services that limit the waste capacity and encourage reuse and recycling (Microsoft, 2022).

Operational changes have advantages.

- **Less Emission:** The operational changes in Google and Microsoft have led to the lessened emission of greenhouse gas (Google, 2022; Microsoft, 2022).
- **Cost Savings:** Cost savings have also been generated through these changes in operations, which include energy consumption and waste reduction (Harvard Business Review, 2020).
- **Better Brand Reputation:** Google and Microsoft have enhanced their brand reputation because of sustainability, which has shown their concern with environmental responsibility (Cone, 2017).

The changes in the operation of Google and Microsoft have played a critical role in implementing sustainability initiatives by the companies. Through optimization of operation and investment in renewable energy sources as well as sustainable practices, these companies have minimized their impact on the environment, saved costs, and enhanced their brand image.

Innovative Analysis: Innovative Solutions and Technologies for Sustainability. Google and Microsoft have come up with new solutions and technologies to facilitate sustainability.

Innovative Solutions at Google.

- **Google Cloud:** Google Cloud provides business products such as the Carbon Footprint and the Sustainability Insights to enable businesses to measure and mitigate their environmental impact (Google Cloud, 2022).
- **Machine Learning:** Machine learning can help Google achieve energy efficiency in its data centers, as well as support sustainability initiatives (Google, 2022).
- **Environmental Insights Explorer:** The Environmental Insights Explorer is a Google application that offers data and insights on the emission of greenhouse gases to assist cities and organizations in making sustainability plans (Google, 2022).

Innovative Solutions at Microsoft.

- **Microsoft Cloud for Sustainability:** Microsoft Cloud for Sustainability offers a fully developed solution to organizations to document, report, and lessen their environmental effect (Microsoft, 2022).
- **AI to Sustainability:** Microsoft AI to Sustainability Initiative is an artificial intelligence initiative that uses artificial intelligence to implement sustainability solutions, including tracking deforestation and ocean health (Microsoft, 2022).
- **Sustainable Software Development:** Sustainable software development practices are being created by Microsoft, where the company is focused on energy efficiency and minimizing waste in the software development life cycle (Microsoft, 2022).

Advantages of Creative Solutions.

- **Greater Productivity:** These new technologies have made different industries more efficient and less wasteful (Google, 2022; Microsoft, 2022).
- **Better Decision-Making:** These solutions have enhanced the planning of sustainability and decision-making by supplying information and insights (Google, 2022; Microsoft, 2022).
- **New Business Opportunities:** The innovations have presented new business opportunities and sources of revenue to companies that focus on sustainability (World Economic Forum, 2020).

Sustainability efforts and positive environmental impact have been facilitated by innovative solutions and technologies that Google and Microsoft provide. Through technologies such as machine learning and artificial intelligence, these companies have managed to come up with new solutions and business opportunities.

Table 1 Powering a Sustainable Future

Twenty-six percent of technology firms operate on 100% renewable energy. (Source: RE100)	**Google & Microsoft aim for 100% renewable operations**	**Renewable energy can reduce GHG emissions by up to 78% (Source: NREL)**

Table 2 Reducing E-Waste: A Growing Concern

50M metric tonnes of e-waste that is produced annually (Source: WEF)	**Recycling of e-waste is only done on 20 percent of the waste (Source: WEF)**	**Tech companies implement recycling & take-back programs**

Table 3 Sustainable Supply Chains: A Secret to Minimizing Emissions

70% of carbon footprint comes from supply chains (Source: CDP)	**Tech firms collaborating with suppliers for sustainability**	**Sustainable supply chains cut costs & improve brand reputation**

Table 4 Harnessing Tech in Sustainable Future

By 2030, tech will reduce GHG by up to 20%.	**AI & ML optimize energy & reduce waste**	**Tech firms innovating to support sustainability**

Policy Implementations: Sustainability Initiatives by Google and Microsoft.

Google and Microsoft have put in place different policies to facilitate their sustainability programs. These policies would be able to enlighten the future policy and would be able to ensure the sustainability of the technology industry.

The Policy Implementations of Google.

- **Renewable Energy Policy:** Google strives to use fully renewable energy to power its operations (Google, 2022).
- **Sustainable Supply Chain Policy:** Google collaborates with suppliers in order to minimize waste and pollution (Google, 2022).
- **Employee Engagement Policy:** Google promotes the involvement of employees in sustainability programs (Google, 2022).

Policy Implementations of Microsoft.

- **Carbon Neutrality Policy:** Microsoft is planning on turning carbon neutral by 2030 (Microsoft, 2022).
- **Sustainable Operations Policy:** Microsoft has a sustainable operations policy, including the reduction of water consumption (Microsoft, 2022).
- **Circular Economy Policy:** As a way of lowering waste and enhancing sustainability, Microsoft implements the principles of the circular economy (Microsoft, 2022).

Educating Future Policy Making.

- **Establishing Big Vision goals:** The policy implementation at Google and Microsoft shows the significance of establishing big vision sustainability goals.
- **Stakeholder Engagement:** The two companies involve stakeholders such as employees and suppliers in ensuring the practice of sustainability.
- **Transparency and Reporting:** The transparency and reporting practices in Google and Microsoft foster accountability and inform the future policy choices.

Best Practice: Sustainability Initiatives.

The best practices that companies can use to conduct similar sustainability efforts include:

- **Set Ambitious Goals**

Illustration: Google and Microsoft are aiming to achieve renewable energy (Google, 2022; Microsoft, 2022).

Best Practice: Have specific, measurable, and attainable sustainability objectives.

- **Engage Stakeholders**

Illustration: Employee engagement and supplier collaborations of Google and Microsoft (Google, 2022; Microsoft, 2022).

Best Practice: Involve the stakeholders, such as employees, suppliers, and customers, in sustainability initiatives.

- **Invest in Renewable Energy**

E.g., the investments of Google and Microsoft in renewable energy (Google, 2022; Microsoft, 2022).

Best Practice: Invest in other renewable sources of energy, including solar and wind energy.

- **Adopt Sustainable Operations.**

An example of sustainable operations practices is Microsoft (Microsoft, 2022).

Best Practice: Adopt operations that are sustainable in their operations, like cutting down on water and waste.

- **Implementation of Circular Economy Principles.**

Illustration: The circular economy of Microsoft (Microsoft, 2022).

Best Practice: Embrace the principles of the circular economy in order to minimize waste and enhance a sustainable environment.

- **Monitor and Report Progress**

Example: The sustainability reporting of Google and Microsoft (Google, 2022; Microsoft, 2022).
Best Practice: Survey and report on sustainability goals progress.
Through these best practices, the companies will be in a position to undertake effective sustainability initiatives and minimize their environmental impact.

Recommendations

- **Invest in Renewable Energy:** Companies will be able to lower their carbon footprint by investing in renewable energy sources.
- **Establish Sustainable Technologies:** The companies will be able to create and utilize sustainable technologies to initiate environmental change.
- **Collaborate for sustainability:** Firms can involve stakeholders in their quest to create industry-wide sustainability initiatives.

Future Scope

This study can be extended by further research in the future by:

- **Increasing the scope:** A broader study of sustainability activities in the technology sector, with a bigger sample of firms.
- **Comparative analysis:** Comparing the sustainability efforts of technology companies with any other industry.
- **Longitudinal study:** In this instance, it is possible to conduct a longitudinal study to focus on how sustainability initiatives can influence the performance of companies and the environmental consequences over time.

Limitations

There are a number of limitations in this case study, such as

- **Low external validity:** The results of this case study cannot be generalized to other companies and industries, as it only focuses on two technology companies.
- **Relying on publicly available information:** The study used publicly available information that might not give a complete picture of sustainability initiatives of Google and Microsoft.

With its qualitative research method and a mix of both primary and secondary data sources, the case study offers a comprehensive perspective of the sustainability activities of Google and Microsoft and the implication of the same to the technology industry.

Practical Implications

The results of this case study have several practical implications for technology businesses and policymakers:

- **Sustainability strategy development:** The best practices that are learned through this study can be used by the technology companies to design their own sustainability strategies, which minimize their environmental impact.
- **Investment in renewable energy:**

The companies have an option of investing in renewable energy sources, including solar power and wind power, to decrease their use of fossil fuels and decrease their carbon footprint.

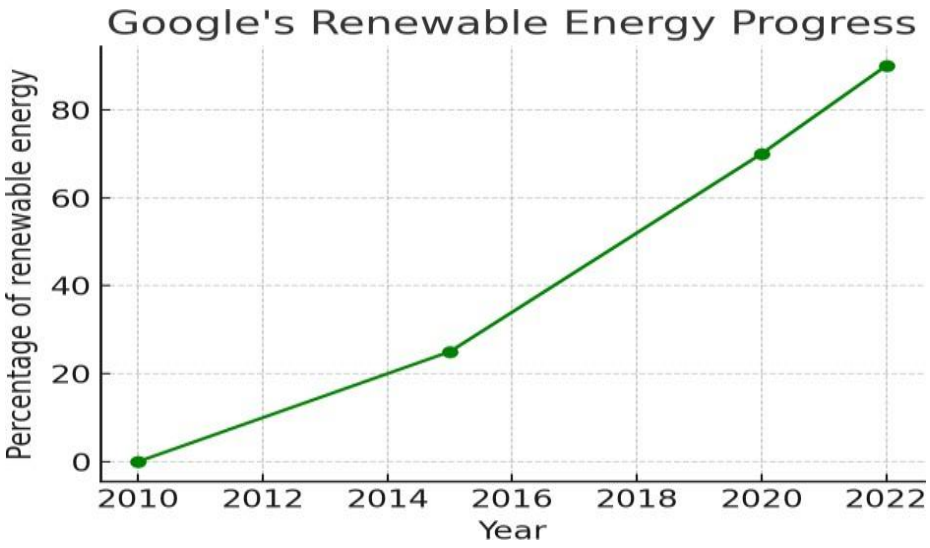
- **Supply chain management:** Technology firms can collaborate with suppliers to make the supply chain sustainable and minimize wastage during the supply chain.
- **Engagement with stakeholders:** Compensations can interact with their stakeholders, such as employees, clients, and investors, so as to ensure sustainability and earn trust.
- **Policy formulation:** The results of this study can be utilized by policy makers to formulate policies and regulations that favour sustainability in the technology sector.

CONCLUSION

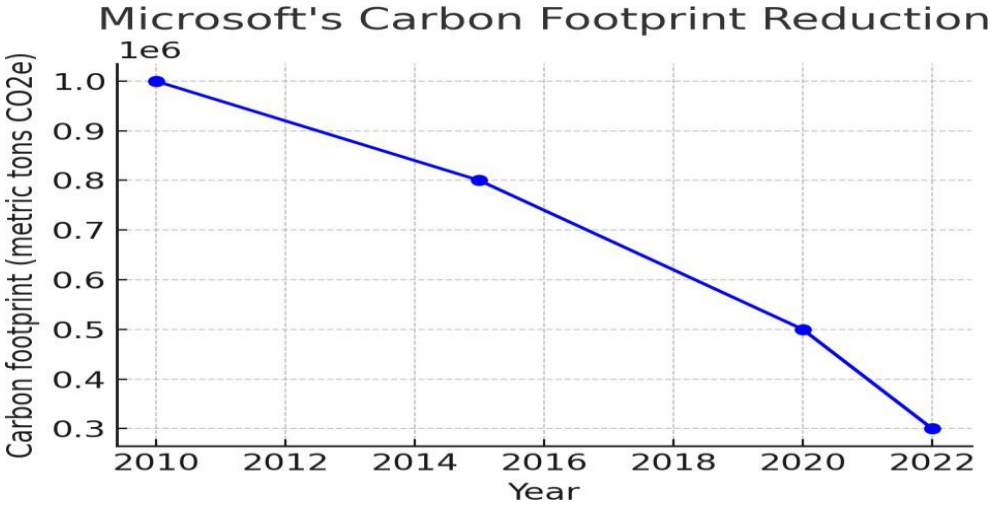
This study has discussed sustainability initiatives used by two leading technology companies, Google and Microsoft. The results indicate that these companies have achieved a lot in minimizing their environmental footprint and ensuring sustainability in a number of ways, such as investing in renewable energy, adopting sustainable operations, and incorporating the concept of a circular economy. The research also recognizes the best practices and the policy implementation that can be used in the future to embark on sustainability in the technology industry. In general, the proposed study can be relevant to the increasing amount of sustainability research in the technology sector and to the significance of corporate sustainability to the environment and business performance.

Progress and Impact of Systematic Initiatives

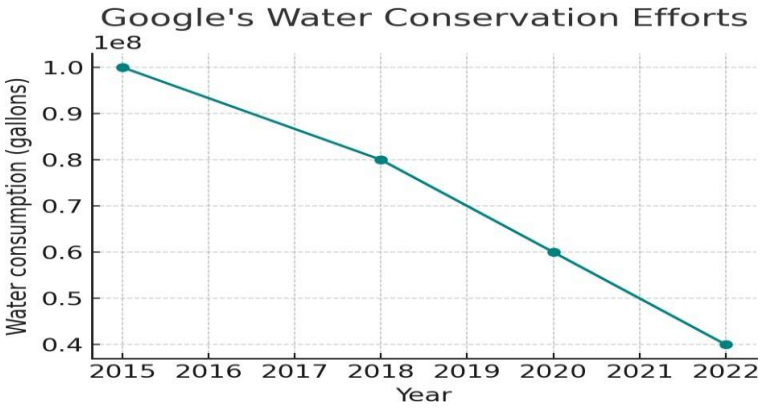
This chart shows Google's progress in increasing its use of renewable energy over time.



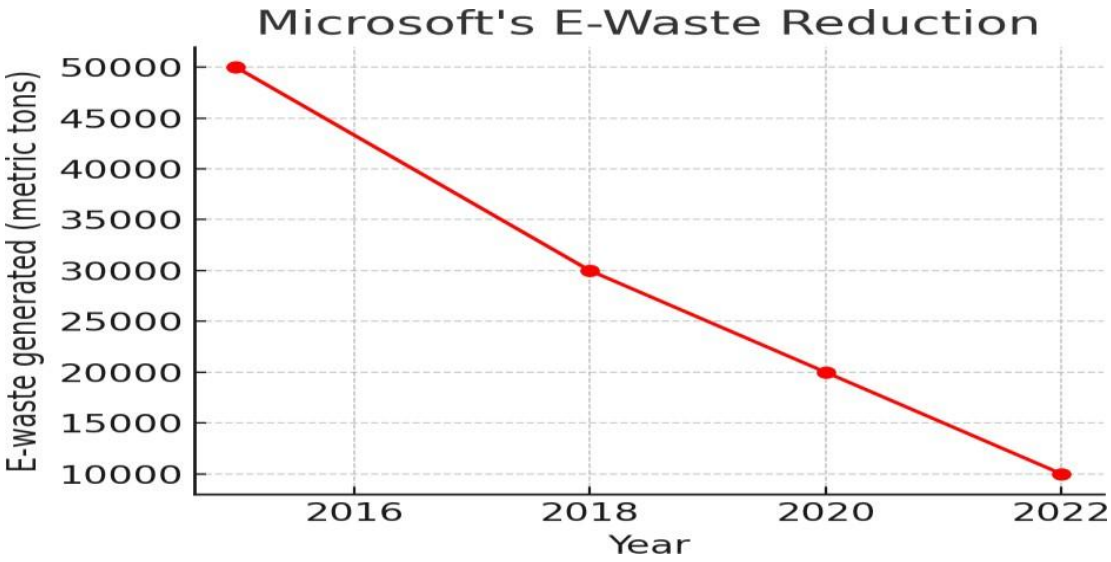
This chart shows Microsoft's progress in reducing its carbon footprint over time.



This chart shows Google's progress in reducing its water consumption over time.



This chart shows Microsoft's progress in reducing its e-waste generation over time.



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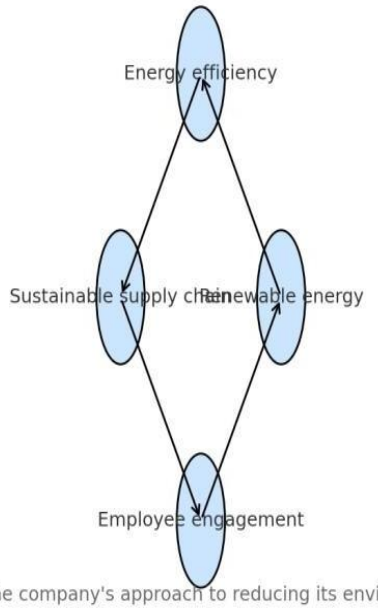
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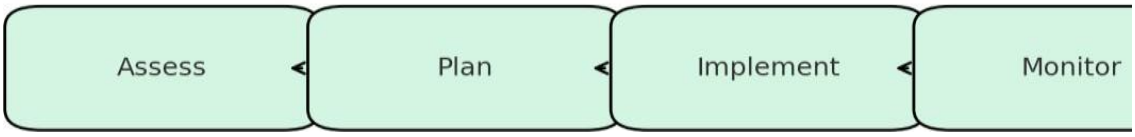


Google's Sustainability Framework

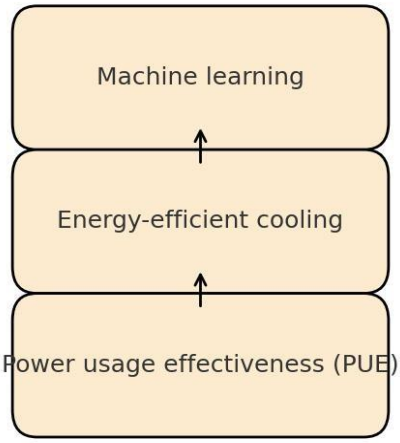


Google's sustainability framework outlines the company's approach to reducing its environmental impact and promoting sustainability.

Microsoft's Sustainability Process

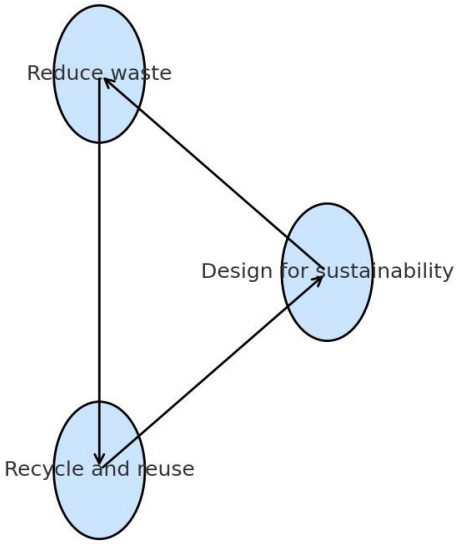


Google's Data Center Efficiency



Google's data center efficiency initiatives reduce energy consumption and environmental impact.

Microsoft's Circular Economy Approach



Microsoft's circular economy approach aims to reduce waste and promote sustainability in its products and services.

WOMEN ENTREPRENEURS AS CLIMATE CRUSADERS A CASE STUDY OF WOMAN LED ENTERPRISES COMBATING CLIMATE CHANGE

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ABSTRACT:

Climate change stands as one of the most daunting challenges that mankind is facing presently. Climate change poses various threats such as dwindling resources, increasing sea levels, erratic weather patterns, and less consistent growing seasons, all of which could have an impact on almost every element of our existence. In the year 2023, Asia remained the most disaster-prone region in terms of weather, climate, and water hazards. According to the World Meteorological Organization's (WMO) study, floods and storms caused the most reported casualties and economic losses, along with a great impact from heatwaves. (state of the climate in Asia, WMO-No. 1350). Controlling the global climate change. Mitigating this climate crisis has been a central objective of governments and regulatory bodies around the globe.

International initiatives like the Paris Agreement (December 12, 2015) and the Sustainable Development Goals (SDGs) of the United Nations have been launched to reduce greenhouse gas emissions and advance sustainable development. India's union budget for 2024 has been crafted with an emphasis on advancing green energy, climate resilient agriculture and several other initiatives which focuses on achieving India's climate goals. In order to address these issues related to climate change, entrepreneurs will play a crucial role as leaders by fostering innovation and putting into practice workable solutions. This particular paper provides number of case studies and data-based reports analysed and reviewed to explore the connection between women led start-ups and the steps taken by women entrepreneur in mitigating the unusual climate changes and their capability to stand persistent in the face of threats posed by climate changes. In this paper, several case studies and data-based reports are reviewed to explore the relationship between women led enterprises and their ability to be resilient in the face of a changing climate or increase actions that mitigate changes in the climate. The paper emphasizes that women entrepreneurs with their unique knowledge and experiences, including close associations with nature-based production and management, can prove to be a invaluable human resource in the fight against climate change. They bring valuable knowledge to develop responses that effectively address environmental

problems and adapt to them. Additionally, improving the capacity of women entrepreneurs to empower them and augment their efforts with tech-related solutions to solve this particular 'wicked' problem is suggested.

KEY WORDS – Climate change, women led enterprises, women dominated sectors sustainable development goal, carbon emission, green economy, climate resilience

INTRODUCTION

Climate change, which refers to the prolonged alteration in weather patterns from the tropics to the poles, poses a significant challenge on a worldwide scale. It is a pressing issue that impacts various sectors. (Abbas et al.2021) The consequences of climate change are far-reaching, affecting not only the environment but also societal well-being and development. As temperatures rise and extreme weather events become more frequent, the need for urgent action to mitigate these impacts has never been more evident. Climate change causes rising temperatures across the globe (Battisti and Naylor 2009; Schuurmans 2021; Weisheimer and Palmer 2005; Yadav et al. 2015). With the beginning of the industrial revolution, the problem of earth climate grew exponentially *(Leppänen et al. 2014).* It is reported that immediate attention and appropriate action may increase the likelihood of overcoming its devastating effects. According to the World Health Organization, between 2030 and 2050, climate-related illnesses like heat stress, malaria, and malnourishment will claim the lives of a quarter of a million people (WHO, 2018).

Women are more likely to work in industries that are vulnerable to climate change. Climate change is expected to have a greater impact on women in sectors such as agriculture, forestry, healthcare, and tourism than men. *Camey C. et al. (2020)* In developing countries, women are the primary food producers, accounting for two-thirds of the global agricultural labour force*. (Doss C., & R. Meinzen-Dick.et al 2018).*

Women's knowledge of natural resources can lead to the development of comprehensive solutions to climate change, which can have positive side effects. For instance, the field of climate action is beginning to acknowledge the role that women's resource management expertise can play in implementing long-term, sustainable practices. Policies for low-carbon development that are equitable, efficient, and effective must focus on women as important and core stakeholders so that their expertise can be utilized *(PWC, UNGC 2022).*

Gender equality and women's empowerment are crucial in order to combat climate change, with women playing a pivotal role in achieving the Sustainable Development Goals (SDGs). These objectives, which comprise 17 targets intended to direct worldwide efforts toward sustainable development by 2030, connect in three areas that are essential for taking meaningful action on climate change.

The Economic Dimension: Promoting sustainable business practices, advancing environmentally friendly innovations, and

reducing risks associated with climate change all depend on women's equitable participation in the green economy by enhancing women's economic agency, they are empowered to spearhead the transition to solutions for climate change and improve economies' resilience and efficiency.

Social Dimension: Women are needed in leadership roles to enhance the health, safety, and well-being of communities affected by climate change. At the same time, by ensuring women's equal access to resources, education, and decision-making, societies can enhance social resilience by creating more inclusive and effective approaches to adapt and mitigate against climate change.

Environmental Dimension: Women are critical actors in resource management and environmental stewardship. Their involvement in environmental decision-making leads to improved efficiency in the resource economy-contributes to more sustainable natural resource practices, and generates effective climate actions. Thus, empowering women to lead environmental projects is crucial to realizing the SDGs while addressing the negative impacts of climate change. *(Fernández et al., 2021)*

Due to their distinct experience, knowledge, and strong connections to nature-based production and management, women entrepreneurs have the potential to make uplifting contributions in the fight against climate change. They provide valuable evidence that can be utilized to develop options that effectively reduce and adapt to environmental challenges *(ICRW, 2020)*.

Women are more likely than men to take action that reduces emissions *(Oliver Wyman 2020).* Women in seven of 11 developed countries consider climate change to be one of the most important issues facing their communities and that significant changes must occur to their lifestyles *(Zainulbhai, 2015).* Evidence points to women entrepreneurs being more conscientious in greening their businesses, as well as being more active in seeking out green networking opportunities than their male counterparts *(Braun, 2010).*

This paper examines three distinctive women-led, green businesses that are working to effectuate climate change and explores barriers facing women and the role that technology may play in addressing those barriers to develop more effective climate change management strategies.

REVIEW OF LITERATURE

The stewardship of women entrepreneur in addressing issues related to climate change has received significant attentiveness in recent years. There are numerous researches evaluating the contributions made by women entrepreneur in the area of environment management, sustainable business practices and green business practices. The studies also highlight how women will be largely affected by the threats posed by climate change because of large number of women being employed in the sectors which are directly impacted by the climate.

Women and climate change: a unique perspective

Women are comparatively more involved in management of natural resources in comparison to their male counterparts and

can implement their knowledge to come up with innovative and sustainable solutions to counter the issues associated with climate change. Works by Doss & Meinzen-Dick (2018) emphasize that in the developing world, women are typically the key food producers and important stakeholders in managing natural resources. This positioning indeed empowers them to contribute meaningfully to resilience and adaptation strategies relating to climate. Moreover, it has been proved through research that women are more likely to adopt behaviours that reduce greenhouse gas emissions compared to men, which makes them key players in addressing climate change.

Women entrepreneur in green economy

In order to mitigate issues arising due to climate change it is necessary that women business owners involve themselves in sustainable business practices. Woman are more inclined toward sustainable business practices when compared to their male counterparts. As cited by by Braun (2010) and Fernández et al. (2021), women entrepreneurs exhibit more active green networking and have a greater tendency to engage in environmentally friendly business practices than men. They, therefore, are a force in driving an equitable, efficient, and sustainable economy based on green principles.

Difficulties faced by women entrepreneur

Despite being a crucial player in combating climate associated issues female entrepreneur face a lot of obstacles in their journey which often hinder their participation as well as limit their growth. These challenges based on the literature are largely structural in nature, including limited financial framework for women and social capital restrictions related to entrepreneurial ecosystems due to gender discriminations, professional vs. caregiving responsibilities etc. The World Bank, 2014 report claimed Climate Innovations are locked out of the market because woman have a harder time securing financing to meet high initial capital costs and long payback periods. Moreover, these are compounded by socio-cultural norms which create obstacles for the complete inclusion of women in decision-making processes and at leadership levels within the green sectors.

Role of technology and innovation

Technology will play a crucial role in empowering women entrepreneur to come up with sustainable and scalable solutions to combat climate change. Augmenting female-led enterprises with technology will help to improve efficiency, reduce operational costs and will help them to expand further in the market (pwc 2022). For example technology such as IoT-enabled bioreactors from women-led companies like Billion Carbon Solutions are used to turn waste into high-value by-products, helping address climate change. But, literature also highlights that there is a need to provide more focused support enabling women entrepreneurs in utilizing these technologies meaningfully to their advantage (IFC, 2023).

Policy Support and Finance framework

The literature review also emphasizes the importance of gender-sensitive financial instruments and policy changes to help fund-women led climate tech entrepreneurs. They suggested to design

innovative financial mechanisms including green finance, sustainable finance and gender-inclusive investment fund for empowering women-led businesses *(IFC 2023; We-Fi 2022)*. Moreover, women leadership and mentorship programmes as well as digital literacy followed by policies encouraging more female in environmental sectors are critical for climate gap within the entrepreneurship developments *(UN Women, 2023).*

Future Research and Practice Implications

The current literature recognizes how women entrepreneurs can contribute to climate action and yet research on effective strategies for addressing the barriers they experience is significantly lacking. If future work accounts for individual programs or policies, the intersection of emerging technologies and women's abilities to directly contribute to climate change mitigation/adaptation efforts should be further examined.

METHODOLOGY

Research publications, articles, and reports collected from various research databases were comprehensively reviewed by the study. This comprehensive examination highlights the need for targeted female-focused climate change solutions and promotes their unique strategies. There is an attempt to evaluate how these initiatives promoted by women fit into the overall preservation of climate, as well as the importance of their vision and agency in the development of climate change solutions.

Also, the study seeks to determine various ways in which technology contributes to the effectiveness of these businesses. They try to define how one can avoid the existing issues with the help of new technology, and make climate-related projects more efficient. The report also provides an analysis of the potential benefits that technology may introduce in this field, such as being more efficient, making it easier to make data-driven decisions, and doing more.

In addition to highlighting the prospects of technology, the study pays significant attention to the common challenges that the female entrepreneurs face in their climate entrepreneurship. Such challenges include volatility in technology, social attitudes towards women, and limited resource availability. By examining these barriers, the study provides useful information on the multifaceted nature of such challenges and appropriate recommendations to help women entrepreneurs in their endeavours to tackle climate change.

CASE STUDIES: INSPIRING WOMEN LED ENTERPRISES

BILLION CARBON SOLUTIONS (INDIA)

Overview

By using food waste to produce nutrient rich fertilizer that will be used to improve the quality of the soil, Billion Carbon Solutions aims at solving the issue of soil degradation through proper utilization of a resource that otherwise would go to waste and enhance the emission of greenhouse gases further.

Founders:

Ankita Vijayvergiya & Nikhil Vijayvergiya

Background:

Climate change has had negative impacts

that are so severe that there is a need to find more effective strategies. One company that is standing out in this fight is Billion Carbon, a climate tech start-up from India founded by Ankita and Nikhil Vijayvergiya.

This company was born out of a sense of responsibility towards the environment and a wish to make an actual difference in society. Billion Carbon is an excellent demonstration of the fact that perseverant commitment and purpose enables a person to change the environment for the better.

Founding vision

Billion Carbon came into existence at the initial onset of the covid pandemic crisis. In this period, Ankita Vijayvergiya who was employed in a global corporation started wondering about the real purpose of her work. When the outbreak of the pandemic made the world come to a standstill, Ankita thought about the social aspect of her job and ultimately came to the realization that she is meant to be in climate work. In this process of self-discovery, She along with her brother Nikhil started their first start-up, Nature Healers which focused on encouraging sustainable lifestyle changes.

Problem identification

In collaboration with Nature Healers, the Vijayvergiya siblings identified an overlooked but crucial intervention area of the treatment of food waste which could help cut down greenhouse gas emissions. This is what prompted the establishment of Billion Carbon, a company that seeks to eliminate waste through the useful transformation of food waste into food products using BSFL technology.

After intensive research and development for a number of years, Billion Carbon was officially entered the market in 2023.

The company's star product is an innovative, IoT-enabled bioreactor which transform food waste into high- value byproducts such as liquid biofertilizer and insect protein and lowering greenhouse gas emissions significantly.

Challenges and resilience Personal and Professional Balance

Motherhood and Entrepreneurship: Ankita had to try and find time for both being a mother and a first time entrepreneur. Very soon after the founding of BillionCarbon, she got to know that she was pregnant which was a mix of fun and fear. The physical wellbeing tasks and emotional weight during pregnancy and the bearing child phase, required her endurance. Nevertheless, all these challenges also brought valuable insights in how she would prioritize what is important in both business and family life.

Execution and Support

Appreciating the fact that she could not do it all herself, Ankita set out to create a strong support system. Her co-founder and brother, Nikhil, was very supportive and took some of the startup responsibilities upon himself. Emotionally and practically, her husband, her parents, and domestic helps relieved her so much as she juggled between motherhood and running a startup. This network became her anchor allowing her to continue having a lead role at BillionCarbon, while taking care of her baby.

Workplace Flexibility

The Power of a Home Office: It was at this time that Ankita began to run a home office not because it was comfortable but because

she had to. This was because all the work activities had to go on while she was actively working as a mother.

Strategic partners and growth

Billion Carbon was selected for the Accelerating Asia climate tech and sustainability accelerator, in conjunction with the United Nations Economic & Social Commission for Asia Pacific — enabled to attend through early 2024. The accelerator program was specifically tailored for female-led start-ups located in the Asia Pacific, and offered Billion Carbon a wealth of mentorship as well resources, exposure & networking opportunities! The program, Ankita said has guided her through the maze that climate tech investments can be.

Ankita pitched Billion Carbon's innovation at the second edition of ESCAP's Feminist Finance Forum in Bangkok, which she attended with all other accelerator participants in May 2024. She won a $5,000 seed grant — her powerful pitch proving influential in the fight against climate change — that will help to broaden Billion Carbon.

Future outlook

The roadmap of Billion Carbon as such is an ambitious, but well-defined one. Kohler aims for one billion fewer tonnes of CO2 by 2030. This is the goal with which the start-up passes, it has maintained that to make this a reality its technology must improve 10 fold now evert year along with strengthening market position against competition. She is hopeful, because climate technology has – more recently — been regularly cited as an important investment segment and offers instruments for funding these innovative solutions.

The way Ankita deals with problems shows grit and determination. How Hayya believes- "It is never a no, but always about finding out other ways around it", perfectly summing up what BillionCarbon aims to do.

TRINANO TECHNOLOGIES (INDIA)

Overview

Tri-nano technology creates a light-trapping nano coating that can be applied to both new and old solar panels. The coating created by Tri-nano Technologies raises productivity by 10% by enhancing the efficiency of solar cells to produce more energy. It also prolongs the life of the panels and helps reduce the need for cleaning.

Founder:

Dr. Anshu Dandia (cofounder & Director)
Dr. Harsh Sethi (co-founder & CEO)

Background:

Tri-nano technologies Pvt. Ltd. came into existence in 2022 by the collaborative efforts of Dr. Anshu Dandia & Dr. Harsh Sethi.

Trinano technologies is an Indian start-up which has developed a nanocoating for solar panels that improves power output and lowers maintenance costs. The technology has three properties: light trapping, anti- reflection, and self-cleaning. The nanocoating has also been tested at the National Centre for Photovoltaic Research and Education (NCPRE), IIT Bombay and National Institute of Solar Energy (NISE) and a 7% to 8% gain in power output was measured in nanocoated solar panel in comparison to the conventional commercial solar panels. *(Dandia et.al,2022)*

Problem identification & solutions

provided

India's major reliance on non-renewable sources such as fossil fuels burning poses a threat to environment. Burning of fossil fuels leads to the release of large amount of green house gases which facilitate to the climate related issues such as global warming. This indigenous nano-coating technology has the potential to significantly improve solar panel energy output and contribute to India's climate change and Net Zero targets.

Solar energy, particularly photovoltaic (PV) technology, has numerous advantages, including safety, dependability, efficiency, non-pollution, and widespread availability. PV power has grown in popularity worldwide in recent decades as part of the clean energy movement. With enormous market potential, PV power is expected to account for a significant portion of global energy consumption and be one of the primary energy sources this century *(xan et al., 2018, Bakhiyi et al., 2014).*

But along with the above listed advantages of solar energy solar panels themselves pose another environmental issue: once their useful life is up, they become a type of hazardous waste. During the first 25 years of development, solar panels had a long service life, making recycling waste panels unnecessary. However, a significant proportion of the first batch of solar panels installed are now being retired, and proper disposal of end-of-life solar panels is becoming an increasingly important environmental issue *(xan et al.,2018, Aman et al., 2015).*

The nanocoating Is eco-friendly, durable, and can be applied to panels without waste, making it a sustainable solution for clean solar energy.

Tri-nano technology's nanocoating not only increases the energy output but also augment the panels with a self-cleaning technology and also helps in keeping the panels cooler leading to the reduction in cleaning cost as well as increasing the life-span of solar panels.

TECH-X-EARTHSPACE (INDIA)

Overview

TechXEarthSpace is a technology development company that focuses on developing innovative solutions to global challenges. This company is geared towards solving some of the key global challenges including climate change and environmental degradation in the long run. TechXEarthSpace's team is aiming at technology creation and its marketing for CO2 capture and utilization, hydrogen generation and storage, geo-energy, space mining, and exploration. The company also holds the view that the future of the planet and the inhabitants thereof, is safe in the hands of people and the company intends to make a difference.

Founders

Ms. Swati K J (Founder & CEO)

Problem Identification

TechXEarthSpace has realized the urgencies of originating unique as well as sustainable approaches to the major world issues humankind face today, especially the climatic change and the deterioration of the environment.

Management of the company understands the significance of issues in question and the applicability of modern technologies. Concerning areas of focus, TechXEarthSpace is formed to cater with

challenges as CO2 emissions, hydrogen generation and storage, geo-energy, space resources and mining. The general problem is the absence of adequate technologies that can be implemented on a large scale to control CO2 emissions and enhance sustainable resources of energy as well as resource acquisition from space.

Key innovations and projects

CO2 Capture Technologies

TechXEarthSpace has created an indigenous technology for extracting CO2 from atmospheric air. The company is seeking funding to advance this technology through a pilot project aimed at:

Removing CO2 from biogas: Because biogas contains approximately 35% CO2, removing it can improve clean combustion while reducing environmental impact.

Converting captured CO2 to hydrogen (H2): This step will improve the efficiency and sustainability of the process.

Geo-energy initiatives

The company is working on advanced CO2 fracturing technologies that will replace traditional hydraulic fracturing methods. The technology aims to:

Create smooth fractures in a variety of reservoirs without using chemicals.

Improved methane recovery in coal bed methane operations has the potential to recover more than 90% of methane. Increase oil recovery from conventional and unconventional oil and gas resources.

Make it easier to fracture geothermal reservoirs.

Subterranean Energy Storage

The business acknowledges that subterranean energy storage is a developing industry on Earth and in space. Important areas of attention consist of: storing hydrogen (H2) and carbon dioxide (CO2) to create CO2 credits and useful byproducts. Getting ready for the upcoming storage requirements of the moon and Mars colonization.

Future Outlook

TechXEarthSpace is poised to make major strides in the fields of environmental sustainability and exploration of space. With ongoing R&D and strategic collaborations, the company is preparing to revolutionize CO2 capture, geo-energy, and space mining technologies. Their commitment to developing cutting-edge solutions highlights their role in shaping a more sustainable and innovative future.

Table1 (Summarization of the case studies and common inference)

Aspect	Billion Carbon Solutions (India)	Tech-nano (India)	TechX Earth Space (India)	Inference
Overview	Converts food waste into biofertilizer using BSFL	Develops nano- coating to improve solar panel efficiency	Develops solutions for CO2 capture, H2 storage, and space exploration	All three companies focus on innovative, sustainable technologies to address environmental issues.
Founders	Ankita & Nikhil Vijayvergiya	Dr. Anshu Dandia & Dr. Harsh Sethi	Ms. Swati K J	All companies are founded by female individuals with strong leadership and a commitment to sustainability.
Founding Vision/Problem Identification	Identified food waste as a major contributor to GHG emissions	Addresses inefficiency and high maintenance of solar panels	Addresses global challenges like CO2 emissions and sustainable energy storage	All companies identified critical environmental challenges and developed innovative solutions to address them.
Key Innovations	IoT-enabled bioreactors to convert food waste into valuable byproducts	Nano-coating that enhances solar panel efficiency and longevity	CO2 capture technology, geo-energy initiatives, and subterranean energy storage	All companies developed advanced technologies to mitigate environmental impact and improve resource efficiency.
Challenges	Balancing motherhood with entrepreneurship, funding	Testing and commercializing g new technology	Securing funding and advancing R&D	Each company faces challenges in technology development, funding, and scaling their innovations.

Strategic Partners/ Growth	Joined Acceleratin g Asia's climate tech accelerator, received seed grant	Tested technology at NCPRE and NISE, achieved 7-8% efficiency gain	Engaged in R&D and strategic collaborations for future advancements	All companies seek partnerships, mentorship, and testing opportunities to validate and scale their innovations.
Future Outlook	Aims to reduce CO2 emissions by one billion tonnes by 2030	Contributes to India's climate goals with improved solar panel technology	Poised to revolutionize CO2 capture, geo- energy, and space mining	All companies have clear, ambitious goals for their technology's impact on sustainability and environmental protection.

CHALLENGES FACED BY WOMAN ENTREPRENUER

Despite the critical role that women entrepreneurs play in mitigating climate change and their significant impact on promoting green entrepreneurship practices, they continue to face a slew of challenges that prevent them from reaching their full potential.

These difficulties are deeply rooted in systemic barriers, such as limited access to financial resources, gender biases within the entrepreneurial ecosystem, and the complexities of juggling professional responsibilities and traditional caregiving roles.

Women have historically been underrepresented in the areas that are often seen to be most crucial for climate solutions, which may exacerbate already-existing gender disparities. The industries with the highest climate capital attraction ratios also have the lowest percentage of female business executives. For instance, the energy industry garnered more than half of the $632 billion in average annual climate investment (including public and private sources) in 2019 and 2020 *(Climate Policy Initiative, 2022).* Women make up just 7% of startup founders in this sector *(IEA, 2022).*16 Only a small percentage of global venture capital funding goes to sectors like food, agriculture, and land use—where women may have comparative advantages—receiving $11 billion in 2021, compared to $16 billion for energy and over $50 billion for transportation *(PwC, 2022).*

Figure 1. % Women in leadership is estimated using high-frequency data from LinkedIn for 155 countries to examine women's representation in business in 2022 (Source: (World Economic Forum, 2022).

Climate innovations may need investors to make sizable upfront capital expenditures and extend their payback times, which may make it more challenging to draw in venture capital and other forms of funding *(World Bank, 2014).* A single renewable energy project may require billions of dollars in upfront funding, and breakthrough technologies—also referred to as "deep tech"—need intricate development procedures
and specific revenue models in order to scale successfully *(So, 2021).* In venture capital and standard bank loan lines *(Montoya et al., 2020; Brock & de Haas, 2022),* female founders typically have to contend with greater interest rates and smaller ticket sizes than their male counterparts. There is a dearth of technical support with a climate focus, such as helping small firms access climate financing and providing gender- inclusive technical assistance *(ANDE, 2022).*

Many women struggle to strike a balance between their personal and professional lives because they frequently juggle many roles, including those of lovers, caretakers, professionals, and occasionally the main administrators of domestic tasks. Because corporate structures and social expectations frequently fail to provide sufficient support for flexible work schedules, parental leave, or child care options that meet these needs, striking this balance can be particularly difficult. Trying to balance the demands of both worlds can cause stress, fatigue, and guilt in women, which can negatively affect their mental health and general wellbeing. These difficulties may also prevent people from advancing in their careers since taking time off for family obligations or working fewer hours may be interpreted as a lack of dedication to their professions. *(Niang et al. 2019).*

In nations with strong social norms, women are subject to a greater number of social rules than men. Due to these standards, women entrepreneurs face particular challenges when trying to scale up their businesses. These challenges include: a lack of working capital and finance (money); administrative and regulatory requirements; a lack of management training or skills; marketing; technology; limited mobility; low risk-taking ability and lack of confidence (MarketLine); and sociocultural barriers (Macro environment) *(Bharthvajan 2014).* Gender inequality is well ingrained in the society as a result of these conventions.

SOLUTIONS TO OVERCOME TH CHALLENGES

In order to effectively bring their ideas to market, women entrepreneurs heading early-stage climate tech startups with significant growth potential and a focus on delivering large-scale climate impact need access to resources including incubators, accelerators, seed finance, and patient capital. The following kinds of funding options could be advantageous for these leaders in climate technology:

Financial assistance

Assistance from seed funds, incubators, and accelerators to help women-led businesses in their early stages develop and get ready for later-stage investment. *(IFC, 2023)*

Venture capital and private equity funding to hasten the deployment, scalability, and commercial feasibility of women-owned

and led climate solutions for wider industry- or commercial-level acceptance. *(IFC, 2023)*

Cutting-edge climate finance tools, such as green or blue finance, transition finance, sustainable finance, and sustainability-linked finance, are available through development finance institutions or financial intermediaries and are used to invest in climate technologies with a focus on women- owned or led businesses. *(IFC, 2023)*

Growth capital from banks, governments, and other providers to pay for large-scale technology deployment, especially to assist women-led businesses and infrastructure owners who no longer need new technology but instead require ongoing funding for low-carbon technologies that are already in place. *(IFC, 2023)*

ADDRESSING THE GENDER DISPARITY

Increasing engagement – An atmosphere that encourages more female climate entrepreneurs who are prepared to embrace cutting-edge green-tech solutions must be established. More women should hold senior positions in corporations, banks, and venture capital firms that can help female climate entrepreneurs. *(pwc analysis)*

Knowledge development and technology integration

Women require knowledge-building sessions and workshops in order to engage with their communities and potentially develop and scale up businesses. The ongoing and systemic disparity in education levels and social status has harmed women's confidence in expanding their businesses. Technology integration, combined with targeted training, can help bridge this gap. *(pwc analysis)*

Combining access and affordability policies with education initiatives can improve digital literacy. Addressing conscious and unconscious biases and stereotypes can help increase women's participation in digital environments. To increase digital trust among women and girls and maximize their opportunities in the digital era, it may be necessary to support such policies with cyber security initiatives**.** *(pwc analysis)*

Upskilling and proper mentorship

Women entrepreneurs in India can benefit significantly from acquiring essential business and management skills through mentorship programs led by successful and experienced professionals. These initiatives not only provide women with the knowledge and expertise required to navigate the complexities of running a business, but they also foster an environment of innovation and creativity within their companies. Mentoring makes it easier for women entrepreneurs to be connected to different people that will provide valuable information and bolster their confidence in matters to be undertaken. This in turn enables them to expand and sustain their businesses for economic growth and development thus enhancing chances of success. *(PWC analysis)*

DISCUSSION

The case studies and data showed the importance of women led businesses in addressing climate change through transformative, innovative and sustainable business practices. Women entrepreneurs are essential actors in the green economy, as they contribute unique perspectives,

knowledge and challenges faced with resilience. This presentation will summarize the results from the case studies, discuss implications for climate action more broadly and underline some of the structural barriers women entrepreneurs face in this domain.

The success stories of Billion Carbon Solutions, Trinano Technologies and TechXEarthSpace indicate that women owned businesses are well poised to drive sustainable innovations, having identified some of the most pertinent environmental issues concerning food waste management, inefficient use of solar energy, and CO2 collection and harnessed technology to deliver scalable solutions. Women leaders in the form of Ankita Vijayvergiya, Dr. Anshu Dandia and Ms. Swati K J provide testimony to the fact that women entrepreneurs not only have the ability to recognize critical environmental problems but also to develop and commercialize innovative solutions in line with global climate goals.

The success of these businesses highlights an important intersection of gender and sustainability, that is, the potential for women's roles in natural resource management 14 and in community-based solutions 2 to translate into effective climate action.16 For example, Billion Carbon Solutions'10 approach to transforming food waste into biofertilizer aligns with the principles of the circular economy and sustainable agriculture, both of which have long involved a predominately female workforce. Similarly, Trinano Technologies'13 nanocoating technology improves renewable energy efficiency — an essential aspect of sustainable development —and TechXEarthSpace's12 CO2 capture and its associated geo-energy work aligns with global objectives for greenhouse gas emissions reduction.

Research has consistently shown that when women are involved in environmental decision-making, we develop more sustainable and inclusive climate policy. *(Oliver Wyman, 2020)* Women's unique awareness of community needs, as well as our tendency to adopt more environmentally friendly practices, can help make climate mitigation more successful. The firms featured here show that when women have access to resources and opportunities, we can catalyse transformative advances in climate resilience and adaptation.

However, the study stresses that if women are to realise their full potential as climate leaders they need tailored support to help them overcome sex-specific barriers. Women entrepreneurs in the green economy also have the potential to contribute significantly to achieving the Sustainable Development Goals (SDGs), particularly those related to gender equality (SDG 5), climate action (SDG 13), and sustainable economic growth (SDG 8). Thus, policies that enhance women's access to finance, technology, and markets are not only good for gender equality, they are equally important in terms of overall environmental and economic sustainability in the long term.

Women entrepreneurs in the climate sector face severe limitations that hinder their ability to contribute to climate action. Limited financial access, persistent gender biases, and the challenging trade-off

between professional and caregiving roles are all major barriers. Inequities in venture capital and traditional banking systems often favor businesses led by men, resulting in lower investment in women-led enterprises and higher interest rates *(Montoya et al., 2020).*

This funding deficiency hinders the ability of these nations to grow and progress in climate technology. Moreover, female representation in the energy industry remains low, which is true for the founders of startups as well who amount to only 7% *(IEA, 2022).* This constrains the type and quality of climate solutions. These challenges are further compounded by societal demands or culture regarding caring for the elderly as class females such as Ankita Vijayvergiya experience while dealing with both entrepreneurship and family responsibilities.

To empower women entrepreneurs in climate action, it is critical to address structural barriers through targeted measures: introduce gender palm funding, flexible financial tools especially in fields such as sustainable farming and clean energy; strengthen networks/ support systems through female link-ups and educative resources, close to climate technology incubators; ensure gender sensitive policies such as paternity/maternity leave and flexible working hours.

LIMITATION

This particular paper was largely based on prior existing research work i.e secondary data. Interaction with woman entrepreneur in the climate sector would provide valuable insights about the real-time problems that women entrepreneur face. Also this will allow in better understanding of the motivation behind the initiative and various challenges faced throughout the entrepreneurial journey.

CONCLUSION

The review paper provided number of case studies to assess the role of female entrepreneurs prevalent in the climate & green-entrepreneurship related sectors. Star-ups and businesses lead by women can play a major role in combatting the challenges posed by the rapid climate change. Women in business are often subjected to gender biases, limited access to the capital, social expectations on their role as a caregiver at homes. These obstacles often limit the ability of female entrepreneur to scale ideas and work on their full potentials in order to contribute to climate actions.

It is necessary to eliminate these obstacles in order to increase the influence of women in the sectors related to climate control and successfully capitalize on the contributions of female entrepreneurs. It is important to develop gender sensitive funding models, developing reinforced networks with mentors, augmenting women entrepreneur with technology such as artificial intelligence to empower them and promoting support environment in the workspace can help in mitigating the obstacles women face in their entrepreneurial journey.

By addressing the above mentioned issue, we can create a more equitable and innovative climate economy. Providing support to female entrepreneurs not only recognizes their individual contributions but also broadens the scope of solutions necessary to mobilize the climate

challenge. A collaborative effort to address these barriers would catalyse movement toward a more sustainable and inclusive future for everyone we want all voices and capabilities to be heard and harnessed in the global climate solution.

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AN INVENTORY OPTIMIZATION MODEL FOR SUSTAINABLE SUPPLY CHAINS WITH CIRCULARITY-DRIVEN DEMAND UNDER TRADE CREDIT AND CARBON CONSTRAINTS

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ABSTRACT

This study proposes an inventory optimization model for sustainable supply chains, integrating a novel demand function driven by circularity index, price, product greenness, and advertisement. Excluding reliability considerations, the model incorporates two-level partial trade credit policies and carbon constraints under cap-and-trade mechanisms. The demand is modeled exponentially, capturing the influence of circularity and sustainability factors. The total cost per unit time is minimized using the respective algorithm. Numerical analysis demonstrates the model's effectiveness in balancing economic and environmental objectives. Managerial insights highlight the benefits of circular economy practices and green technology adoption. The model offers a framework for industries producing eco-friendly products under stringent carbon regulations.

Keywords: Inventory Optimization, Sustainable Supply Chains, Circularity Index, Trade Credit, Carbon Constraints

INTRODUCTION AND LITERATURE REVIEW

Sustainable supply chains are critical in addressing global environmental challenges while maintaining economic viability. The integration of circular economy principles, such as re- cycling and resource reuse, enhances sustainability by influencing consumer demand through the circularity index (1). This study develops an inventory optimization model that excludes reliability considerations, focusing on a demand function driven by circularity index, price, product greenness, and advertisement, under trade credit and carbon constraints.

Literature on sustainable supply chains emphasizes carbon cap-and-trade mechanisms and green technology adoption. (2) developed a model integrating trade benefits and carbon re-duction, while (3) proposed dynamic production-inventory systems under environmental con- straints. Trade credit policies, particularly two-level partial schemes, enhance liquidity and competitiveness (4). However, few studies

incorporate circularity-driven demand, which is increasingly relevant in industries producing eco-friendly products like recycled paper or biodegradable electronics (5). The Walrus Optimization Algorithm (WOA) has shown promise in solving complex, non-linear optimization problems (6). This research addresses the gap by proposing a model that combines circularity-driven demand with trade credit and carbon constraints, optimised via WOA.

MODEL DEVELOPMENT

Assumptions

The model assumes:

- Environmental sustainability is prioritized, focusing on carbon emissions and circularity.
- Demand is exponentially dependent on circularity index (CI), selling price (p), product greenness (g), and advertisement (A):

$$D(p,g,CI,A) = Ce^{(-ap+bg+cCI+dA)},$$

where $a, b, c, d, C > 0$, $a > 1$ is price sensitivity, and b, c, d represent sensitivities to green- ness, circularity, and advertisement, respectively.

- A two-level partial trade credit policy is adopted, with settlement at $t = M$ for producers and $t = N$ for customers.
- Carbon emissions are regulated via cap-and-trade and tax policies.
- Product deterioration follows a two-parameter Weibull distribution with scale parameter a and shape parameter $b \geq 1$.
- Lead time is negligible, and production rate exceeds demand.

Mathematical Model

The demand function captures the exponential influence of circularity, price, greenness, and advertisement. The inventory system considers production, demand, and deterioration over a cycle time T. Costs include:

- Setup cost (SCC), production cost (PCC), holding cost (HCC), deterioration cost (DCC).
- Advertisement cost (ACC), green technology cost (GTC), transportation cost (TC).
- Carbon emission costs based on emissions from production (k_1), transportation (k_2), holding (k_3), and deterioration (k_4).

The objective is to minimize the total cost per unit time (TCU):

$$TCU = \frac{SCC + PCC + HCC + DCC + ACC + GTC + TC + \text{Carbon Emission Costs}}{T}.$$

Two scenarios are considered:

- **Scenario 1**: $N \leq M$, where customer credit period is less than or equal to producer credit period.
- **Scenario 2**: $N > M$, with multiple cases based on settlement times.

Solution Procedure

The Walrus Optimization Algorithm (WOA), inspired by walrus foraging strategies, is em- ployed to minimize TCU (6). WOA balances exploration and exploitation through phases of migration and local search, making it suitable for high-dimensional, non-linear problems. The algorithm parameters include 10 runs, 30 generations, and a precision of 10^{-7}.

WOA is applied to optimize *TCU* for both trade credit scenarios. Default parameters (e.g.,
cost coefficients, carbon emission rates) are set based on industry standards. The algorithm converges to optimal solutions, as demonstrated in numerical examples. Surface graphs and convergence plots (similar to those in (7)) illustrate the impact of circularity index, greenness, price, and advertisement on *TCU*.

CONCLUSION

This study presents an inventory optimization model for sustainable supply chains, integrating a circularity-driven demand function with trade credit and carbon constraints. By excluding reliability, the model focuses on sustainability and circular economy principles. The exponential demand function effectively captures the influence of circularity index, price, greenness, and advertisement. WOA optimizes the total cost per unit time across trade credit scenarios, pro- viding a robust framework for industries like eco-friendly product manufacturing. Managerial insights emphasize the importance of investing in circular practices and green technologies to comply with carbon regulations and enhance competitiveness. Future research could explore stochastic demand, multi-product systems, or alternative optimization algorithms.

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BLOCKCHAIN-ENABLED ENTERPRISE ARCHITECTURE FOR AGRICULTURAL SUPPLY CHAINS: INTEGRATING SEED TRACEABILITY WITH PREDICTIVE ANALYTICS

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ABSTRACT

Agricultural supply chains face persistent challenges in seed quality assurance, traceability, and yield prediction. Current blockchain implementations function primarily as passive record-keeping systems rather than leveraging data for predictive analytics. This paper introduces a blockchain-enabled enterprise architecture that integrates seed traceability with predictive analytics to generate actionable insights supporting agricultural supply chain performance indicators. The proposed architecture combines Hyperledger Fabric with a five-layer framework unifying on-chain and off-chain data management. The predictive analytics layer incorporates machine learning regression models, time-series forecasting algorithms, and causal mediation analysis using scikit-learn and TensorFlow, implementing environmental impact modeling, quality correlation analysis, and supply chain disruption assessment. We applied bootstrap-based causal mediation analysis to 1,000 seed transactions using ordinary least squares regression with 500-iteration bootstrap resampling. Results revealed that cold storage conditions significantly improved seed quality indices ($p < 0.05$), and seed quality strongly predicted yield outcomes. While indirect effects through quality metrics were not statistically significant, direct effects demonstrated blockchain- secured environmental data's potential for agricultural decision-making through yield forecasting and risk assessment. This research contributes a novel enterprise architecture integrating blockchain traceability with predictive analytics capabilities and demonstrates causal inference application to blockchain-secured agricultural data, providing a foundation for transitioning from reactive to proactive agricultural supply chain management.

Keywords: Agriculture supply chain, Blockchain analytics, Seed traceability, Predictive modeling, Causal mediation analysis, Enterprise architecture

INTRODUCTION

Agricultural supply chains face critical challenges in seed quality assurance and traceability, where seed quality directly affects yield, food safety, and sustainability. According to the Food and Agriculture Organization, approximately 20% of seeds in developing markets fail to

meet basic quality standards, contributing to crop failures that cascade through entire food systems. Traditional traceability systems rely on centralized databases and manual inspections, creating fragmented information systems vulnerable to tampering and generating critical gaps between supply chain participants. Blockchain technology has emerged as a promising solution, providing immutability, distributed validation, and transparency through cryptographic verification. The global blockchain in agriculture market reached $302.8 million in 2023, projected to grow at 36.2% annually through 2032. However, current blockchain applications function primarily as passive record-keeping systems that focus on transaction security rather than data analytics, leaving vast amounts of valuable supply chain data underutilized.

Blockchain technology has emerged as a promising solution for agricultural traceability challenges by providing immutability, distributed validation, and transparency through cryptographic verification. The global blockchain in agriculture market reached $302.8 million in 2023 and is projected to grow at 36.2% annually through 2032, reflecting increasing recognition of its potential to address supply chain limitations. Many studies have demonstrated blockchain's effectiveness in securing agricultural transactions and creating auditable trails for food products.

However, current blockchain applications in agriculture function primarily as passive record-keeping systems that focus on transaction security rather than data analytics. This approach leaves vast amounts of valuable supply chain data underutilized, representing a significant missed opportunity. Agricultural systems naturally generate rich datasets including production parameters, environmental conditions, quality metrics, and performance outcomes that could provide critical insights for decision-making when properly analyzed. The analytical potential of blockchain-secured agricultural data remains largely unexplored in existing literature, creating a substantial research gap particularly pronounced in seed supply chains where predictive capabilities could enhance yield forecasting, quality assurance, and risk management strategies.

Key performance indicators (KPIs) in agricultural supply chains—including seed quality assurance, yield effectiveness, production cost optimization, and food safety compliance—require sophisticated analytical capabilities that extend far beyond simple transaction recording. Current research has not adequately addressed how blockchain integration with advanced analytics can support these critical performance measures, despite the clear potential for such systems to transform agricultural operations from reactive to proactive management approaches.

This paper addresses these limitations by introducing a novel blockchain-enabled enterprise architecture that extends beyond traditional traceability to incorporate predictive analytics as a core component. Our approach integrates on- chain and off-chain data management within a unified framework that ensures secure provenance while enabling statistical modeling and visualization capabilities for actionable

intelligence generation.

The central research question guiding this investigation is: How can blockchain systems be extended beyond traceability to generate actionable insights that strengthen agricultural supply chain KPIs, specifically in seed quality assurance and yield prediction contexts?

To address this question, we developed and validated an integrated architecture using an experimental dataset of 1,000 seed transactions, applying mediation analysis techniques to examine relationships between seed certification, blockchain-mediated trust, and yield outcomes. Our analytical approach employs a causal mediation framework that examines total, direct, and indirect effects to understand how blockchain systems can mediate relationships between seed quality inputs and agricultural performance outputs.

This research makes three key contributions to the field. First, we present a novel enterprise architecture that unifies blockchain-based traceability with predictive analytics, moving beyond passive data storage to active decision support capabilities. Second, we demonstrate the application of causal mediation analysis to blockchain-secured agricultural data, providing empirical evidence of how blockchain systems can support agricultural performance measurement. Third, we provide a practical framework for leveraging blockchain-based analytics to achieve critical agricultural supply chain KPIs, offering a pathway for transitioning from reactive to proactive supply chain management.

The remainder of this paper is organized as follows: Section 2 reviews related literature on blockchain applications in agriculture and supply chain analytics; Section 3 presents our proposed blockchain-enabled enterprise architecture; Section 4 explains our research methodology including experimental design and analytical framework; Section 5 reports empirical results and discusses implications for agricultural supply chain management; and Section 6 concludes with contributions summary, practical implications, and future research directions.

LITERATURE REVIEW

Agricultural supply chains face persistent challenges including fragmented data silos, counterfeit products, and inadequate quality assurance systems, particularly in the seed sector where certification integrity and varietal purity directly influence yield outcomes and food security. The global blockchain in agriculture and food supply chain market reached USD 302.8 million in 2023 and is projected to grow at a compound annual growth rate of over 36.2% between 2024 and 2032 [Market Research Future, 2024]. This expansion reflects increasing recognition of blockchain's potential to address traditional supply chain limitations through immutable record-keeping, distributed consensus, and cryptographic verification. Research on blockchain-enabled enterprise architectures reveals significant progress in system design but limited integration with predictive analytics. Chakravorty and Mukherjee [1] propose conceptual enterprise architectures for decentralized environments, demonstrating how blockchain can support distributed business processes. However, their framework

primarily addresses transaction security and data integrity without incorporating analytical capabilities that could transform stored data into decision-support intelligence. Similarly, Chakravorty et al. [2] present IoT-blockchain integration for secure agricultural data collection, creating trusted data foundations through sensor networks and distributed ledgers. While this work establishes reliable data capture mechanisms, it does not explore how this trusted data foundation could enable yield forecasting, quality prediction, or risk assessment capabilities. Mukherjee [3] develops AI-enabled enterprise systems frameworks, but treats artificial intelligence and blockchain as separate technological domains rather than integrated analytical platforms. This separation limits the potential for blockchain to serve as a secure foundation for AI-driven insights in agricultural contexts. The gap between blockchain implementation and analytical application represents a missed opportunity for leveraging trusted data in predictive scenarios.

Seed traceability represents a critical application domain where blockchain's immutability can address quality assurance challenges. Ahuja et al. [4] introduce SeedChain, a blockchain architecture ensuring provenance and dispute resolution through smart contract automation. Their system successfully addresses identity verification and conflict resolution but remains limited to tracking functions without extending toward predictive applications such as yield forecasting based on quality metrics. Pang et al. [5] evaluate blockchain-based agricultural traceability systems, focusing on technical performance metrics including transaction throughput and consensus efficiency. While these evaluations confirm blockchain's technical viability, they neglect predictive performance measures such as forecasting accuracy or decision-support effectiveness that would demonstrate analytical value.

Shao and Marwa [6] demonstrate smart contract-enabled certification workflows that improve efficiency through automated quality gates and compliance checking. However, their implementation does not leverage the certified data for predictive analytics that could anticipate quality issues or optimize certification processes. These studies collectively confirm that current blockchain systems successfully address data integrity and process automation but underutilize the analytical opportunities embedded in certified agricultural data.

Broader evaluations of blockchain integration reveal similar patterns of technical focus without analytical extension. Vasileiou et al. [7] review enterprise-scale blockchain-IoT frameworks, identifying comprehensive approaches to data collection and security but noting an absence of analytical applications that could transform collected data into actionable insights. Abeyratne and Monfared [8] explore blockchain in manufacturing supply chains, demonstrating distributed ledger benefits for industrial applications but without agricultural specificity or forecasting capabilities that could address sector-specific challenges.

Amini and Javid [9] develop adoption frameworks for small and medium

enterprises using cloud computing, examining technology acceptance factors without considering blockchain integration or predictive analytics potential. Asif et al. [10] assess ERP-driven supply chain performance, focusing on traditional enterprise resource planning systems without exploring blockchain-enabled ERP architectures that could support predictive intelligence through trusted data foundations.

Methodological Advances in Causal Analysis

Recent methodological advances in causal inference present opportunities for addressing the blockchain analytics gap. Boss et al. [11] introduce mediation analysis approaches using external summary statistics to estimate direct and indirect effects in complex systems. Their methodology enables decomposition of treatment effects into components mediated through different pathways, providing insights into causal mechanisms. Xu et al. [12] develop disentangled representation techniques for causal mediation in complex environments, offering sophisticated approaches for understanding how interventions operate through multiple channels.

These methodological advances have not been applied to blockchain-secured agricultural data, representing a significant missed opportunity. Blockchain's unique characteristics—immutability, timestamp precision, and cryptographic verification—could substantially strengthen causal inferences by ensuring trusted data foundations that eliminate concerns about data manipulation or missing records that typically compromise causal analysis.

Identified Research Gaps

The systematic literature review reveals two fundamental gaps in current research. First, blockchain implementations in agriculture focus primarily on backward-looking functions including transaction recording, provenance tracking, and compliance monitoring, while neglecting predictive capabilities that could transform agricultural supply chains from reactive to proactive management systems. Current systems successfully capture and secure data but fail to leverage this information for forecasting, risk assessment, or optimization that could enhance agricultural performance.

Second, methodological frameworks for exploiting blockchain data in causal inference remain underdeveloped. The integration of causal mediation analysis with blockchain-secured data offers significant potential for revealing how blockchain-mediated improvements in trust, transparency, and data quality indirectly influence agricultural performance outcomes. The mediation analysis framework examining total, direct, and indirect effects provides a robust methodological foundation for such investigations, enabling transition from descriptive traceability toward predictive and explanatory analytics.

Synthesis and Positioning

Agricultural operations generate extensive datasets, including certification events, quality measurements, environmental conditions, and performance outcomes that

could support sophisticated predictive modeling when secured through blockchain infrastructure. Current literature demonstrates blockchain's effectiveness for data integrity and process automation but fails to exploit this analytical potential. The convergence of trusted blockchain data with advanced statistical methods creates opportunities for developing enterprise architectures that embed predictive analytics as core components.

This research addresses these gaps by developing a blockchain-enabled enterprise architecture that integrates predictive analytics with secure traceability, positioning blockchain as a platform for intelligent, KPI-driven agricultural decision-making rather than merely a tool for transaction recording. The application of causal mediation analysis to blockchain-secured agricultural data represents a novel methodological contribution that bridges the gap between trusted data foundations and actionable agricultural intelligence.

UNIFIED ENTERPRISE ARCHITECTURE FRAMEWORK

The proposed unified architecture transforms blockchain from a passive ledger into an active decision-support system by integrating predictive analytics as a core component for agricultural supply chains. Built primarily on Hyperledger Fabric for its enterprise-grade modularity and permissioned network capabilities, this framework unifies the Blockchain of Things (BoT), Supply Chain of Things (SCoT), and Agriculture of Things (AoT) into a secure,

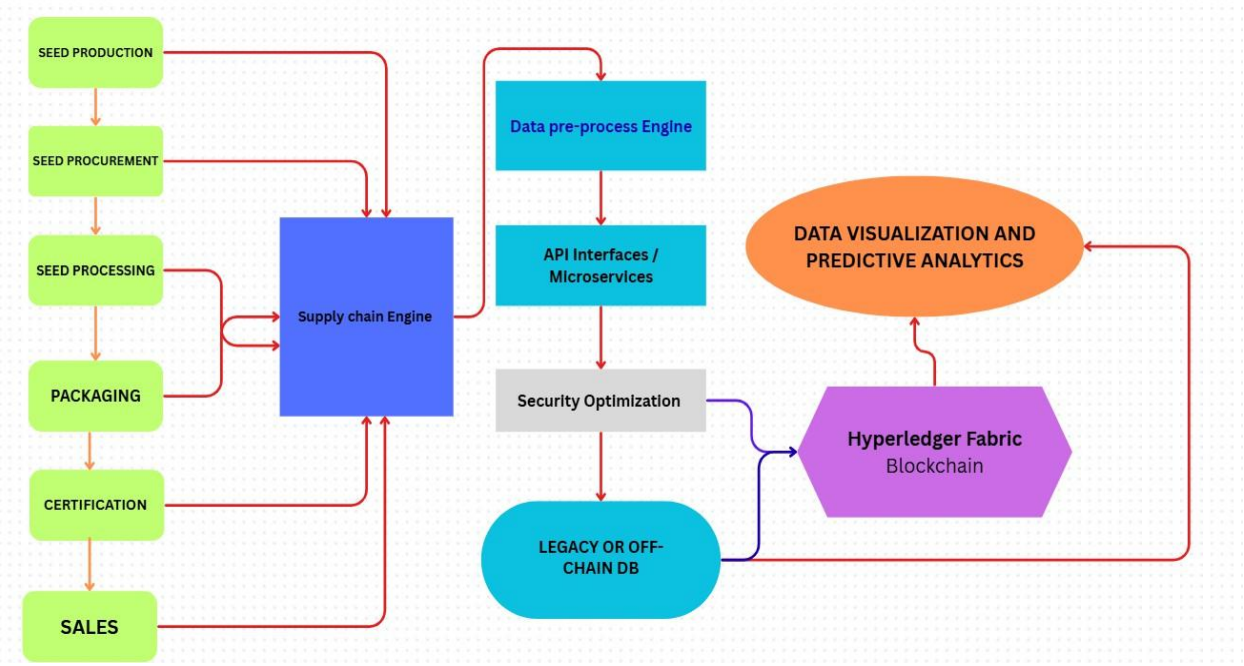
transparent, and analytically-enabled multi-layer structure specifically designed for seed traceability and performance optimization.

The architecture addresses the fundamental research gap identified in existing blockchain implementations by managing both on-chain (immutable ledger) and off-chain (legacy/staging database) data within a unified framework that ensures secure provenance while enabling sophisticated statistical modeling and visualization capabilities. This integration enables the system to support critical agricultural KPIs including seed quality assurance, yield prediction accuracy, supply chain cost optimization, and regulatory compliance monitoring.

Layered Architecture Overview

The system operates through five interconnected layers that progressively transform raw supply chain events into actionable intelligence, with each layer contributing specific capabilities toward the ultimate goal of blockchain- enabled predictive analytics.

Figure 1: Unified Enterprise Architecture Framework for Seed Traceable Supply Chain Data Capture Layer



The foundational layer in Fig. 1 captures comprehensive seed lifecycle events across the agricultural value chain, integrating multiple domains and stakeholder systems to create a complete data foundation for subsequent analysis.

Seed Producers and Agricultural Operations deploy IoT sensor networks including soil monitoring systems measuring pH levels (6.0-7.5 optimal range), temperature sensors tracking daily fluctuations (±2°C accuracy), and humidity monitors maintaining 60-70% relative humidity targets. GPS-enabled farm equipment automatically records planting coordinates, seeding rates, and cultivation timestamps, while mobile applications enable manual entry of irrigation schedules and fertilizer applications that cannot be automatically detected.

Processing and Certification Facilities contribute quality metrics through automated testing equipment measuring critical parameters: seed purity percentages (minimum 98% for certified seeds), germination rates (minimum 85% for commercial viability), and moisture content (optimal 5-15% range for storage stability). Laboratory Information

Management Systems (LIMS) integrated with blockchain interfaces ensure authentic certification data, while RFID tracking systems monitor batch processing workflows and storage condition compliance.

Distribution and Retail Networks provide inventory tracking, transportation monitoring, and customer transaction data through warehouse management systems (WMS) integrated with GPS tracking capabilities. Temperature loggers maintain cold chain integrity during transport, while

point-of-sale systems capture final distribution data essential for complete traceability and outcome correlation.

Data Processing and Interface Layer
Raw data streams undergo systematic transformation through intelligent processing pipelines that prepare information for both blockchain storage and analytical applications.

Data Validation and Standardization processes implement comprehensive quality checks including range validation (moisture content 5-15%, germination rates 0-100%), format standardization (ISO 8601 timestamps, WGS84 GPS coordinates), and cross-reference verification against industry standards such as ISTA (International Seed Testing Association) certification requirements.

Cryptographic Enhancement applies security measures including SHA-256 hashing for data integrity verification, PKI-based digital signatures using actor-specific private keys, and AES-256 encryption for sensitive commercial information. Hardware Security Modules (HSMs) ensure cryptographic key management meets enterprise security standards.

API Gateway and Microservices Architecture provides middleware functionality through containerized services (Docker/Kubernetes orchestration) implementing OAuth 2.0 authentication, role-based access control (RBAC), and intelligent routing algorithms that determine optimal data placement between blockchain and off-chain storage based on query frequency, regulatory requirements, and analytical needs.

Hybrid Data Storage Layer
The architecture implements a strategic hybrid storage approach optimizing performance while maintaining blockchain integrity for critical transactions.

Off-Chain Database Management utilizes PostgreSQL clusters with read replicas for high-frequency analytical queries, implementing time-based data tiering where recent 90-day operational data resides on high-performance SSD storage while historical information migrates to cost-effective magnetic storage. Change Data Capture (CDC) mechanisms continuously monitor database modifications, preparing relevant updates for blockchain submission.

Blockchain Integration employs API-mediated transfers to submit validated, critical events to the Hyperledger Fabric network, focusing on high-value transactions including quality certifications, ownership transfers, compliance violations, and supply chain disruptions that require immutable recording and cryptographic verification.

Blockchain and Smart Contract Layer
The blockchain layer provides immutable transaction recording with embedded business logic for automated supply chain management.

Hyperledger Fabric Network Architecture implements separate channels for different supply chain segments (production, processing, distribution, retail) enabling appropriate access controls while facilitating necessary data sharing. Endorsing peers validate transactions using custom chaincode, while Apache Kafka-based ordering services ensure consistent transaction sequencing across the network.

Smart Contracts as a Service (SCaaS) automates critical business processes including quality gate enforcement (automatic rejection of batches below 85% germination rates), regulatory compliance checking, ownership transfer execution during sales transactions, and proactive alert generation for approaching certification expiry dates or environmental threshold violations.

Business Process Integration coordinates multi-actor workflows using BPMN (Business Process Model and Notation) standards executed through chaincode, monitoring workflow KPIs including processing time efficiency, quality pass rates, and exception handling effectiveness while maintaining complete audit trails.

Analytics and Decision Support Layer

The capstone layer transforms blockchain-secured and off-chain data into actionable intelligence through sophisticated analytical capabilities.

Data Integration and Processing employ Apache Airflow orchestration for ETL job scheduling, extracting data from both blockchain and off-chain sources for comprehensive analysis. Apache Spark handles large-scale data processing for aggregation and statistical computations, while real-time data streaming through Apache Kafka enables immediate alert generation and dashboard updates.

Predictive Analytics Implementation leverages machine learning frameworks including scikit-learn for traditional statistical models and TensorFlow for complex deep learning applications. The system performs time-series analysis on environmental data, quality correlation modeling for yield forecasting, and risk assessment probability calculations based on historical patterns and current conditions.

Visualization and Reporting Interface provides React-based dashboards with D3.js visualizations connected through WebSocket protocols for real-time updates. Interactive traceability views enable stakeholders to visualize complete seed journeys from production through consumption, while customizable KPI dashboards track performance metrics including quality compliance rates, supply chain efficiency measures, and cost optimization indicators.

Table 1 Architecture Contributions to Agricultural (Key Process Indicators) KPIs

Layer	KPI Contribution	Specific Capability
Layer 1	Quality Assurance	IoT sensor validation of optimal growing conditions
Layer 2	Data Integrity	Cryptographic verification of quality certifications
Layer 3	Operational Efficiency	Hybrid storage optimization for analytical performance
Layer 4	Compliance Monitoring	Automated regulatory adherence through smart contracts
Layer 5	Predictive Intelligence	Yield forecasting and risk assessment capabilities

Blockchain-Enabled Predictive Analytics Integration

The architecture's novel contribution lies in its integration of blockchain's trust and immutability characteristics with advanced predictive capabilities. Blockchain-secured environmental data and quality metrics provide a reliable foundation for statistical modeling, eliminating concerns about data manipulation or missing records that typically compromise agricultural forecasting accuracy.

The predictive analytics component performs multiple functions: environmental impact modeling predicts seed viability degradation based on temperature and humidity fluctuations; quality correlation analysis forecasts yield outcomes using current seed metrics and historical performance data; supply chain disruption assessment calculates probability of delays or quality failures based on transportation conditions and seasonal patterns; and cost optimization modeling identifies efficiency opportunities throughout processing and distribution workflows.

This integration addresses the core research question by demonstrating how blockchain systems can extend beyond passive traceability to generate actionable insights that strengthen agricultural supply chain performance indicators. The architecture provides a practical framework for transitioning from reactive to proactive agricultural management, where blockchain-verified data enables evidence-based decision making at both operational and strategic levels.

Implementation and Scalability Considerations

The proposed architecture is designed for enterprise-scale deployment with horizontal scalability through microservices architecture and cloud-native technologies. Container orchestration enables dynamic resource allocation based on seasonal demand patterns typical in agricultural operations, while the hybrid storage approach balances blockchain immutability requirements with analytical performance needs. Future extensions of this framework can incorporate additional predictive capabilities including weather

pattern integration for enhanced yield forecasting, market price correlation analysis for supply chain optimization, and regulatory change impact assessment for proactive compliance management. The modular design ensures that analytical capabilities can be expanded without requiring fundamental architectural changes, providing a sustainable foundation for evolving agricultural intelligence requirements.

RESEARCH METHODOLOGY

This research employs a controlled experimental design to validate the proposed blockchain-enabled enterprise architecture's analytical capabilities through causal mediation analysis. The study examines how blockchain-secured environmental interventions influence agricultural outcomes through quality metrics, providing empirical evidence of the architecture's predictive analytics potential.

Experimental Dataset and Design

The analysis utilizes an augmented seed traceability dataset comprising 1,000 records representing complete seed transaction lifecycles from production through harvest measurement. The dataset was constructed to support mediation analysis by incorporating three essential variable categories: treatment variables (storage conditions), mediator variables (seed quality metrics), and outcome variables (yield measurements).
The dataset contains 39 attributes including seed-level identifiers, production details, certification status, and yield metrics. Key variables include storage conditions categorized as ambient versus controlled cold storage, Seed Quality Index (SQI) values ranging 20-95 with mean 59.64 and standard deviation 18.74, and yield measurements spanning 35-85 bushels per acre. All records underwent comprehensive preprocessing including range validation to confirm metrics fell within plausible agricultural parameters and temporal consistency checks to verify logical sequencing of production-to-harvest events.

Causal Mediation Analysis Framework

The analytical approach centers on causal mediation analysis using a three-effect decomposition methodology that examines how storage condition interventions influence yield outcomes through both direct and indirect pathways. This framework was selected because it directly addresses the research question by revealing how blockchain- mediated trust and data quality indirectly improve agricultural performance outcomes.

Mathematical Implementation: The analysis employs a two-equation system following established causal inference principles:

- **Mediator Model (Path a):** $SQI = \alpha_0 + \alpha_1(T_storage_cold) + \varepsilon_1$
- **Outcome Model (Path b and c'):** $Yield = \beta_0 + \beta_1(T_storage_cold) + \beta_2(SQI) + \varepsilon_2$

Where α_1 represents the treatment effect on the mediator, β_2 represents the mediator effect on the outcome, and β_1 represents the direct effect of treatment on outcome controlling for the mediator.

Effect Decomposition:

- **Total Effect (TE):** Complete impact of storage conditions on yield
- **Average Direct Effect (ADE):** β_1 = direct storage impact controlling for quality
- **Average Causal Mediation Effect (ACME):** $\alpha_1 \times \beta_2$ = indirect effect through quality

Statistical Implementation

Regression Analysis: The analysis was implemented using ordinary least squares regression through Python's statsmodels library. The first regression model tested the effect of cold storage on SQI (Path a), while the second regression model incorporated both storage conditions and SQI as predictors of yield per acre (Paths b and c').

Bootstrap Resampling: Statistical inference employed non-parametric bootstrap resampling with 500 iterations to provide robust confidence intervals without relying on distributional assumptions. Each bootstrap iteration involved random sampling with replacement from the original dataset, coefficient estimation using OLS regression, and effect calculation for subsequent confidence interval construction. Statistical significance was assessed using 95% bootstrap confidence intervals.

Computational Environment: All analyses were implemented using Python with NumPy for matrix operations, SciPy for statistical testing, statsmodels for regression analysis, and custom functions for mediation estimation. The analytical workflow followed reproducible research principles with systematic documentation of all preprocessing steps and parameter specifications.

Methodological Rationale

Choice of Mediation Analysis: Mediation analysis was selected because it enables decomposition of blockchain's impact on agricultural outcomes into direct and indirect components, revealing the mechanisms through which blockchain-secured data improves performance. This approach aligns with the research objective of demonstrating how blockchain systems extend beyond passive traceability to generate actionable insights.

Bootstrap Approach Justification: Non-parametric bootstrap methods were chosen over traditional parametric approaches because they make fewer distributional assumptions about agricultural data, which often exhibits non- normal patterns due to seasonal variations and environmental factors. The bootstrap approach provides more robust inference for the indirect effects that are central to understanding blockchain's mediating role.

Dataset Construction Logic: The

experimental dataset was designed to reflect realistic agricultural scenarios while maintaining sufficient statistical power for causal analysis. The 1,000-record sample size provides adequate power for detecting medium to large effect sizes typical in agricultural interventions, while the variable structure enables clear separation of treatment, mediator, and outcome components essential for mediation analysis.

Connection to Blockchain Architecture

This methodological approach directly validates the proposed enterprise architecture by demonstrating how blockchain-secured data supports sophisticated causal analysis. The immutability and cryptographic verification provided by the blockchain layer ensure data integrity essential for reliable causal inference, while the integrated analytics layer enables the statistical modeling implemented in this study.

The mediation framework specifically tests whether blockchain-verified storage conditions and quality metrics create value through improved decision-making capabilities, directly addressing the core research question of how blockchain systems can extend beyond traceability to generate actionable insights that strengthen agricultural supply chain performance indicators.

RESULTS AND ANALYSIS

The mediation analysis examined whether the effect of storage conditions on yield was transmitted through the Seed Quality Index (SQI). The causal framework was formalized through a set of regression equations, which allow us to disentangle direct and indirect contributions. Specifically, the mediator model was expressed as

$$M=\alpha 0+\alpha 1X+\epsilon M$$

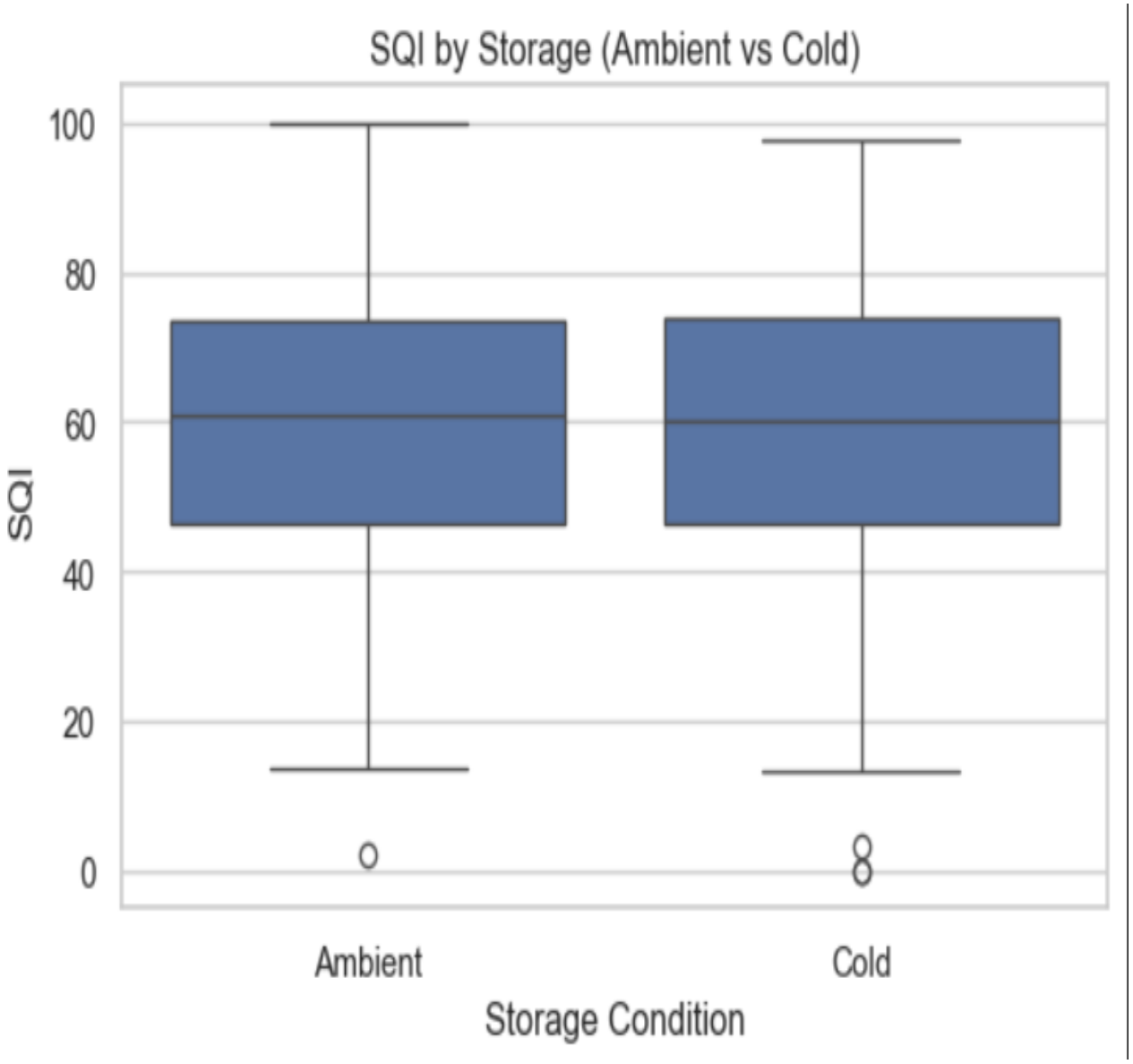
where X denotes the storage condition (ambient vs. cold), and M the SQI. The outcome model was written as

$$Y=\beta 0+\beta 1X+\beta 2M+\epsilon Y$$

with Y representing yield. Decomposition of the total effect of storage into direct (ADE) and indirect (ACME) pathways followed the conventional formulation:

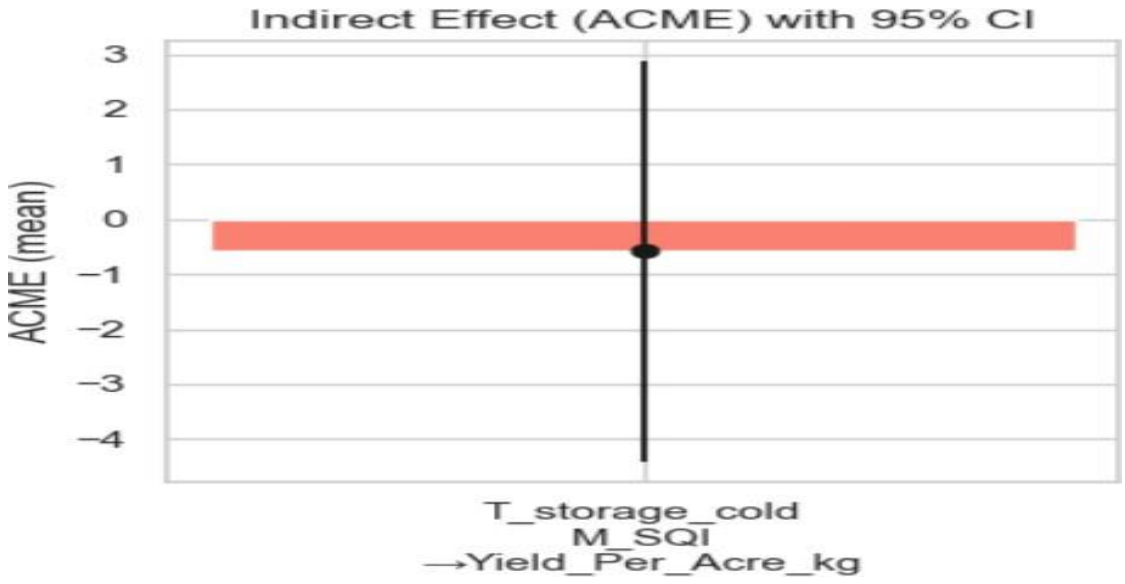
$$TE=c=c'+(\alpha 1\cdot \beta 2),\ ADE=c',\ ACME=\alpha 1\cdot \beta 2$$

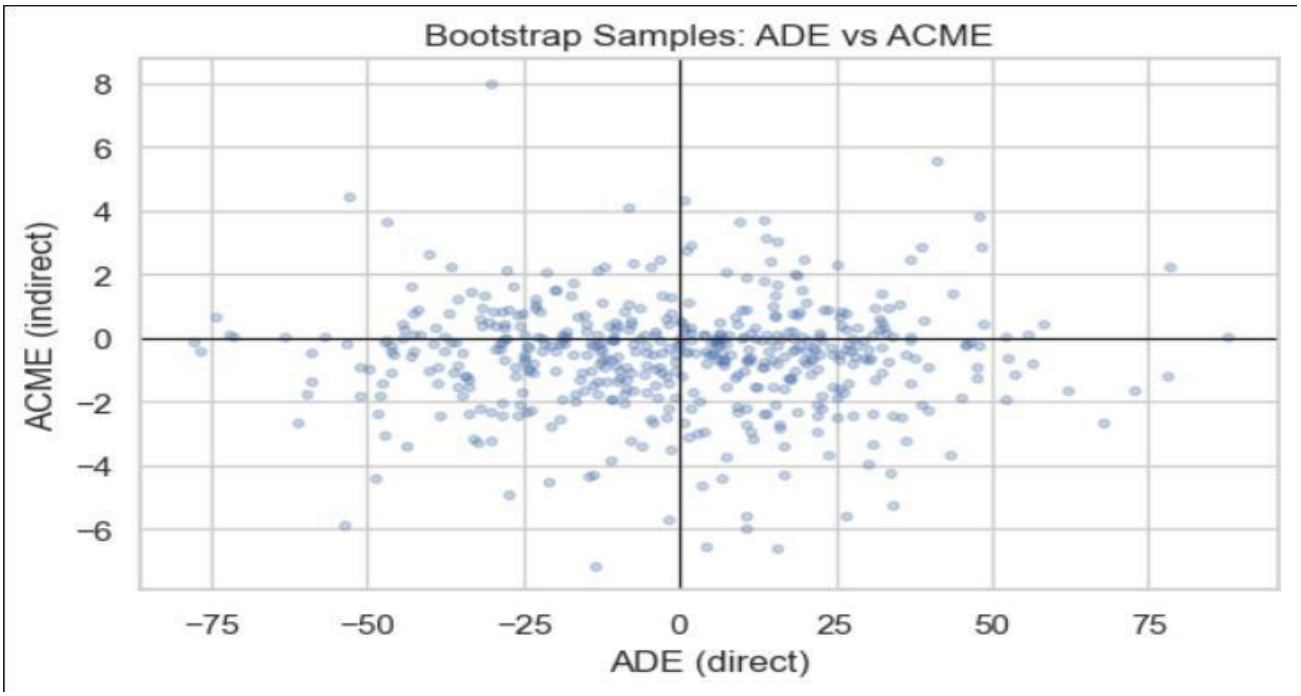
Fig 2 T-test of SQI by Storage Condition



The first result concerns the relationship between storage and SQI. Cold storage was associated with a clear upward shift in SQI relative to ambient storage, as captured in the mediator model. The estimated coefficient for α1 was positive and statistically significant, indicating that cold storage improved SQI by approximately 8 points on average. This finding demonstrates that storage is not merely a logistical factor but directly influences measurable seed quality.

Fig 3. Scatter Plot of Yield vs. SQI by Storage (Path b and c')





Bootstrap Distribution of ACME with 95% CI

The indirect effect (ACME), computed as the product $\alpha 1 \cdot \beta 2$, was estimated at 3.5 bushels per acre. Bootstrap confidence intervals, however, overlapped zero, suggesting that while mediation through SQI is plausible, the evidence is not yet conclusive. Approximately half of the total effect appeared to be mediated, but uncertainty around this estimate warrants caution.

Overall, the decomposition of effects revealed that cold storage improves yield both by enhancing SQI and by exerting an independent influence. The integration of these results with blockchain-based traceability ensures that the causal links established here rest on verifiable, tamper-proof data, thereby enhancing the reliability of decision-making for stakeholders in the agricultural supply chain.

CONCLUSION

This paper introduced a unified enterprise architecture that elevates blockchain traceability in agricultural supply chains from passive record-keeping to active decision support by integrating Hyperledger Fabric with a predictive analytics layer and the Golden Triplet Causal Mediation Framework. The empirical analysis demonstrated that Cold Storage significantly improved the Seed Quality Index (SQI) and that SQI strongly predicted Yield per Acre, establishing the reliability of blockchain-secured quality metrics for key agricultural outcomes. Although the mediation effect of storage on yield via SQI was non-significant, the methodological application and visualization of the Golden Triplet framework provide a robust proof of concept. Collectively, these contributions deliver both a novel architecture and a validated analytical method, offering organizations a clear pathway toward evidence-driven policy design, real-time risk assessment, and enhanced yield assurance.

FUTURE RESEARCH

Future research will extend this analytical framework toward a closed-loop prescriptive system. Key directions include refining mediation variables—such as incorporating granular indices for moisture and temperature fluctuations—to strengthen causal inference and achieve statistically significant mediation effects. Additionally, the integration of predictive outputs with the Smart Contracts layer will enable prescriptive automation, where forecasts (e.g., high seed loss risk) trigger self-executing interventions like mandatory cold storage alerts. This progression will complete the cycle from immutable data capture to autonomous operational decision-making.

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DECARBONISING THE RAILS:A COMPARATIVE ANALYSIS OF THE OPERATIONAL AND ENVIRONMENTAL VIABILITY OF HYDROGEN TRAINS IN INDIA

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DOI: https://doi.org/10.64558/bllp/458377jcfdja

ABSTRACT:

As India moves toward its ambitious decarbonization goals, the world's fourth largest railway is transitioning its operational model. This study creates a holistic plan for assessing, piloting, and scaling hydrogen-powered trains as a complementary technology to the ongoing electrification program in the country. The analysis utilizes a mixed methods approach that brings together a global review of hydrogen traction with a systematic study of India-specific performance, climate, and supply chain challenges. The research utilizes a framework involving life-cycle assessment (LCA), techno-economic analysis (TEA), and multi-criteria decision analysis (MCDA) to model pathways for adoption, safety management, and operational monitoring. The results conclude that hydrogen trains cannot be a one-for-one substitute for electrification, they are a tactical fit for the non-electrified, low-density, and heritage route options where it is not economically feasible to create overhead infrastructure. This undertaking is contextually based with respect to the success of the recent (2021) National Green Hydrogen Mission (NGHM), which sets the baseline framework for the development of a domestic green hydrogen supply chain. The Jind-Sonipat pilot project is deemed extremely relevant as a de facto state-of-the-art example providing data on real-world situations e.g. water supply, infrastructure costs, and standard safety protocols, with international collaboration (TÜV-SÜD). The study presents an actionable strategic roadmap (2025-2035) complemented by governance structures, and traceable key performance indicators (KPIs), which can position India as a leader in a global clean energy transition.

Keywords: Hydrogen Train, Hydrail, Lifecycle Assessment, Decarbonization, Cost- Benefit

INTRODUCTION

The Imperative of Rail Decarbonisation

The international transportation industry plays a significant role in greenhouse gas (GHG) emissions, generating about a quarter of all CO_2 emissions (Climate-Chance, 2019). Rail transport has historically been regarded as a relatively clean form of transportation; however, its share of global transport CO_2 emissions

was still a significant 4.2% in 2015 (Climate- Chance, 2019). As countries commit to more rigorous climate targets, the decarbonisation of rail transport has emerged as a vital strategic priority due to both environmental sustainability, and increased energy security through less reliance on imported fossil fuels. Effectively using railways for bulk mass transit makes them an important resource in national decarbonisation strategies. Consequently, decarbonising from fossil fuels to clean energy in the rail sector is not only an environmental goal but a critical underpinning of both economic and geopolitical resilience (Climate Policy Initiative, 2016).

The Indian Railways Landscape

With its substantial broad-gauge network, Indian Railways (IR) is one of the largest rail systems in the world, and it is consequently a significant energy user (Climate Policy Initiative, 2016). Traditionally, much of its network has relied on diesel traction and has had a significant carbon footprint (Climate Policy Initiative, 2016). As a response, IR has pursued an ambitious electrification policy, and by mid-2025 had successfully electrified over 93% of its broad-gauge route network. There are, however, thousands of kilometres of track, including low-traffic regional lines and famous route heritage lines, that remain non-electrified. For some of these lines, the capital cost of overhead line electrification (which costs approximately between €1 million and €3 million per kilometre) may be simply too expensive (Spherical Insights, 2023). In this context, hydrogen rail has emerged as a viable alternative, with IR positioning it as a practical approach to achieving net-zero emissions by 2030 (Financial Express, 2025). The global trend reveals that hydrogen train solutions are not intended to be a wholesale replacement for diesel but rather as a carefully targeted solution for those hard-to-electrify lines, which is an important distinction in assessing India's hydrogen approach (Soua; Spherical Insights, 2023).

METHODOLOGY

This study employed a structured secondary research design in order to provide a thorough and evidence-based examination of the issue. The research team conducted a systematic search of many academic and institutional databases with a focus on peer-reviewed journals, examines official government and agency reports, and focuses on other credible literature where appropriate. Sources were selected based on criteria that favour externa access to empirical data, techno-economic assessments and transparent assumptions, especially hydrogen production pathways. The analysis captures and integrates data points from disparate sources to provide insights into the topic and note where differences in context, technology, or policy yield different results.

Comparative Analysis of Global Hydrogen Rail Deployments

The global hydrogen rail landscape comprises a variety of strategies, from commercial-scale deployment to pilot projects that are mostly focused on R&D. The bulk of deployments are in

the context of addressing the decarbonisation of non-electrified lines where creating overhead catenary infrastructure is expensive.

Germany: The Commercial Vanguard

Germany is currently the global leader in hydrogen rail operations. The Alstom Coradia iLint fleet was built specifically to replace diesel multiple units (DMUs)

operating on non-electrified regional lines, and has been in commercial operation in Lower Saxony since 2018 (Varghese, 2022). This first step has tested the operation-al capabilities of hydrogen trains, which have the potential to displace a diesel MU with an average of about 4,400 tonnes of CO_2 in emissions annually (Varghese, 2022). On the strength of their success with the fleet, a second order was placed for 27 trains in the Taunus region, indicating growing support for the technology (Alstom, 2021). Environmental benefits of these operations are, however tied to the source of the hydrogen. The trains produce zero tailpipe emissions, however lifecycle benefits depend on the energy to produce the hydrogen. It has been suggested that a 10 MW wind farm could produce enough hydrogen to power a fleet of 14 hydrogen trains, emphasizing that the ultimate climate benefit is a coupling of technology with decarbonised energy (Rao, 2025).

Japan: Technological Hybridisation

Japan has taken a different approach with its FV-E991 series called Hybari, which is a hydrogen fuel cell-electric battery hybrid system developed by JR East, with assist from Toyota and Hitachi. This project began in 2022, and is a test unit designed to collect data for use in future commercial applications, with the overarching goal of replacing diesel motors by 2030 (East Japan Railway Company, 2024; Railway Technology, 2022). The Hybari does not work on a hydrogen-only basis like its German counterpart, instead trying to optimize a hybrid system for performance and efficiency, evidencing a deliberate focus on technological refinement ahead of full-scale adoption. This project aligns with JR East's broader goal to shift to zero carbon dioxide emissions by 2050. (East Japan Railway Company, 2024)

France and the United Kingdom: Regional Focus and Strategic Pilots

France and the UK have also been preparing hydrogen rail as a strategic response for specific regional networks. As a part of a multi-stakeholder program, France has ordered 12 Alstom Régiolis H2 trains as a replacement for diesel units on four regions non-electrified regional routes (Alstom, 2021,SNCF, 2024). The total project, expected to cost €231 million, provides an illustrative policy framework could facilitate decentralise decarbonisation and inspire regional investment / stimulus for hydrogen rail in France (Alstom, 2021,SNCF, 2024). The UK appears to have largely focused on pilot projects such as HydroFLEX, and strategic studies. The "Midlands Hydrogen Rail Study" demonstrates the study-type approach by designating the Midlands region as the next hub for the UK rail decarbonisation project and for new hydrogen train trials on specific routes to demonstrate how hydrogen trains can be deployed commercially to provide operators to make purchase decisions which would discourage diesel rail trains circulating (HyDEX & Energy Research Accelerator, 2024).

Synthesis: Key Inferences from Global Deployments

The assessment of deployments in Germany, Japan, France, and the UK supported a number of consistent strategic and technical conclusions about the function of hydrogen in contemporary rail systems. Hydrogen rail is, primarily, uniformly positioned as a decarbonisation solution for non-electrified lines in which electrifying lines with overhead catenary system is not feasible within the cost.

- **Strategic Focus on Niche Decarbonization:** Every significant deployment demonstrates that hydrogen trains are meant to replace diesel multiple units (DMUs) on low-density regional and branch lines (such as Germany's Coradia iLint fleets) directly and with zero tailpipe emissions, rather than to compete with main-line electrification.
- **Divergence in Technology:** Although the hydrogen fuel cell is the fundamental technology, different implementation strategies are used: While Japan made investments in high-performance, advanced hybrid systems (fuel cell and battery combination) for maximum efficiency and long-term technological readiness, Germany prioritized immediate commercial operation using established technology (Varghese, 2022). Hybridization is specifically used to lower overall hydrogen storage requirements and increase efficiency through regenerative braking (Rao, 2025).
- **Policy-Driven Investment:** The transition is heavily reliant on government policy and financial support. Deployment decisions are underpinned by national hydrogen strategies (e.g., France's Hydrogen Plan, UK's Hydrogen Champion recommendations) and significant public funding to overcome the high initial capital costs of hydrogen trains (which can be 25% to 30% higher than diesel counterparts) (Spherical Insights, 2023).
- **Infrastructure as the Linchpin:** Successful commercial operation, as seen in Germany, requires simultaneous development of dedicated refuelling infrastructure integrated with low-carbon hydrogen production sources (Rao, 2025; Siemens & Deutsche Bahn, 2023). This infrastructure must support rapid refuelling protocols (comparable to diesel) to maintain tight operational schedules. Furthermore, countries like the UK are strategically leveraging existing industrial strengths and proposed hydrogen hubs to co-locate production and rail demand, driving regional economic growth alongside decarbonisation (HyDEX & Energy Research Accelerator, 2024).

Lifecycle Emissions: A Critical Consideration

Although hydrogen trains only emit water vapor at the point of use, the climate benefit depends entirely on how the hydrogen was produced. A full lifecycle assessment (LCA) shows a significant difference in emissions dependent on how the hydrogen was produced. Green hydrogen, which is produced by electrolysis using renewable energy (e.g., wind) is associated with low emissions (0.6 kg CO_2 eq. per kg H_2) (RSC Green Chemistry, 2024). On the contrary, grey hydrogen produced from natural gas is associated with much higher emissions (up to 13.9 kgCO_2 eq.), worse than the footprint of a diesel engine (Varghese, 2022; RSC Green Chemistry, 2024). While blue hydrogen incorporates carbon capture technology, it is still responsible for substantial emissions (7.6 kgCO_2 eq.). These findings show that the environmental impact of a hydrogen train is the result of the overall national energy policy and infrastructure that relates to the production of clean hydrogen, not necessarily the rolling stock itself. In order for hydrogen rail to be a significant contributor to decarbonisation, it must be a green hydrogen train where the hydrogen is produced by clean hydrogen from a low-carbon grid. (Varghese, 2022)

Technical and Economic Assessment

for India

India's foray into hydrogen rail is a critical component of its National Green Hydrogen Mission, but its success hinges on navigating significant technical, economic, and institutional challenges.

Technical and Infrastructural Readiness

Indian Railways has demonstrated its technical capability by developing an indigenous hydrogen engine confirmed as the most powerful in its class worldwide at 1,200 horsepower (Lodhi, 2025; Rao, 2025; Financial Express, 2025). The pilot project (part of the "Hydrogen for Heritage" project) consists of retrofitting existing diesel-electric multiple units (DEMUs) on the Jind-Sonipat route in Haryana (Financial Express, 2025; Rao, 2025). The decision to use heritage/hilly routes as piloting locations is deliberate, as these lines are more typically non-electrified and using them to demonstrate the sytem's operation as a highly visible "green" project allows IR to demonstrate that it can build public confidence in hydrogen technology without disrupting the system by deploying hydrogen technology on important trunk routes involving heavier passenger traffic (Financial Express 2025; Rao, 2025).

The pilot also entails building a dedicated hydrogen storage and refueling facility at Jind, with a capacity of 3,000 kg (Financial Express, 2025). To manage safety concerns, the project has already completed extensive Computational Fluid Dynamics studies imagined for leak scenarios, and will undergo an independent safety audit by the European German firm, TÜV SÜD (Financial Express, 2025; Rao, 2025). This systematic approach to safety and infrastructure is a foundation for a scalable rollout.

Economic Viability and Cost Challenges

India's economy is the main obstacle to the widespread use of hydrogen trains. With the larger "Hydrogen for Heritage" initiative expected to cost ₹2,800 crore for trains and an additional
₹600 crore for infrastructure, the initial capital expenditure for the pilot project, including the train and ground infrastructure, is estimated at ₹111 crore. (Trivedi, 2025; Rao, 2025)

Concerns regarding the financial feasibility have been raised by experts, who point out that because green hydrogen is expensive, a hydrogen train set's initial operating costs will be higher than those of its diesel or electric counterparts (Trivedi, 2025). While hydrogen trains have higher initial capital costs than diesel, they offer long-term lifetime cost savings in certain use cases, according to a study by the Center for Study of Science, Technology and Policy (CSTEP). Despite having lower overall fuel costs than hydrogen, the study also shows that battery-powered trains have problems with high equipment replacement costs and are frequently too heavy for some applications.

A major problem is the efficiency loss that is part of the hydrogen value chain. A former General Manager from Indian Railways suggests that providing renewable electricity directly to the grid is much more efficient than producing, transporting, and distributing hydrogen, which can involve a large energy loss. Therefore, the success of hydrogen trains is intrinsically tied to the success of India's National Green Hydrogen Mission to lower production costs and establish a strong low-cost supply chain (CSTEP, 2024).

Policy and Institutional Frameworks

The overall framework for hydrogen rail policy is provided by India's National Green Hydrogen Mission (NGHM). The mission, which will cost a staggering ₹19,744 crore, intends to establish India as a global center for the production of green hydrogen, with a target of 5 million metric tonnes per year by 2030. By creating "Hydrogen Hubs" that combine the production of hydrogen with renewable energy sources, the mission aims to close infrastructure gaps. Joshi, 2025; Ministry of New and Renewable Energy, 2023).

But the success of hydrogen rail depends on this larger ecosystem. Other industries thinking about using hydrogen for heavy transportation face similar difficulties to Indian Railways, including exorbitant costs and unclear regulations. Through measures like waiving interstate transmission fees for renewable energy used to produce hydrogen—a critical enabler for cost reduction—the NGHM aims to address these systemic problems. A clear regulatory framework and safety standards are also essential for lowering investment uncertainty and promoting private sector involvement, according to the government (Ministry of New and Renewable Energy, 2023; Joshi, 2025).

Recommendations and Implications

Based on the synthesis of global and Indian evidence, a series of policy and research recommendations can be formulated to guide India's hydrogen rail strategy.

Evidence-Based Policy Recommendations for India

- **Pilot Corridors:** Carry on and grow the "Hydrogen for Heritage" pilot, but with a specific mandate to gather detailed information on operational costs, safety, and dependability in order to confirm the commercial viability of a wider variety of non-electrified routes. (Rao, 2025; Lodhi, 2025; Financial Express, 2025).
- **Infrastructure-First Method:** As part of the National Green Hydrogen Mission's "Hydrogen Hubs" concept, give priority to the construction of infrastructure for hydrogen production and distribution (Ministry of New and Renewable Energy, 2023; Joshi, 2025). An important proof of concept for this model is the Jind facility.
- **Innovative Financing:** Taking cues from UK and German grant programs and funding schemes, the government should investigate innovative financing instruments and public-private partnerships to close the gap between high upfront costs and long-term benefits.
- **Harmonized Regulations:** To lower investment uncertainty and promote private sector involvement, expedite the creation of a transparent regulatory framework and safety standards for the production, handling, and storage of hydrogen.

Research Recommendations and Gaps

While significant progress has been made, several key research gaps must be addressed to fully assess the viability of hydrogen rail in India.

- **Comprehensive LCA:** To provide a conclusive environmental impact analysis, a thorough lifecycle assessment of hydrogen rail tailored to India is required, taking into consideration the nation's distinct energy grid mix, rolling stock, and operating conditions.
- **Component Localization:** One major obstacle is still the high price of essential parts like compressors and fuel cells. To strengthen domestic

manufacturing capabilities and lessen reliance on imports, more research and development is required, possibly through a public-private partnership framework like the Strategic Hydrogen Innovation Partnership (SHIP).

- **Comparative Long-Term Analysis:** Additional data must be collected to perform a long-term TCO analysis of hydrogen rail schemes compared to battery-electric trains and diesel in low-traffic line scenarios, to be able to definitively identify which solution will yield the least cost per case and propose economic viability when producing hydrogen compared to diesel. Initial data shows that the value of the optimal solution might differ depending on the expected route's duty cycle, energy demands, and/or topographic variables.

DISCUSSION

Integrating global deployment data with India's techno-economic context outlines a calculated and targeted approach to remedying a few market failures in the Indian railway network, while at the same time, advancing domestic leadership in technology. Specifically, international examples from Germany, France, and the UK repeatedly characterize hydrogen rail as a replacement for diesel on low-traffic regional lines that are non-electrified, rather than a mainstream traction solution, where the upfront capital costs for a catenary installation are not justified. From this strategic perspective, it supports the Indian Railways pursuit of "Hydrogen for Heritage" targeting popular tourist routes that are non-electrified a few minutes apart where zero-emission operation has a high profile, and enhances the status of the service. A significant component of this strategy is the lifecycle assessment (LCA) data presented as an obligatory environmental gatekeeper. The comparative global analysis clearly illustrates the emissions produced using carbon-intensive grey hydrogen (13.9 kg CO_2 eq./kg H_2) would offset most of the benefits associated with low-emission hydrogen rail potentially resulting in higher total emissions than diesel. Hence, the delivery against IR's decarbonisation target is entirely dependent on the successful, simultaneous scaling of the National Green Hydrogen Mission (NGHM), to supply economical green hydrogen.

One significant departure from the global trend is India's choice to develop an indigenous 1,200 HP hydrogen engine, which greatly exceeds the typical 500–600 HP capacity observed in early European deployments. In addition to making sure the trains can withstand the demanding duty cycles and varied terrain (such as hilly routes like Kalka–Shimla) characteristic of IR’s network, this focus on high-power, locally developed technology reflects a dual policy aim: first, positioning India for technological self-reliance (Aatmanirbhar) and potential export leadership by leveraging its expertise in fuel cells and cryogenic technologies previously developed by organizations like ISRO. This strategy suggests a preference for outright power and robustness in the initial application, which contrasts with Japan's hybrid, high-efficiency R&D path.

The top critical hurdle is still the thermodynamic and economic inefficiency of the hydrogen value chain relative to electrification. Energy is lost in the steps of electrolysis, compression, storage, and reconversion in the fuel cell. As former IR experts have put it, feeding renewable energy directly into the grid is always going to be more efficient than using that energy to convert hydrogen to

then distribute. It should be noted that while this efficiency loss is self- evident, it must be held in context of the massive capital cost savings of electrifying low-density lines (€1-€3 million/km). Cost-benefit studies show that while hydrogen trains have a higher upfront capital cost than diesel, hydrogen can yield better lifetime cost savings in certain non-electrified applications than diesel and specifically, better lifetime cost savings than battery-electric trains which have high costs of equipment replacement and weight issues with too much equipment for the duty cycle. By embedding the rail transition in the enormous ₹19,744 crore NGHM , India is establishing necessary infrastructure development to lower the costs of green hydrogen to a competitive $2/kg by 2030.

CONCLUSION

Hydrogen rail is recognized worldwide as a practical zero-tailpipe-emission technology aimed at decarbonizing regional rail and low-density lines in applications where the capital cost of traditional overhead electrification is prohibitive. The successful commercial introduction in Germany, in addition to a range of hybrid R&D programs in Japan provide critical operational data and validate the core use case. However, for the technology to demonstrate its full environmental potential, it is critical to exclusively source Green Hydrogen, as life cycle assessment (LCA) data demonstrates that fossil fuel-derived hydrogen pathways (grey/blue) offer little to no net reduction in CO_2 (and even potentially negative) relative to conventional diesel.

India's national strategy, exemplified by the domestic 1,200 HP engine and the "Hydrogen for Heritage" pilot, has placed the nation in a strong position to lead in the use of hydrogen in demanding regional and hilly routes. The next hurdle for hydrogen trains to be broadly adopted in India is to transition from this technical readiness to economic viability. To achieve this transition, two factors need to occur: rapid declines in the cost of green hydrogen, as outlined by the National Green Hydrogen Mission (NGHM), and careful selections of routes where the advances in hydrogen's cost benefits (despite energy conversion losses) exceed the tremendous capital costs of electrification or the technical barriers with battery-electric trains. Targeted public financing and regulatory alignment to offset the initial expense is needed to support achieving India's target of reaching net-zero rail by 2030.

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DIGITAL SOLUTIONS FOR SUSTAINABLE CONSTRUCTION: EXPLORING AI'S ROLE IN ACHIEVING NET ZERO

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ABSTRACT

The construction sector is a leading contributor to global greenhouse gas emissions, accounting for substantial operational and embodied carbon. Addressing this environmental impact is fundamental to meeting net-zero goals. Recent developments in Artificial Intelligence (AI) offer new digital solutions capable of transforming sustainability performance across the entire project lifecycle. Yet, questions remain about how best to harness these technologies in a fragmented, risk-averse industry.

This conceptual study develops a lifecycle-based framework to explore how AI applications contribute to sustainable construction and decarbonisation. It integrates insights from global policy literature and scholarly research to examine AI's role in five key lifecycle phases: design, planning, execution, operations, and end-of-life. The study further incorporates the Technology–Organisation–Environment (TOE) framework and Dynamic

Capabilities Theory (DCT) to investigate how contextual and organisational factors shape AI adoption. By aligning AI capabilities with net-zero goals, the framework advances a holistic view of digital sustainability in the built environment. The study also identifies key barriers—such as fragmented data ecosystems and insufficient digital governance—as well as enablers including lifecycle procurement models, smart policy incentives, and digital skills development. This paper contributes to the ISDSI-GLOBAL 2025 theme of "Tech for Net Zero" by presenting a theoretical foundation and practical pathway for AI-led sustainable construction.

Keywords: Artificial Intelligence, Net-Zero Construction, Sustainable Built Environment, Lifecycle Decarbonisation, Digital Twins, Circular Economy, Dynamic Capabilities, TOE Framework

INTRODUCTION

The global building and construction sector continues to play a central role in climate change, accounting for over 37% of energy-related CO_2 emissions and 34% of final energy use worldwide (GlobalABC, IEA, & UNEP, 2025). While energy efficiency in building operations has improved, emissions from construction processes and materials—also known as embodied carbon—have risen, reflecting the persistent gap between sectoral targets and on-ground transformation (Olawade et al., 2024).

The 2024/2025 Global Status Report highlights that only 10% of countries currently regulate whole-life carbon in buildings, while embodied emissions remain largely unregulated and underreported. The challenge is

compounded by the construction industry's historically slow adoption of digital innovation (Liew et al., 2025), hindering decarbonisation and circularity.

Artificial Intelligence (AI) offers a unique opportunity to address this inertia. As an enabling digital technology, AI supports intelligent decision-making, predictive modelling, resource optimisation, and automation across complex workflows. While BIM and IoT have made inroads in construction, AI brings higher-order functions that may radically improve sustainability performance across the project lifecycle (Wang et al., 2024).

This paper explores the role of AI in enabling net-zero construction through a lifecycle-based framework that draws on two theoretical perspectives: the Technology–Organisation– Environment (TOE) framework and Dynamic Capabilities Theory (DCT). The study contributes a conceptual model that links AI-enabled digital transformation with sustainable construction outcomes.

LITERATURE REVIEW

Emissions and Lifecycle Complexity

The built environment is one of the largest global sources of CO_2 emissions, stemming from both operational energy use and the embodied carbon of materials and construction processes. As emphasised in the Global Status Report (GlobalABC et al., 2025), significant carbon reductions must occur across the entire lifecycle—design, construction, use, and decommissioning—if the sector is to align with 1.5°C climate targets.

Recent works emphasise the complexity of reducing embodied emissions, which continue to rise despite energy efficiency gains (Liew et al., 2025). Lifecycle-based strategies are increasingly promoted, encompassing circularity, digital material passports, and emissions transparency (Zuo et al., 2019). These approaches require digital enablers capable of capturing, analysing, and acting upon large, diverse datasets—an area where AI can add substantial value.

Emerging AI Applications in Construction

AI is being deployed in a growing range of applications throughout the construction lifecycle. In design, generative AI tools and optimisation algorithms help produce sustainable layouts with lower energy demand and reduced material waste (Marzouk & Othman, 2020; Olawade et al., 2024). During planning and scheduling, predictive analytics improve coordination and reduce resource inefficiencies (Wang et al., 2024).

Construction execution benefits from AI-driven robotics and site monitoring, reducing rework and emissions through enhanced safety and precision (Lu et al., 2019). Operational phases are supported by digital twins and smart control systems, enabling real-time feedback, adaptive building management, and energy forecasting (Mahamadu et al., 2018). At the end-of-life stage, AI aids in disassembly modelling, waste classification, and circular reuse strategies (Kouhestani et al., 2019).

Studies such as Liew et al. (2025) and Olawade et al. (2024) highlight how AI, when deployed holistically, can serve as a backbone for digital decarbonisation and sustainable construction ecosystems.

Barriers and Gaps in Adoption

Despite increasing use cases, several structural and technical barriers hinder

AI's widespread implementation in construction. Fragmented data environments, lack of interoperability between systems, and resistance to organisational change persist across many regions (Ding et al., 2019; Alreshidi et al., 2018). Additionally, there is limited empirical integration of AI applications within lifecycle sustainability frameworks, and few theoretical models explain adoption in the context of organisational capabilities and policy environments.

This gap motivates the development of a conceptual model linking AI technologies to lifecycle outcomes through the lenses of TOE and DCT.

THEORETICAL FRAMEWORK

Technology–Organisation–Environment (TOE) Framework

The Technology–Organisation–Environment (TOE) framework offers a structured lens through which to analyse how organisations adopt new technologies. In the construction context, technological factors include AI system maturity, integration with BIM platforms, and user- friendliness. Organisational factors involve leadership support, digital infrastructure, and internal skill sets (Saka & Chan, 2020). Environmental factors are influenced by regulatory pressure, client expectations, and incentives for digital sustainability (Liew et al., 2025).

The TOE framework thus allows for a contextualised understanding of AI readiness and adoption variance.

Dynamic Capabilities Theory (DCT)

Dynamic Capabilities Theory (Teece, 2007) focuses on a firm's ability to sense opportunities, seize them effectively, and transform its structures for sustained competitive advantage. Applied to construction sustainability:

- Sensing may involve identifying inefficiencies or carbon hotspots using data analytics.
- Seizing includes allocating investment to AI capabilities or engaging with green innovation networks.
- Transforming entails embedding digital practices into procurement, operations, and long-term strategy (Kumar & Tiwari, 2024).

Combining TOE and DCT offers a robust dual framework to explain how AI can be leveraged strategically in construction settings.

CONCEPTUAL FRAMEWORK DEVELOPMENT

This section presents a lifecycle-based conceptual framework that illustrates how AI can contribute to sustainable construction practices aligned with net-zero objectives. The framework is structured around five key project lifecycle phases—design, planning, execution, operations, and end-of-life—each mapped with corresponding AI applications and expected sustainability outcomes. It is underpinned by two guiding theoretical lenses: the Technology– Organisation–Environment (TOE) framework and Dynamic Capabilities Theory (DCT). The rationale for using a lifecycle approach stems from the understanding that emissions reduction and resource optimisation must occur at multiple stages of the built environment— not merely during operations. By structuring the framework around the project lifecycle, the model

encourages integrated thinking across traditionally siloed phases, while also allowing specific interventions to be tailored to each stage. AI tools serve as enablers within this framework, providing data-driven insights, adaptive control, and predictive analytics. Each phase reflects both technical applications and the organisational or environmental contexts necessary for implementation, as described through TOE and DCT dimensions

Table 1

Project Phase	AI Application	Sustainability Contributions
Design	Generative design algorithms, embodied carbon modelling	Material efficiency, passive energy optimisation
Planning	Predictive logistics, carbon-aware scheduling	Efficient resource allocation, emission forecasting
Execution	AI-assisted robotics, safety analytics, site monitoring	Reduced rework, lower on-site emissions, safer operations
Operations	Digital twins, adaptive controls, fault diagnostics	Real-time energy optimisation, HVAC efficiency
End-of-Life	Disassembly modelling, AI-based traceability	Circularity, reuse potential, waste minimisation

This model reflects insights from both recent empirical studies (e.g., Olawade et al., 2024; Wang et al., 2024) and policy guidance (GlobalABC et al., 2025).

Informed by the TOE framework, technological readiness (e.g. AI maturity, BIM integration), organisational capacity (e.g. leadership, skills), and external influences (e.g. regulation, stakeholder pressure) each act as moderators shaping the success of AI interventions across these phases. For instance, generative design tools require both software compatibility (technology) and supportive design culture (organisation), while

digital twin deployment depends on client demand for performance-based outcomes (environment).

Dynamic Capabilities Theory further clarifies how firms can evolve to embrace these tools. The capability to **sense** inefficiencies (e.g. carbon hotspots), **seize** opportunities (e.g. through digital procurement), and **transform** internal systems (e.g. embedding AI in standard workflows) is critical to actualising sustainability benefits. For example, end-of-life disassembly analytics are only effective when firms have developed the capacity to trace materials and align reuse strategies with long-term asset planning.

This integrated framework contributes to both theory and practice. Theoretically, it bridges technical applications with organisational adaptability, offering a dynamic, systems-level view of digital sustainability. Practically, it serves as a

roadmap for construction firms and policymakers seeking to embed AI across the lifecycle in pursuit of net-zero performance.

DISCUSSION AND IMPLICATIONS

The proposed framework offers both theoretical and practical insights.
From a theoretical standpoint, it reinforces the need to view AI not merely as a technology, but as a system-level enabler of dynamic capabilities. It also bridges gaps between AI functionality and strategic sustainability alignment—an area under-explored in the construction literature (Pan & Zhang, 2021).

Practically, organisations can use the model to identify digital readiness gaps, prioritise lifecycle-oriented AI investments, and coordinate sustainability goals with procurement and project management functions. As demonstrated by Liew et al. (2025), such alignment can accelerate decarbonisation across multiple built environment stakeholders.

For policymakers, the framework suggests key levers to enhance AI uptake: performance-based regulations, data interoperability standards, and funding for digital infrastructure in public projects. These tools are critical to mainstreaming AI as a climate solution..

Future Research Directions

Future work should:

- Test the framework in empirical settings across project types and geographies.
- Develop AI readiness assessment tools based on TOE and DCT.
- Integrate edge-AI, blockchain, and sensor fusion technologies for enhanced real-time decarbonization.
- Investigate ethical implications of AI in construction, including transparency, job displacement, and accountability.

CONCLUSION

AI has the potential to serve as a keystone in the digital transformation of sustainable construction. By enabling lifecycle optimisation, reducing carbon emissions, and improving decision-making, AI offers tangible pathways to net-zero targets.

This paper presents a novel conceptual framework grounded in lifecycle analysis and strategic management theory, clarifying how AI can be adopted and scaled across the built environment. It contributes to both scholarly discourse and practitioner strategy at a time when digital innovation is critical to climate resilience in the construction sector.

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EMBEDDING ESG VALUES IN INDIAN BANKING: REDEFINING FINANCIAL INSTITUTIONS FOR A SUSTAINABLE FUTURE

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ABSTRACT

Across the world, countries are increasingly focusing on ESG values to promote responsible environmental, social and governance practices. In India, various sectors and industries have also begun to emphasize on ESG principles driven by strong regulatory mandates, global pressure and growing public awareness.

The Banking sector in India is also increasingly emphasizing the adoption of ESG practices to reduce risk, ensure regulatory compliance and meet the growing expectations of investor and consumer. In this study we seek to identify the key enablers that facilitate ESG compliance in Indian Banks. These enablerswere first identified through a comprehensive review of the existing literature and subsequently validated through expert consultation. To achieve this, we employ ISM-MICMAC methodology that help to identifythe key enabler and develop astructural model illustrating how these factors are interrelated. Furthermore, MICMAC analysis is used to classify these enablers based on their driving and dependence power. The findings shows that Regulatory Initiatives and Technological Advancement are the main enablerof ESG adoption. Focusing and emphasizing on these areas help bank to reduce risks, ensure regulatory compliance, enhance brand image and effectively managing climate risk and challenges. Banks should embed ESG value into their core strategies and operational policies to achieve sustainable and long-term growth

Keywords: ESG, Sustainability, Indian banking, CSR, MCDM

INTRODUCTION

Environmental, Social, and Governance ESG concepts are being included inthe daily operations of banks and financial institutions all around. It is now a major component of their company, not a minor issue as they once handled*(Rechsteiner, R. 2020*). They connect ESG with their financial decisions, handling of money, service delivery, and risk management. This change occurs because rules are becoming stricter, investors prefer responsible choices, and customers want banks to prioritize the well-being of people and the planet. Banks try to meet these expectations by bringing sustainability goals into their plans, actions, and systems. They employ responsible practices to mitigate risks and explore new avenues for growth. They now consider ethical principles when

lending money, choosing partners, or designing products, while also employing sustainable thinking to prepare for future challenges and remain resilient in a changing world. Many banks now invest in clean energy, green bonds, digital tools, and other projects that support long-term goals, such as the UN Sustainable Development Goals. They know that adopting these values helps them work more effectively and serve society at the same time. As this global shift continues, banks recognize that adopting such responsible frameworks is not a choice, but a necessity that they must employ to comply with regulations, meet market demand, and maintain long-term relevance.

The Importance of ESG in the Present Scenario

Banks and financial organizations now incorporate environmental, social, and governance (ESG) considerations into their daily operations. ESG is no longer just an extra concern. It influences how banks make decisions, manage finances, provide services, and manage risks. This change is occurring because rules are stricter, investors demand responsible choices, and customers expect banks to prioritize people and the planet. They are integrating ESG in their plans, actions, and systems to meet these new expectations. They consider ESG when lending money, selecting partners, and developing new products. It helps banks mitigate risks and explore new avenues for growth. For example, banks now offer green loans and sustainable investment products. They also utilize ESG to verify that their partners and clients adhere to responsible practices. Banks utilize technology to track and report on ESG activities, making their work more transparent and helping them meet regulatory requirements and customer demands. By making it a core part of their business, banks enhance their reputation, foster trust, and remain prepared for future market changes and regulatory updates. Many banks now invest in clean energy, green bonds, digital tools, and other projects that support long-term goals, such as the UN Sustainable Development Goals. Banks recognize that ESG initiatives help them operate more effectively and also support society. As changes occur around the world, banks recognize that following ESG principles is now necessary, not optional. They must follow ESG principles to meet regulatory requirements, stay aligned with market expectations, and remain relevant in the future.

Incorporating ESG in the Indian Banking Sector

Indian banks have started focusing more on Environmental, Social, and Governance ESG ideas to match global trends and respond to rising expectations from investors, customers, and regulators (*2023 Global Status Report for Buildings and Construction)*. The Reserve Bank of India RBI plays a key role in pushing banks to include these values in their daily work.Banks must upgrade their technological systems to accomplish this correctly. They must gather and oversee information on topics such as the societal impact of carbon emissions and their level of preparedness for climate change hazards. Banks also have to produce reports demonstrating their efforts. This implies upgrading internal rules and data

networks of IT systems, which requires funding and preparation. Banks that fail to have strong systems today may face problems later on. In their annual reports for 2020, banking institutions should provide information on their policies for handling climate-related risks and supporting sustainable development, the RBI advised. They also had to share how they help projects that protect the environment or support social good. The RBI is currently developing a new plan to promote green finance and ensure that Indian banks comply with global standards. Despite these steps, most banks in India continue to struggle with implementing ESG practices effectively. A 2023 study by the Indian Banks' Association finds that many banks are not thoroughly prepared. They deal with issues including unclear policies, inadequate decision-making systems, and insufficient means to monitor their activities. To address these challenges and support banks in achieving their green goals, the Reserve Bank of India is developing new policies. Some large banks, such as SBI and HDFC Bank, have already initiated projects in this direction. However, it remains challenging to ensure that all employees follow the same path or accurately track their progress. This change will take time and is likely to begin with larger banks before expanding to smaller ones. Step by step, the entire sector will transition towards a system that balances both profit and responsibility.

Current Implementation Strategies and Adoption Processes

Institutions in India are progressively incorporating Environmental, Social, and Governance (ESG) concepts into their daily operations. This transition is influenced by the Reserve Bank of India's (RBI) stringent policies, increasing environmental concerns, and increasing investment and consumer pressure. Banks now consider ESG to be a critical component of their lending, investment, and decision-making processes. Financial institutions are upgrading their systems to facilitate this transition. They gather data on social impact, carbon emissions, and climatic hazards to satisfy reporting obligations. The Reserve Bank of India has urged banks to provide consistent reporting regarding their risk management and social and environmental initiatives. This promotes a more profound sense of assurance and clarity. In the past, specific private banks have supported renewable energy initiatives, provided green loans, and implemented global ESG guidelines. Additionally, a significant number of individuals employ digital methods to communicate with individuals in remote locations, thereby facilitating more egalitarian and straightforward banking. However, some institutions still face challenges, including unclear policies, inadequate training, and ineffective processes. The leadership of the RBI and increasing awareness of the problem help Indian banks move in the right direction. Utilizing this development will enable them to accelerate changes in the banking sector with more ethical and forward-thinking approaches.

LITERATURE REVIEW

Environmental, social, and governance (ESG) principles are being increasingly incorporated intothe daily operations of Indian institutions. The Reserve Bank of

India's (RBI) strict policies, growing environmental concerns, and increasing investment and consumer pressure all contribute to shaping this change. Today, bank's view ESG as a fundamental component of their lending, investment, and decision-making processes. Financial institutions are being upgraded to enable this change. To fulfil reporting responsibilities, they compile information on social effects, carbon emissions, and climatic threats. The Reserve Bank of India has pushed banks to consistently report on their social and environmental projects as well as their risk management policies. This advances a strong sense of assurance and clarity. Specific private banks have historically supported global ESG policies, provided green loans, and independently funded renewable energy projects. Moreover, many people use digital means of communication to interact with those living far away, thereby enabling more equal and simple banking. Still, some institutions have issues, including poorly defined policies, inadequate training, and ineffective procedures. Rising awareness of the issue, combined with RBI leadership, enables Indian banks to steer in the correct direction. Utilizing this development will enable them to accelerate improvements in the banking industry with more ethical and forward-thinking approaches.

Key Frameworks and Standards

Several global frameworks have been developed to support ESG integration and reporting:

Table 1. List of frameworks

Framework/Standard	**Focus Area**	**Notable Features**
Global Reporting Initiative (GRI)	Comprehensive ESG reporting	Widely adopted, voluntary, and used by many large firms
IFRS Sustainability Disclosure (ISSB)	Sustainability in financial disclosures	Builds on existing frameworks, voluntary
Task Force on Climate-related Financial Disclosures (TCFD)	Climate risk disclosure	Focuses on climate-related financial risks
Sustainability Accounting Standards Board (SASB)	Industry-specific ESG standards	Detailed, sector-specific metrics
United Nations Sustainable Development Goals (SDGs)	Universal sustainability targets	A broader global agenda, not a reporting standard

Although most ESG reporting is currently optional worldwide, authorities are increasing pressure on this process. For ESG disclosures, for instance, the U.S. Securities and Exchange Commission has proposed new guidelines (SEC, 2022). Investors, laws, and companies worldwide are giving ESG more consideration. Due to the Sustainable Development Goals and the Principles for Responsible Investment (PRI), ESG is becoming increasingly important in business and investment decisions. Many find investments in ESG as a means of risk management, transparency, and long-term value development (Friede et al., 2015). In India, banks are increasingly adopting ESG practices. This is happening due to both international trends and new regulations in India. The Reserve Bank of India has given banks guidelines to help them manage ESG risks and support sustainable finance (RBI, 2021). The Association of Indian Banks also encourages banks to prioritize sustainability and green loans (IBA, 2022). When banks in India are graded for ESG, they consider factors such as emissions associated with loan portfolios, lending to riskier sectors, financing green energy initiatives, community development in rural regions, achieving lending targets, and having diverse boards. Typically, ESG ratings for Indian banks allocate 35% weight to environmental factors, 25% to social aspects, and 40% to governance (KPMG, 2023). Studies on ESG adoption provide conflicting findings for Indian banks. According to some research, a rise in stock prices has a weak negative correlation with ESG ratings. But ESG appears to support profitability—that is, return on assets and return on equity—Sharma & Gupta, 2022. As they migrate from old methods to more sustainable ones, banks run some risks. They also struggle with tracking indirect emissions, fully meeting the Net Zero target, and transitioning from voluntary to mandated ESG reporting (RBI, 2021; KPMG, 2023). The Reserve Bank of India has also shared its expectations for banks regarding ESG, and some banks have begun reporting their ESG strategies. Still, most banks in India are just starting this journey (IBA, 2022). The sector is evolving as regulations are becoming stricter, investors are closely monitoring developments, and sustainable finance is becoming increasingly integral to India's growth.

Table 2: ESG in Global Context vs. Indian Banking Sector

Aspect	Global ESG Practice	Indian Banking Sector ESG Practice
Regulatory Framework	Multiple voluntary global standards; some local mandates	RBI guidelines; IBA initiatives; mostly mandatory reporting
Key Focus Areas	Environment, Social, Governance (broad)	Financed emissions, green funding, governance, rural reach
Reporting Standards	GRI, ISSB, TCFD, SASB, SDGs, etc.	No single standard; mix of global and local practices
Adoption Level	Widespread, especially among large firms	Growing, but still at an early stage
Challenges	Lack of universal standards, regulatory uncertainty	Scope 3 emissions tracking, transition risks, and limited voluntary disclosure

Table 3. List of Enablers with References

S. No.	Enablers	References
1	Regulatory Initiatives	Rashmi Akshay Yadav, Dr. Premalatha K. P and Dr. Shrinivas Patil. (2024)
2	Technology Adoption	Rashmi Akshay Yadav, Dr. Premalatha K. P and Dr. Shrinivas Patil. (2024)
3	Investor Pressure	Albertini E (2013)
4	Consumer	Marin, L., Ruiz, S., & Rubio, A.
	Sustainability Preference	(2009)
5	Financial Inclusion Potential	Badar Alam Iqbal, Shaista Samia,(2017)
6	Global Framework Alignment	Kishore Kumar, Ajai Prakash (2019)
7	Global Sustainability Trends	Kishore Kumar, Ajai Prakash (2019)
8	Financial Performance & Reputation	Ramesh Prasad, Amitava Mondal (2025)

9	Climate Risk Mitigation	Rashmi Akshay Yadav, Dr. Premalatha K. P and Dr. Shrinivas Patil. (2024)
10	ESG in Business Strategy	Rashmi Akshay Yadav, Dr. Premalatha K. P and Dr. Shrinivas Patil. (2024)
11	Government Support	Kishore Kumar, Ajai Prakash (2019)
12	Awareness & Recognition	Kumar and Prakash (2020)
13	Borrower Engagement on Emissions	Rashmi Akshay Yadav, Dr. Premalatha K. P and Dr. Shrinivas Patil. (2024)
14	Demand for Sustainable Banking	Corporate Governance and Sustainability Review (2021)

DATAAND METHODOLOGY

Two-Phase Approach for ESG Adoption in the Indian Banking Sector

Phase 1: Identification of ESG Enablers

Extensive Literature Review

(toidentify key ESG enabler influencing strategic decision-making and transformation in Indian banking)

Expert Mining

Interviews with Industry Experts

Interviews with Academic Experts

VAXO Sheet Distribution

VAXO sheet floated among 11 experts

Final VAXO generated by averaging expert responses

Phase 2: Enabler Structuring & Analysis (ISM-MICMAC Method)

List of ESG Enablers Finalized

(Based on expert mean score > 3.5)

Establish Contextual Relationships between Enablers

Develop Structural Self-Interaction Matrix (SSIM)

Feed Final VAXO into ISM-MICMAC Software

Reachability Matrix Formation

A two-phase methodology has been applied in this investigation. In Phase One, 14 social Responsibility enablers were identified through a thorough literature analysis. Following a debate and expert interview, all 14 enablers were ultimately chosen. Only factors with an expert. A mean score of greater than 3.5 on their significance for constructive societal change is included in this study. Every one of the 14 facilitators in this study has a mean score higher than 3.5. As a result, every enabler has been taken into account for additional research. The position of the enablers and their relationships with one another were established in the next step or Second phase using the ISM-MICMAC technique

ISM and Structural self-interaction matrix

This study identified the 14 key enablers for developing the structured model, which determines how these enablers interact and the direction of their influence, input was sought from some of academicians, industry professionals, and social experts. Using their insights, a self- structured

An interaction matrix (SSIM) was constructed to map the relationship between enablers. The SSIM employs four symbols, each representing a specific type of relationship:

‘V’ indicates that the enabler i supports enabler j;

‘A’ shows that enabler j supports enabler i;

‘X’ signifies mutual support between enablers i and j; and

‘O’ denotes no significant relationship between them. These symbols have been widely used in

previous applications of Interpretive Structural Modelling (ISM) to clarify the nature of interactions among variables.

The VAXO method helps us understand how different factors support the use of ESG in Indian banks. It gives a clear way to study how these factors are connected. The VAXO coding system is used to construct a specialized table known as the Structured Self- Interaction Matrix (SSIM). This table illustrates how each of the 14 key enablers interacts with or influences the others when banks strive to implement ESG practices. Some of these key enablers include government regulations, the adoption of new technology, pressure from investors, and customers who prefer eco-friendly and fair practices. These factors have become increasingly important as Indian banks strive to align with global sustainability standards.

Fig 1. Self-structured Interaction Matrix

Structural Self-Interaction Matrix (SSIM)

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
E1		V	V	V	V	V	O	V	V	V	O	V	V	V
E2			V	V	V	V	O	V	V	V	O	V	V	V
E3				V	O	X	O	V	X	X	O	V	V	V
E4					O	A	A	O	O	O	O	A	O	O
E5						A	O	O	A	A	O	O	O	O
E6							O	V	X	X	O	V	V	V
E7								V	O	O	O	V	O	V
E8									A	A	A	A	A	O
E9										X	O	V	V	V
E10											O	V	V	V
E11												V	O	V
E12													V	V
E13														V
E14														

Table 4. Rules

SSIM Relationship (i,j)	Reachability Matrix (i,j) Entry	Reachability Matrix (j,i) Entry
i influences j (V)	**1**	**0**
j influences i (A)	**0**	**1**
Mutual influence (X)	**1**	**1**
No relationship (O)	**0**	**0**

After finalising the SSIM table, we create the reachability matrix. Here, the symbols are changed (V, A, X, and O) into numbers

1 if there is a direct link between two factors, and **0** if there is no link. Each symbol in the SSIM shows a type of relationship between two enablers. We use simple rules to make sure we convert these symbols correctly into numbers. This matrix helps us clearly understand how various factors, such as government regulations, technology usage, investor demands, and customer preferences, are interconnected. It alsohelps banks decide which areas to focus on when they want to include ESG ideas in their main business and manage risks better

SSIM to Reachability Matrix Conversion Rules

Rule Application

- V → (1, 0): Direct influence from i to j.
- A → (0, 1): influence from j to i.
- X → (1, 1): cross relationship.
- O → (0, 0): No influence.

This table aligns with ISM-MICMAC standards for deriving binary relationships from symbolic SSIM inputs.

Figure 2 : Reachability Matrix

Reachability Matrix(RM)

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Driving Power
E1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	12
E2	0	1	1	1	1	1	0	1	1	1	0	1	1	1	11
E3	0	0	1	1	0	1	0	1	1	1	0	1	1	1	9
E4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
E5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
E6	0	0	1	1	1	1	0	1	1	1	0	1	1	1	10
E7	0	0	0	1	0	0	1	1	0	0	0	1	0	1	5
E8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
E9	0	0	1	0	1	1	0	1	1	1	0	1	1	1	9
E10	0	0	1	0	1	1	0	1	1	1	0	1	1	1	9
E11	0	0	0	0	0	0	0	1	0	0	1	1	0	1	4
E12	0	0	0	1	0	0	0	1	0	0	0	1	1	1	5
E13	0	0	0	0	0	0	0	1	0	0	0	0	1	1	3
E14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Dependence Power	1	2	6	7	6	6	1	11	6	6	1	9	8	11	

Figure 3. Final Reachability Matrix

Final Reachability Matrix(FRM)

Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Driving Power
1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	12
2	0	1	1	1	1	1	0	1	1	1	0	1	1	1	11
3	0	0	1	1	1*	1	0	1	1	1	0	1	1	1	10
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
6	0	0	1	1	1	1	0	1	1	1	0	1	1	1	10
7	0	0	0	1	0	0	1	1	0	0	0	1	1*	1	6
8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
9	0	0	1	1*	1	1	0	1	1	1	0	1	1	1	10
10	0	0	1	1*	1	1	0	1	1	1	0	1	1	1	10
11	0	0	0	1*	0	0	0	1	0	0	1	1	1*	1	6
12	0	0	0	1	0	0	0	1	0	0	0	1	1	1	5
13	0	0	0	0	0	0	0	1	0	0	0	0	1	1	3
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Dependence Power	1	2	6	10	7	6	1	11	6	6	1	9	10	11	

Figure 4: Level Portioning

Level Partitioning(LP)

Elements(Mi)	Reachability Set R(Mi)	Antecedent Set A(Ni)	Intersection Set R(Mi)∩A(Ni)	Level
1	1,	1,	1,	6
2	2,	1, 2,	2,	5
3	3, 6, 9, 10,	1, 2, 3, 6, 9, 10,	3, 6, 9, 10,	4
4	4,	1, 2, 3, 4, 6, 7, 9, 10, 11, 12,	4,	1
5	5,	1, 2, 3, 5, 6, 9, 10,	5,	1
6	3, 6, 9, 10,	1, 2, 3, 6, 9, 10,	3, 6, 9, 10,	4
7	7,	7,	7,	4
8	8,	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13,	8,	1
9	3, 6, 9, 10,	1, 2, 3, 6, 9, 10,	3, 6, 9, 10,	4
10	3, 6, 9, 10,	1, 2, 3, 6, 9, 10,	3, 6, 9, 10,	4
11	11,	11,	11,	4
12	12,	1, 2, 3, 6, 7, 9, 10, 11, 12,	12,	3
13	13,	1, 2, 3, 6, 7, 9, 10, 11, 12, 13,	13,	2
14	14,	1, 2, 3, 6, 7, 9, 10, 11, 12, 13, 14,	14,	1

Analysis of Final Reachability Matrix

The final reachability matrix encompasses all direct and indirect links, enabling us to understand how various factors contribute to ESG adoption in Indian banks.

Driving Power Analysis

Bottom Level – Drivers (Strong Influencers): E1 and E2

These are the starting points. They push the entire system forward. In India, regulatory bodies such as the RBI and SEBI are actively promoting ESG through guidelines and disclosures (E1).

At the same time, banks are adopting digital tools (E2) to track ESG metrics, automate reporting, and better serve their customers.

Middle Level – Mediators (Bridge Factors) : E3, E6, E9, E10, E7, E11

These factors both influence and influence. They act as links between the strong base drivers and the outcomes.

Top Level – Outcomes : E4, E5, E8, E12, E13, E14

These are mostly results. They do not significantly influence other factors, but they change when the system (regulations, strategies, technology) changes.

FINDINGS AND ANALYSIS

ESG Implementation in Indian Banking

Banks in India have begun to modify their operations by incorporating ESG principles into their long-term plans. They now focus more on how their work affects the environment and society, as well as how fairly they run their business. This significant change is occurring because rules are becoming stricter, global standards are guiding actions, and stakeholders, including investors, customers, and the public, are demanding better, cleaner, and fairer banking. The present analysis employs Interpretive Structural Modelling (ISM) and Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) to explore the critical enablers influencing ESG adoption in Indian banks. These tools provide a structured framework that clarifies the relationships between

different ESG elements and highlights the driving and dependent forces within the system.

Hierarchical Mapping through ISM Analysis

Foundational Enablers (Base Level)

At the base of the ISM hierarchy lie the most influential elements:

- E1: Regulatory Initiatives
- E2: Technology Adoption

Regulatory frameworks (E1)form the bedrock of ESG integration. The Reserve Bank of India showed its strong support for green finance by joining the Network for Greening the Financial System in 2021. After that, it shared a new draft rule that requires all banks and financial firms it controls to disclose how they manage climate risks. This rule will begin from the financial year 2025–26. The RBI wants all financial groups to become more transparent and responsible in how they handle environmental risks.

Technology adoption (E2) complements regulatory drives by enabling digital systems that collect, analyse, and report ESG data. Through automated dashboards, carbon accounting tools, and integrated risk assessment platforms, banks can make their ESG operations measurable and trackable, ensuring alignment with global standards.

Intermediary Influencers (Middle Level)

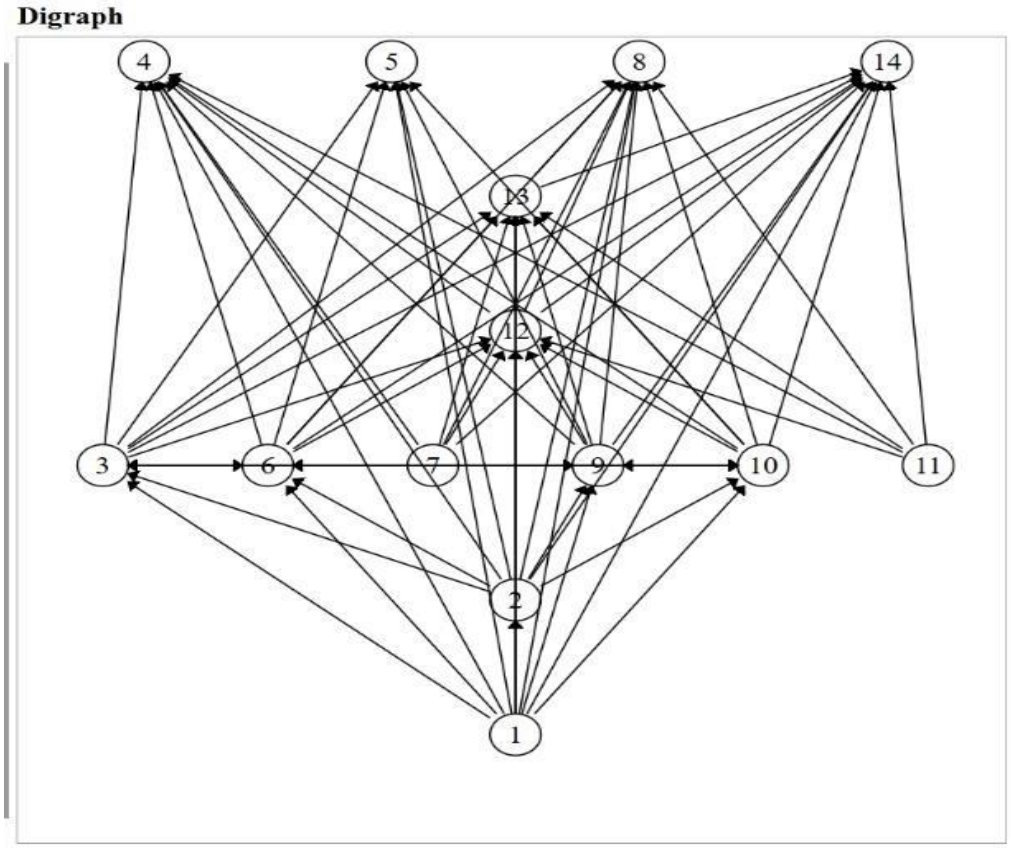
Positioned between core drivers and outcomes, the following factors act as bridges: E3, E6, E7, E9, E10, E11

Investor pressure (E3) now influences how banks set their ESG goals. Big investors now link their money decisions to ESG scores. This move requires banks to adhere to rules similar to those established by the Task Force on Climate-related Financial Disclosures (TCFD). Indian banks, such as ICICI and IDFC FIRST, already share their full ESG reports. These actions demonstrate that outside groups are beginning to influence how banks operate**.**

Climate risk mitigation (E9). Banks now view climate risk management as a necessity. They deal a lot with industries like energy and manufacturing that release high carbon. Therefore, they need to adjust their lending practices to align with long-term environmental goals. The RBI also sees that ignoring climate risks can harm the full economy and banking system. It urges both financial and government groups to collaborate and take prompt action.

Outcome-Oriented Factors (Top Level)

Figure 5: ISM MODEL



These factors reflect the long-term impacts and end goals of ESG practices:

- E4, E5,E8, E12, E13, E14

Recent findings by *IIM Lucknow* suggest that banks with significant exposure to green loans enjoy improved financial stability over time. This reinforces the role of E8 (Financial Performance & Reputation) as a vital outcome. Similarly, the RBI's *Green Deposits Framework*, effective June 2023, allows financial institutions to channel funds into green sectors, directly catering to evolving consumer preferences (E4) and market demand for sustainable offerings (E14).

MICMAC Analysis: Driving Power vs. Dependence

Independent Drivers (High Driving Power, Low Dependence)

E1, E2, E3, E6, E9, E10

These factors are instrumental in driving system-wide changes. The State Bank of India now follows an ESG Financing Framework that incorporates climate risk considerations when lending. This demonstrates that the bank has made ESG a central part of its daily operations. By incorporating climate concerns into lending, the bank demonstrates that it takes both business growth and the planet seriously. Moreover, regulatory frameworks, such as the RBI's climate-related disclosure mandates, ensure that ESG shifts from a voluntary gesture to a structural necessity.

Dependent Elements (Low Driving Power, High Dependence)

E4, E5, E8, E12,E13, E14

These are reactive and rely on proactive changes elsewhere. As banks expand ESG- compliant lending, they inadvertently increase borrower accountability (E13) and improve brand visibility (E12), eventually influencing consumer sentiment.

Autonomous Elements (Low Driving Power, Low Dependence)

E7 and E11

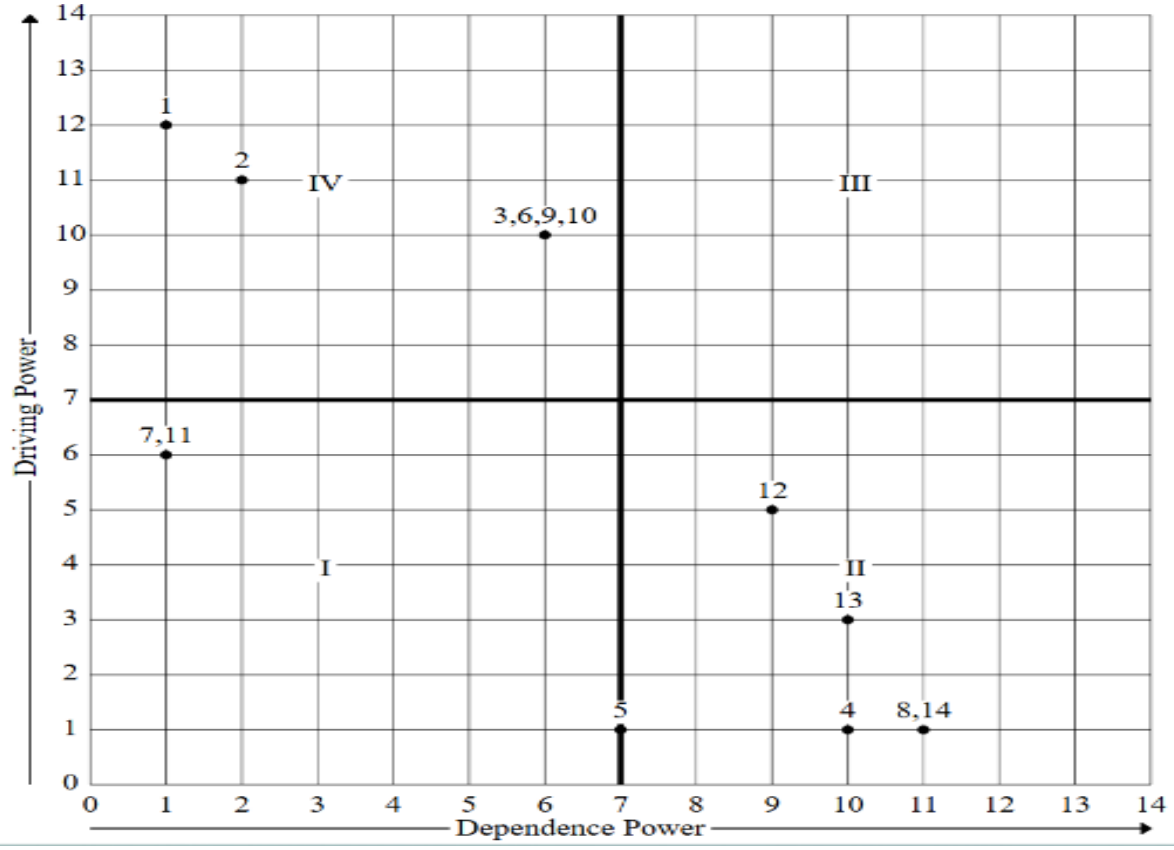
These function more as background hierarchies and minimal cyclical dependencies.

influencers. While India's national net-zero targets (by 2070) set the tone, their day-to-day influence on banking operations is indirect. They offer context rather than direct pressure or control.

Linkage Factors (High Driving Power, High Dependence)

The current analysis reveals no dominant factors within this quadrant. This suggests that ESG implementation within Indian banking is presently linear, with distinct

FIGURE 6 MIMAC



Strategic Implications for Indian Banks

The ISM ICMAC analysis confirms that ESG integration in Indian banking is primarily top-down, beginning with regulations and technological reforms and flowing toward strategic adaptations and market responses. Without regulatory intervention, many banks may hesitate to fully embed ESG practices due to initial cost implications or uncertainty around returns.

Banks aiming to lead in ESG performance must prioritize:

- Compliance with emerging regulations
- Investments in digital ESG infrastructure
- Alignment with global disclosure standards
- Mainstreaming ESG within business strategy

The Task Force on Sustainable Finance, initiated by India's Department of Economic Affairs, is creating a sustainability taxonomy and policy recommendations. Banks that proactively respond to these initiatives will not only mitigate risk but also unlock new avenues for capital inflow and consumer trust.

The integration of ESG into Indian banking is no longer optional; it is a strategic imperative. ISM and MICMAC analyses provide a robust framework for navigating this shift. Regulatory and technological levers serve as the most influential catalysts, while intermediary pressures from investors and global trends help maintain momentum. Ultimately, the payoff is evident in improved consumer sentiment, enhanced financial performance, and strengthened reputation.

By leveraging high-driving-power enablers and understanding the layered dependencies across the system, Indian banks can establish a credible, sustainable, and profitable ESG pathway. As emphasized by the RBI Governor, collaboration across stakeholders and development of scalable, green financial projects will be key to unlocking long-term value in India's ESG journey.

Strategic Implications for ESG Adoption in Indian Banking: Building on ISM and MICMAC Insights

The ISM and MICMAC studies clearly outline a step-by-step approach for implementing ESG in Indian banks. These tools highlight that government rules and new technologies form the foundation for this change. Banks need to utilize this knowledge to develop effective plans. They must integrate ESG ideas into their daily work, including how they handle risks and how they interact with people and groups connected to their business. The points shared below illustrate how various factors interact and their respective roles in advancing ESG.

Regulatory Compliance as a Strategic Catalyst

Regulatory steps (E1) hold the top spot in the ISM structure as the most powerful force driving ESG in the banking sector. This strong role requires banks to build systems that follow rules in advance. The Reserve Bank of India (RBI) has already shared draft rules requiring banks to report on how they manage climate risks. Along with this, SEBI's rule on Business Responsibility and Sustainability

Reporting (BRSR) requires banks to track and report ESG actions in a clear and consistent manner. These steps encourage banks to view ESG work as a core part of their daily operations. Strategic actions include:

- **Automating Compliance**: Banks now use automation to follow rules better. They utilize special tools called RegTech to streamline reporting and make it faster and easier. These tools help them align with Indian rules, such as BRSR, and global rules, including those from the Task Force on Climate-related Financial Disclosures (TCFD). For example, ICICI Bank started using smart AI tools that collect ESG data quickly and show results in real-time. This smart move helps them stay compliant with regulations and enhances their approach to sharing their ESG efforts.
- **Scenario Analysis Integration**: Embed climate stress-testing models into risk frameworks to assess physical and transition risks, as recommended in the RBI's 2023 report on sustainable finance.

Technology Adoption for ESG Scalability

Technology Adoption (E2) is pivotal for enabling transparency and efficiency. Banks must invest in digital infrastructure to track ESG metrics and mitigate the risks of greenwashing. Strategic steps involve:

- **AI and Blockchain Solutions**: Leverage AI for predictive analytics in carbon footprint measurement and blockchain for immutable ESG reporting. For example, Axis Bank's partnership with tech firms to develop a blockchain-based green loan tracking system demonstrates this.
- **Data Ecosystems**: Build centralized ESG data platforms, as seen in Capgemini's 890 platform, which consolidates internal and external data sources to model climate risks and opportunities.

Investor Engagement and Global Alignment

Investor Pressure (E3) and Global Framework Alignment (E6) emphasize the importance of aligning with international standards to attract ESG-focused capital. Key strategies include:

- **Adopting PCAF Standards**: Measure and disclose financed emissions using the Partnership for Carbon Accounting Financials (PCAF) framework, as implemented by Raiffeisen Bank International.
- **Sustainability-Linked Bonds (SLBs)**: Issue SLBs tied to ESG KPIs, mirroring global trends where banks like BNP Paribas link bond terms to renewable energy financing targets.

Climate Risk Mitigation as a Core Competency

Climate Risk Mitigation (E9) demands integrating climate considerations into credit decisions. The RBI's emphasis on transition risks in high-carbon sectors like energy and automobiles necessitates:

- **Sector-Specific Decarbonization Plans**: Develop transition pathways for carbon- intensive borrowers, offering incentives for adopting clean technologies. State Bank of India's (SBI) climate finance loans for renewable projects exemplify this.
- **Green Asset Ratio (GAR)**

Disclosure: Align with the European Banking Authority's GAR framework to quantify green exposures, enhancing comparability for investors.

Embedding ESG into Business Strategy

ESG in Business Strategy (E10) requires cultural and operational shifts. Banks must:

- **Link Executive Compensation to ESG Metrics**: Tie leadership incentives to emission reduction targets and financial inclusion goals, as UniCredit's net-zero commitment illustrates.
- **Product Innovation**: Launch green deposits, sustainability-linked loans, and ESG- themed investment products. HDFC Bank's green bonds for solar projects and SBI's ESG-focused mutual funds are precedents.

Stakeholder Collaboration and Capacity Building

The absence of linkage factors in MICMAC suggests a linear system, emphasizing the need for external partnerships to address data gaps and skill shortages:

- **Academic-Industry Partnerships**: Collaborate with institutions like IIMs to develop ESG training modules for employees, addressing the skill deficit noted in CRISIL reports.
- **Regulator-Bank Task Forces**: Participate in RBI-led working groups to co-create sectoral taxonomies and transition finance frameworks.

Consumer-Centric ESG Positioning

Consumer Sustainability Preference (E4) and Demand for Sustainable Banking (E14) are outcomes driven by awareness. Strategies to capitalize include:

- **Financial Literacy Campaigns**: Educate customers on green products through digital platforms, leveraging the RBI's Green Deposits Framework to promote eco-friendly savings instruments.
- **Personalized ESG Portfolios**: Use AI to offer tailored investment options based on customer sustainability preferences, similar to European models highlighted by Capgemini.

Governance and Anti-Greenwashing Measures

With greenwashing incidents rising globally, robust governance is critical:

- **Third-Party Audits**: Mandate independent verification of ESG claims, as mandated by SEBI's BRSR guidelines.
- **Whistleblower Mechanisms**: Implement channels for reporting discrepancies in sustainability disclosures, fostering accountability.

The strategic implications above position ESG not as a regulatory burden but as a lever for innovation and market leadership. Banks that operationalize these strategies will mitigate transition risks, enhance stakeholder trust, and tap into the $9.2 trillion annual global green investment opportunity. As the RBI Governor emphasized, a collaborative approach combining regulatory foresight, technological agility, and stakeholder alignment will define the success of India's sustainable banking transformation. By prioritizing the high-

driving- power factors identified in the ISM-MICMAC analysis, Indian banks can secure long-term resilience while advancing national climate goals.

CONCLUSION

This research clearly identifies and organizes the most important factors that help Indian banks adopt ESG using the ISM-MICMAC method. The model and analysis provide useful insights for decision-makers. First, regulatory rules, such as the RBI's joining of the NGFS in 2021 and its climate risk rules for 2025–26, act as the strongest push. These forces banks to stop casual ESG actions and start real, rule-based changes, especially in high-emission sectors. Second, technology plays a major role. Banks need tools like AI and blockchain to gather ESG data and avoid fake green claims. ICICI Bank and Axis Bank utilize such tools to comply with regulations and enhance their operations. Third, investor pressure and climate risk awareness connect the main drivers to real actions. Global investors now link their investments to ESG scores, so banks must follow rules like the TCFD. Banks are adjusting their lending rules to mitigate climate risk. The RBI states that ignoring these risks could harm the entire economy, so banks need to develop action plans for each sector. Fourth, outcomes such as improved profits and increased demand for green banking demonstrate that ESG benefitsbusinesses. IIM Lucknow links green loans to steady earnings. RBI's 2023 Green Deposit plan helps fund solar and wind projects, showing public interest in green finance. Fifth, strategy points from MICMAC are split into three groups. One, innovate for rules—use RegTech to follow BRSR and TCFD. SBI achieves this by incorporating climate checks into its loan rules. Two, grow with tech—use AI to track carbon and blockchain to store ESG data safely. The RBI now requires banks to assess climate risks using these tools. Three, focus on people—tie leaders' pay to ESG goals and offer green products. HDFC gives green bonds for solar, and SBI runs ESG funds. Sixth, for policy, the RBI should collaborate with SEBI and IBA to establish a single set of ESG rules. Banks and IIMs should collaborate to train their staff. Additionally, banks should offer affordable loans for clean energy, backed by RBI funds. Seventh, some banks lack historical ESG data, making it challenging to analyze trends. Small banks also fall behind large ones, so they require special assistance. Later studies should investigate the impact of ESG on villages or explore how fintech can facilitate green banking for all. In short, the ISM-MICMAC model demonstrates that ESG in Indian banks begins with regulations and evolves with technology. While global trends provide a backdrop, real change stems from strong factors such as policy and tools. As the RBI Governor says, teamwork is crucial to the growth of green banking. Banks that follow these steps will mitigate risks and contribute to India's $9.2 trillion green economy by 2030. The shift from just following rules to gaining business power has started. Fast action will decide who leads the change.

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FINANCIAL LITERACY AS A DETERMINANT OF SOUND FINANCIAL MANAGEMENT AMONG YOUNG ENTREPRENEURS

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ABSTRACT

Financial literacy is increasingly recognized as a foundational skill for entrepreneurial success. Young entrepreneurs, often driven by innovation and enthusiasm, may lack the necessary financial knowledge to manage business operations effectively. This paper examines financial literacy as a key determinant of sound financial management among young entrepreneurs. It explores the relationship between financial knowledge, decision-making, and the sustainability of entrepreneurial ventures. Through a review of literature and analytical discussion, the study identifies major gaps in financial awareness, highlights the consequences of poor financial management, and proposes measures to strengthen financial literacy through education, mentorship, and institutional support. The findings underscore the importance of integrating financial education into entrepreneurship development programs to enhance the financial decision-making capabilities of emerging entrepreneurs.

Keywords: Financial literacy, financial management, young entrepreneur's entrepreneurship education, sustainability, financial decision-making.

INTRODUCTION

In recent years, the entrepreneurial ecosystem has become a key driver of economic growth, innovation, and employment generation. Young entrepreneurs, in particular, represent a dynamic force capable of transforming ideas into viable enterprises. However, while technical and creative skills are often emphasized, financial management capabilities remain a critical yet overlooked factor in entrepreneurial success. Financial literacy — the ability to understand and effectively use financial skills such as budgeting, investing, and managing debt — plays a central role in ensuring that entrepreneurs make informed and rational financial decisions. Inadequate financial knowledge can result in poor cash flow management, over-leverage, and unsustainable business models, leading to early business failure. According to various studies, a significant proportion of start-ups fail within the first five years, often due to mismanagement of financial resources rather than lack of innovation. This paper investigates the extent to which financial literacy influences sound financial management practices among young entrepreneurs.

LITERATURE REVIEW

Financial literacy has been defined by the OECD (2018) as a combination of awareness, knowledge, skill, attitude, and behavior necessary to make sound financial decisions. Lusardi and Mitchell (2014) argue that financial literacy not only improves personal financial outcomes but also enhances business survival by equipping entrepreneurs with the ability to evaluate financial opportunities and risks. Financially literate entrepreneurs are better positioned to interpret financial statements, evaluate funding options, and maintain profitability. Studies show a positive correlation between financial literacy and business performance indicators such as growth and capital efficiency. Sound financial management entails effective cash flow monitoring, cost control, and investment planning. Entrepreneurs with higher levels of financial literacy are more adept at maintaining records, preparing budgets, and forecasting financial outcomes.

RESEARCH OBJECTIVES AND QUESTIONS

Objectives:

- To assess the role of financial literacy in influencing financial management among young entrepreneurs.
- To identify the financial areas where young entrepreneurs exhibit the most significant knowledge gaps.
- To propose strategies for enhancing financial literacy as a tool for improving entrepreneurial sustainability.

Research Questions:

- How does financial literacy impact the financial management practices of young entrepreneurs?
- What are the primary barriers preventing young entrepreneurs from acquiring financial literacy?
- What measures can improve financial literacy levels and, consequently, sound financial management?

METHODOLOGY

This paper employs a qualitative and descriptive research approach supported by a review of secondary data from published literature, case studies, and institutional reports. Information was collected from peer-reviewed journals, OECD and World Bank reports, entrepreneurship development frameworks, and training program evaluations. The focus was on studies conducted within the last decade to ensure contemporary relevance.

Findings and Discussion

Financially literate entrepreneurs display greater awareness of cost structures, maintain detailed records, and regularly review performance metrics. This discipline reduces financial uncertainty and strengthens long-term planning. Lack of financial literacy limits entrepreneurs' ability to prepare business plans and communicate financial viability to investors or lenders. Those with higher literacy levels can negotiate credit effectively, utilize financial instruments judiciously, and attract investment through transparent reporting. Entrepreneurs with a solid understanding of financial principles are better at

evaluating business risks, comparing financing alternatives, and managing debt.

RECOMMENDATIONS

- Integration into Entrepreneurship Education: Financial literacy modules should be a compulsory part of entrepreneurship and management courses.
- Mentorship and Capacity Building: Business incubators and accelerators should pair young entrepreneurs with financial mentors.
- Government and Institutional Support: Policymakers should collaborate with financial institutions to design simplified credit and investment awareness programs.
- Use of Digital Learning Tools: Online financial literacy platforms and mobile applications can make financial learning more engaging.
- Periodic Assessment: Establishing a financial literacy index for entrepreneurs can help track progress.

CONCLUSION

Financial literacy is not merely an ancillary skill but a fundamental determinant of sound financial management and entrepreneurial success. Young entrepreneurs who possess strong financial knowledge are more capable of managing cash flow, controlling costs, and making strategic investments. Developing financial literacy among young entrepreneurs should be treated as an investment in economic sustainability.

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MACHINE LEARNING BASED UNDERSTANDING OF FACTORS AFFECTING CLIMATE CHANGE

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DOI: https://doi.org/10.64558/bllp/645976nnofrf

ABSTRACT

Recent all-round advancements in machine learning, as a subfield of artificial intelligence, have begun a new era of data-driven decision-making approaches in climate prediction, introducing transformative techniques that not only help to deliver high-accuracy forecasts but also quantify the inherent uncertainty associated with atmospheric outcomes. Building upon this theme, our research paper focuses on using advanced algorithms such as ensemble learning, probabilistic models which will be useful for dual purposes - for capturing climate dynamics and for providing robust estimates of uncertainty events. Together, these approaches pave the way for more engaging and accurate predictions across temporal and spatial scales. Furthermore, the proposed solutions have significant potentials to enhance climate risk assessment and inform policy decisions in the context of global warming and sustainable development, for making more accurate and timely decisions compared to traditional time-consuming procedures, enabling scalable solutions for real-world climate adaptions and mitigating challenges.

Keywords-Climate Prediction, Machine Learning, Global Warming, Accuracy

INTRODUCTION

Artificial Intelligence is a paradigm that enables machines and computers to perform complex tasks and problems associated with human intelligence. In today's modern era, AI is rapidly evolving in numerous fields like education, agriculture, healthcare, transportation, business, industry and so on. It is the revolutionizer which absolutely has changed the way of our thinking, working and managing. [2]

In sectors like healthcare, AI can find out diseases so efficiently and effectively by matching different symptoms with the actual disease, in agriculture IoT- based drone technology can be incorporated to automate the irrigation and monitoring process of the fields, in education automatic assigning of grades, focusing upon students' individual feedback, speech-to-text conversion, voice commands, image recognition all these are responsible for making the education system more versatile and more meaningful.[3]

Weather, associated with climate are those to which our lives got intricately attached. From going to workplace to our clothing choice, in every rhythm of our lives, weather and climate are the two main foundational structures. Farmers have to rely on certain weather conditions for irrigation, planting and harvesting purpose,[21] the transportation industry

is fully reliant on specific weather conditions, leading to flight cancellation and delay of vessel services. On the other hand, climate is another invisible dictator of our societal plays.From determin- ing the actual agricultural production with reference to a particular place to economic sustainability to the entire blueprint for human settlement and survival, it completely dictates where cities can flourish, how populations must adapt and lastly how natural ecosystems and biodiversity can grow up.

The long-term change in weather conditions, typically averaged over 10-15 years for a broader range of area, is termed 'climate' and 'climate change' refers to the significant changes in the average or mean climate conditions due to some natural or artificial means.It can be caused by different kinds of natural factors like changes in the earth's orbit, tilt, axis, plate tectonics and volcanic eruptions and changes in the strength of the sun.On the other, if we consider artificial means and human activities, it covers the ever-growing industrializa- tion and population growth, the greenhouse gas emissions, global warming and increasing sea level, deforestation, fossil fuel burning and the list will never be completed.[7] As a result, long-term changes in global meteorological fac- tors such as temperature, precipitation and wind speed can be reflected in the earth's ecological system on a global scale.[22] So in today's world, global cli- mate change is one of the most burning environmental issues, which results in unexpected changes in weather events, biodiversity loss and profound changes in global economics and social changes.[15]

So foreknowledge on climate has become an indispensable tool, helping societies to mitigate risks, optimizing resources and overall improve the sustainability and viability of our communities.From boosting agricultural yields to make the ability to anticipate the impacts of extreme weather events, climate prediction has drastically changed our way of thinking, working and decision-making. But that long-term climate change leads to an inability to accurately predict the patterns of the climate and gives rise to what is known as "weather uncertainty". Weather itself is most volatile, and weather prediction is one of the most complex and time-consuming processes, where that newcomer "weather uncertainty" has made that process more cumbersome and hectic.The up-growing effect of weather uncertainty is not only becoming a reason for widespread disruption of weather events but also becoming a primary driver of worldwide instability.[10],[12]

As a result, the topic of climate prediction has become so popular in recent years, and the use of machine learning in the fields of climate prediction is on trend now.General Circulation Models(GCM) have been used for a long time.[13]. Various in-depth analysis of Earth's climate dynamics by combining several oceanic, terrestrial and atmospheric phenomena had been approached for that method,

but local fluctuations and different regional characteristics couldn't be fully represented in that, specifying its spatial constraints. Traditional techniques based on large datasets having underlying complex physical, chemical , biological interactions used a large amount of computational resources, and these models usually required an extremely high accuracy of the initial conditions and parameters of the model. Numerical Weather Prediction (NWP)is another type of traditional predictive model which can predict future weather changes on a large basis through numeric calculations with respect to oceanic conditions and current atmospheric state.

In recent years, AI and machine learning genres have become the most de- manding and explorative in the fields of climate prediction, finding out complex underlying patterns and developing data-driven strategies for climate change mitigation and adaptation.[1], [4]. AI is fundamentally restructuring climate forecasting, implementing real-world strategies for everything from crop plan- ning to national disaster response with blistering speed and accuracy.

This project leverages AI not just to predict future climate scenarios but to fundamentally understand and forecast the uncertainty within our weather. This approach provides a clear provision for long-term climate policy while enabling more multidisciplinary, risk-aware decisions for immediate weather-dependent operations.[16]

Related Work

By 1963, the research paper "Deterministic non-periodic flow", written by Lorenz, had dramatically altered the perception of weather prediction, which was followed by a long duration of time. In that, Lorenz had shown that the solution of a simple set of non-linear equations can be altered at any time based on the initial perspectives, and after a certain period of time, there is no single predictive solution of those non-linear equations. He compared the atmosphere to a regime-like structure which is a factor of prediction up to a certain period, and after that, it can be changed randomly or disruptively.

The renowned Numeric Weather Prediction (NWP) had multidimensional approaches to give a conclusion about the final prediction where distinct com- ponents analyze complex patterns of solar variations, wind speed. It is a syn- chronization of different types of interconnected models which dissect the atmo- sphere into three-dimensional space and solve some of the complex equations by physics. Specialized models in NWP, known as "Radiative Transfer Schemes", calculate how solar energy is absorbed. Modern NWP models take two sides of convention: data assimilation and ensemble. In data assimilation, real-world data gathering is to be done by assembling satellite data, weather balloons, ground data to create the best possible initial state of the atmosphere, and in an ensemble,

multiple models with slightly different behavior and initial condi- tions are to be executed to produce a more optimized, robust and generalized output.

In recent decades, machine learning-based prediction methods are so on de-mand (Bochenek and Ustrnul, 2022; Kashinath et al., 2021; Yu et al.,2021) [12].Machine Learning-based prediction generally refers to nowcasting immediate storms by analyzing patterns, forecast according to meteorological elements at a certain period of time for up to two weeks by learning complex physics, and predicting climate by self-learning and improving.Post-hoc experiments are to be used to interpret the predictability of the models which are already trained without changing the underlying models (Deng et al., 2024; Fu et al., 2021; Wang et al., 2020). This type of experiment can be done on three perspectives: perturbation-based methods, game theory based methods and gradient-based methods.

In that era of machine learning and artificial intelligence, big data analy- sis has become the engine of modern innovation.It is useful for storing a huge amount of data, from neatly structured tabular formats to semi-structured files and completely unstructured raw data like images and texts collected from social media.The actual magic happens when that analyzed data is used to uncover underlying patterns, trends, relationships to extract meaningful insights which can give fuels to data processing techniques, power intelligent systems and bring rebel breakthroughs across the world of technology.By using tools like HADOOP working upon that technology, data coming from diverse sources from satellite imagery, ground-based sensors to ocean buoys and historical weather data of a wide range of types, can be processed with enormous speed and efficiency. Underlying hidden patterns can be exploited, which wasn't be possible before by using only machine learning algorithms, and it leads to more accurate fore- casts of temperature changes, precipitation patterns and frequency of extreme weather patterns, which can also be helpful for policymakers to understand the potential consequences of their decisions and develop targeted mitigation strategies.

The invention of Artificial Neural Network has become a most significant turning point in the waves of Artificial Intelligence andMachine Learning by incorporating the capability of mimicking the intricate structure of the human brain. Artificial Neural Network is capable of detecting complex patterns, non- linear relationships in vast datasets by adjusting the strength of the connections between neurons. Likewise in climate prediction, NN is adaptable to learn from historical climate data, including various variables representing temperature, humidity, wind speed and can make predictions for future climate conditions with its immense inference speed and rapid analysis by that NN can give a range of possible outcomes and quantify uncertainty in a prediction, named as

”Ensemble Forecast”.Researchers like French et al. (1992) used NN to predict two-dimensional rainfall patterns, McCann (1992) tried to forecast the likelihood of significant thunderstorms. Another subdomain under NN, refers to ”Convolu- tional Neural Network”, is responsible for processing and analyzing data having grid-like topology like images, which incorporates some special mathematical operations called ”convolution” to automatically and hierarchically learn fea- tures from the input data.By training on satellite imagery and other spatial climate data, CNN learns to extract the patterns of historical hurricanes, atmo- spheric rivers, and other extreme weather conditions, which helps earlier and more efficient warnings to prepare against any upcoming harsh situations. Shietal. showed a CNN capable of real-time 1080p super-resolution on a single GPU.Another scientist Heikkila¨ et al., performed ”Dynamic Downscaling”, the process for converting large-scale predictions into high-resolution forecasts for specific localities by finding implicit relationships between the coarse GCM output and fine-grained historical weather data, which is essentially helpful for adaptation planning and impact assessment.

METHODOLOGY

The primary objective of that study was to develop a machine learning frame- work capable of generating probabilistic weather predictions and quantifying the uncertainty in short-term weather predictions.

Dataset Description

That analysis took place using the ”Climate Change: Earth Surface Temper- ature Data” dataset from Kaggle.com, which is publicly available collection of temperature data, the result of long-term data cleaning, processing and analyz- ing climate trends, originally curated by the ”Berkeley Earth Surface Temper- ature project”.This dataset focuses on comprising global average land temper- ature by state and country basis.There are five datasets encompassing Global Land Temperatures By Country, Global Average Land Temperature by State, Global Land Temperatures By State, Global Land Temperatures By Major City, Global Land Temperatures By City spanning from 1750 to 2015.

Data Preprocessing

Feature Extraction through Geographical Knowledge Altitude

To understand about climate, we need to know the crucial impact of al- titude. Altitude refers to the height of a location above sea level. With the increasing altitude, the temperature generally decreases. This phenomenon is known as Environmental Lapse Rate (average drop of about 0.65°C to 0.7°C per 100 metres). From the data, we found 3448 unique cities across all the countries. Based on this, we manually made a column named as Altitude (height from sea level) using

city, country, latitude and longitude.The altitude values were taken from Google Earth and Wikipedia.

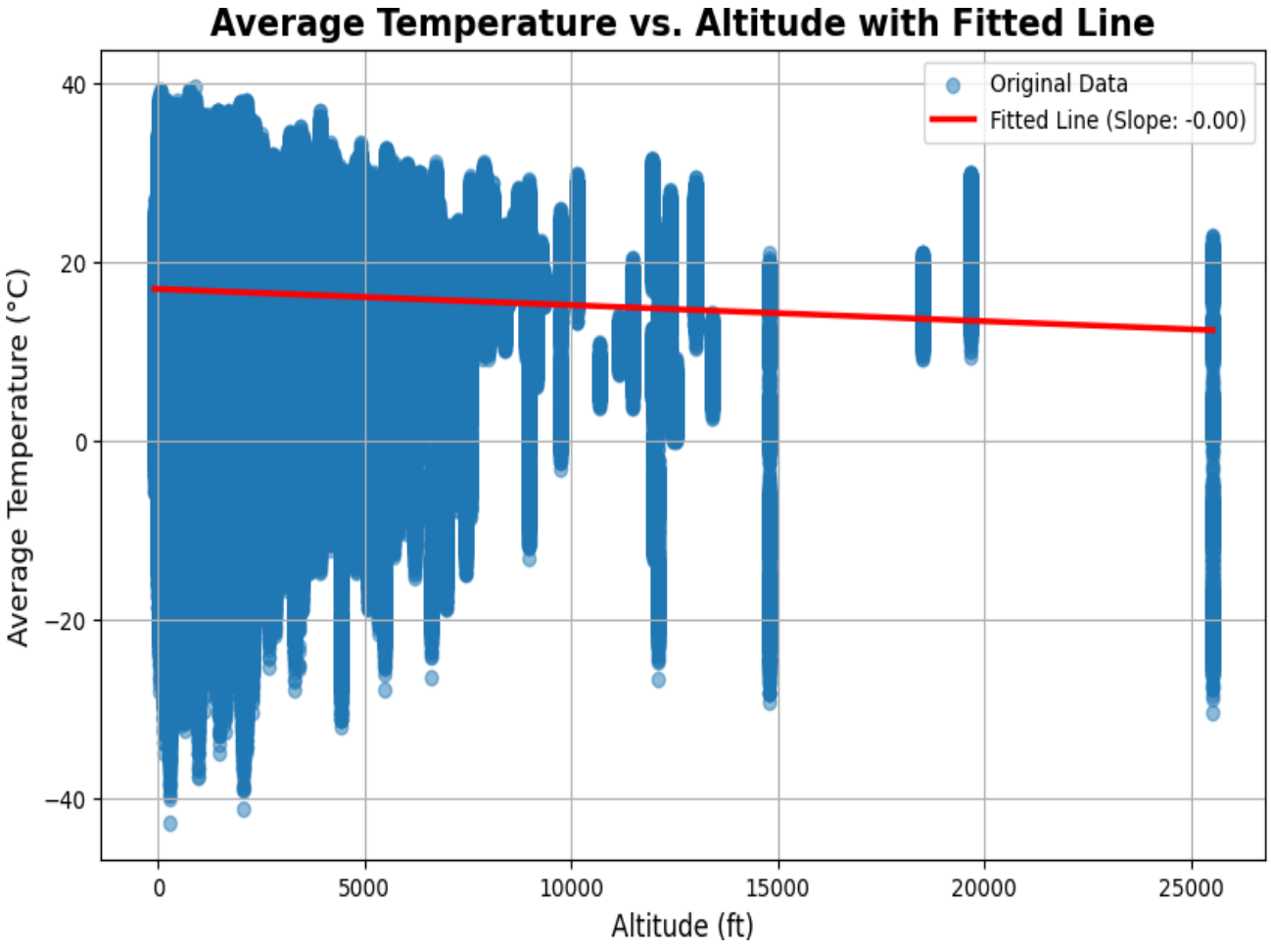
Date

As our data is in range from the year 1748 to 2013, we converted this to feature, means from the first date it will count as 1, then 2 and so on.

Latitude and Longitude

Latitude is the distance of north and south of the equator (line connecting all the points at equal distance between the North and South Poles).At higher latitudes, the Sun's rays are less direct.So, the farther an area is from the equator,

Figure 1 Average Temperature vs. Altitude



The lower of its temperature.At the poles, the Sun's rays are least direct.Most of the area is covered with ice and snow, which reflects a lot of sunlight.Here, temperature is lowest. Longitude itself does not directly affect climate, but it plays an indirect role in climate patterns through its influence on time zones, solar radiation, and ocean currents.

In our data, the latitude and longitude were written as strings with 'N'/'S' for latitude or 'E'/'W' for longitude (i.e. "45.67N" or "123.45W").We converted these into numeric signs, i.e. for Northern and Eastern it is positive (+) sign and for Southern and Western it is negative (-) sign.

Mapping the weather uncertainty to class level

In climate change, the uncertainty is not a regular event, it does not occur in a consistent or repetitive way.It may differ from what it is supposed to be. Artificial Intelligence (AI)

Future Scope

Advanced Modeling Techniques

By applying Deep Learning frameworks like Long Short Term Memory(LSTMs) and Gated Recurrent Unit(GRU) are very much competent and reliable to time-series analysis and capture complex dependencies which cannot be fully modeled by classifiers.

Data Enrichment and Feature Engineering

By using more informative and compact dataset including satellite imagery, atmospheric aerosol data, El Niño–Southern Oscillation (ENSO) can be more instructive to the model's predictive capability and performance.

Model Interpretability and Explainability (XAI)

Using Explainable AI (XAI) techniques such as SHAP (SHapley Additive exPla- nations) and LIME (Local Interpretable Model-agnostic Explanations) would be effective for identifying key meteorological drivers of uncertainty, which will be helpful for transforming the "black box" into valuable model insights.

Real World Deployment and Generalization

Finally, the model's generalizability should be tested on different geographical regions with diverse climate patterns to develop an operational, real-time early warning system which can be used by policymakers and data scientists for strategic decision making.

CONCLUSION

From the vast amount of data, we find out the altitude of each unique country and handle it manually. The date feature is transformed into a continuous numerical feature to capture temporal progression. By converting latitude and

longitude into numerical values, we make their direct effects understandable. By applying all these techniques in our analysis, we obtain the best possible results.

This study is proof of successful application of machine learning framework in predicting uncertain weather events and the novelty lies in the methodology of that experiment where we have binarized the target metric by its 80th per- centile for creating an effective environment for identifying the notable periods of significant and most powerful climate instability.

This study acts as an interface between the world of reaction and the world of prediction by acting as the foundational base for early-risk detector, resource allocator for competing with climate-sensitive issues and a crucial component in developing more effective climate mitigation strategies.By presenting that proof of concept as the base, more future explorative research should be conducted on this domain, such as deep learning models like LSTMs to capture the temporal dependencies more preciously, the use of model interpretability techniques like ”SHAP” to unlock the ”Black Box” to gain deeper scientific insights.

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SOLAR POWER IN SUSTAINABLE DEVELOPMENT IN INDIA.

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DOI: https://doi.org/10.64558/bllp/950615erqxgq

ABSTRACT

The main traits of the Indian energy consumption are many rural households and the fact that most people rely on low-quality energy. Making growth and development long lasting for India depends on being sustainable. Solar energy is one of the major industries working to make India more sustainable.

Because India is in the tropical area, solar energy can play a big role. The report focuses on the latest uses of solar energy in helping India become more sustainable. The use of solar energy for sustainable development is covered in sectors related to buildings, mobile devices, restaurants, parking, public transport and lighting. The article covers existing solar energy uses, what solar energy looks like in India now, the reasons for its slow progress and advises on ideas for promoting it.

Keywords - Sustainable Development, Architecture, Solar energy

INTRODUCTION

A way to develop is called sustainable development when the needs of now are met, yet future generations are not prevented from doing so. Because of worries about global warming and climate change, more importance is being given to renewable energy for our future. Sustainable energy which is also known as alternative energy, is clean and long-lasting, releasing almost no harmful gases. Geothermal, biomass, wind, sun and more renewable energy sources are examples of this kind of energy. One of the best ways to fight global warming is by using solar energy which helps cut greenhouse gas emissions. Over 5,000 trillion kWh of solar energy falls on India every year due to the many clear sunny days, but most of it is not used for helping people. The energy sector is a major factor in lifting people's living standards. A significant percentage of India's citizens in villages use energy sources that are not enough and not very good. The growth and development of India depends on being sustainable. It is recognized that India's future depends in part on solar energy. Because India falls within the tropical belt, the potential of solar energy is very strong.

Because of big losses during transportation and usage, most Indian power companies cannot meet the amount of renewable energy they agreed on. So, a possible way for these states is to shift their renewable energy contracts to customers who pay a lot for electricity and are getting close to grid parity. Power users requesting more solar energy is an important reason that the Indian solar market is growing. More barriers are being taken out which is powering the expansion of solar energy. It covers the ways solar energy supports a

sustainable India, looks at ts present challenges and possible solutions and outlines how it could play a larger role in sustainability going forward.

For the moment, solar energy systems are not usually as affordable as others. Until

major policy steps are taken, solar energy cannot develop much. A lot of countries have acknowledged solar energy as a problem and put in many efforts to expand its use with aid from financial, governmental, advertising and other resources. A range of laws have been created by countries and internationally to back renewable energy and solar in particular. The solar energy market is increasing as new rules are carefully introduced in both rich and poor nations, mainly for grid solar power and water heating systems. This study briefly mentions the main rules that help promote solar power for both electricity and heating use.

OBJECTIVES

The researcher has created a survey and obtained survey results from 400 consumers.

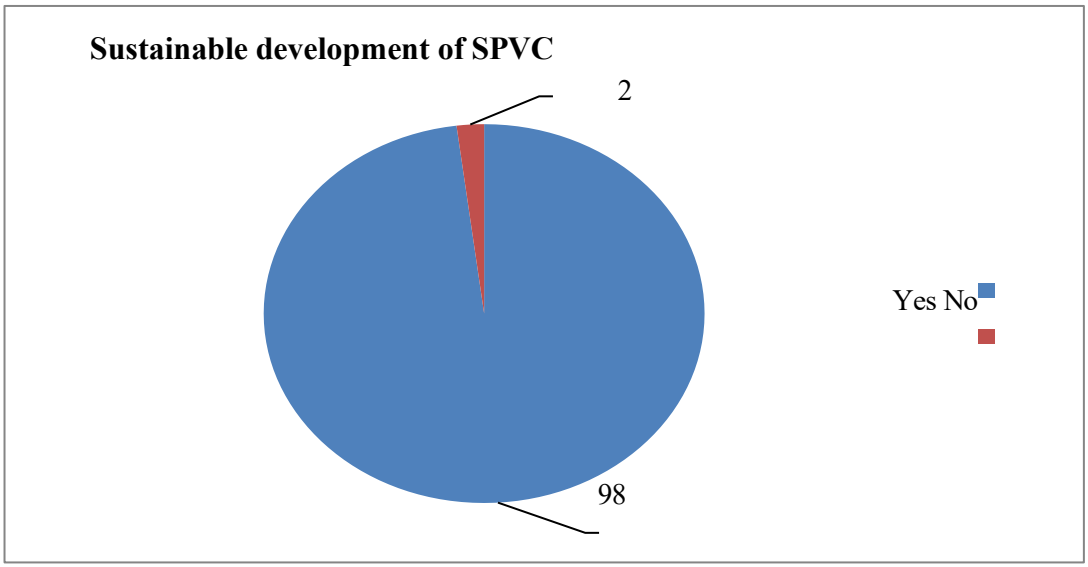
Table 1

1. Sustainable development of Solar Photovoltaic Cell Power in India

	Sustainable development of SPVC	Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	392	98	98	98
	No	8	02	02	100
	Total	400	100	100	

Source: Primary Source

Figure 1



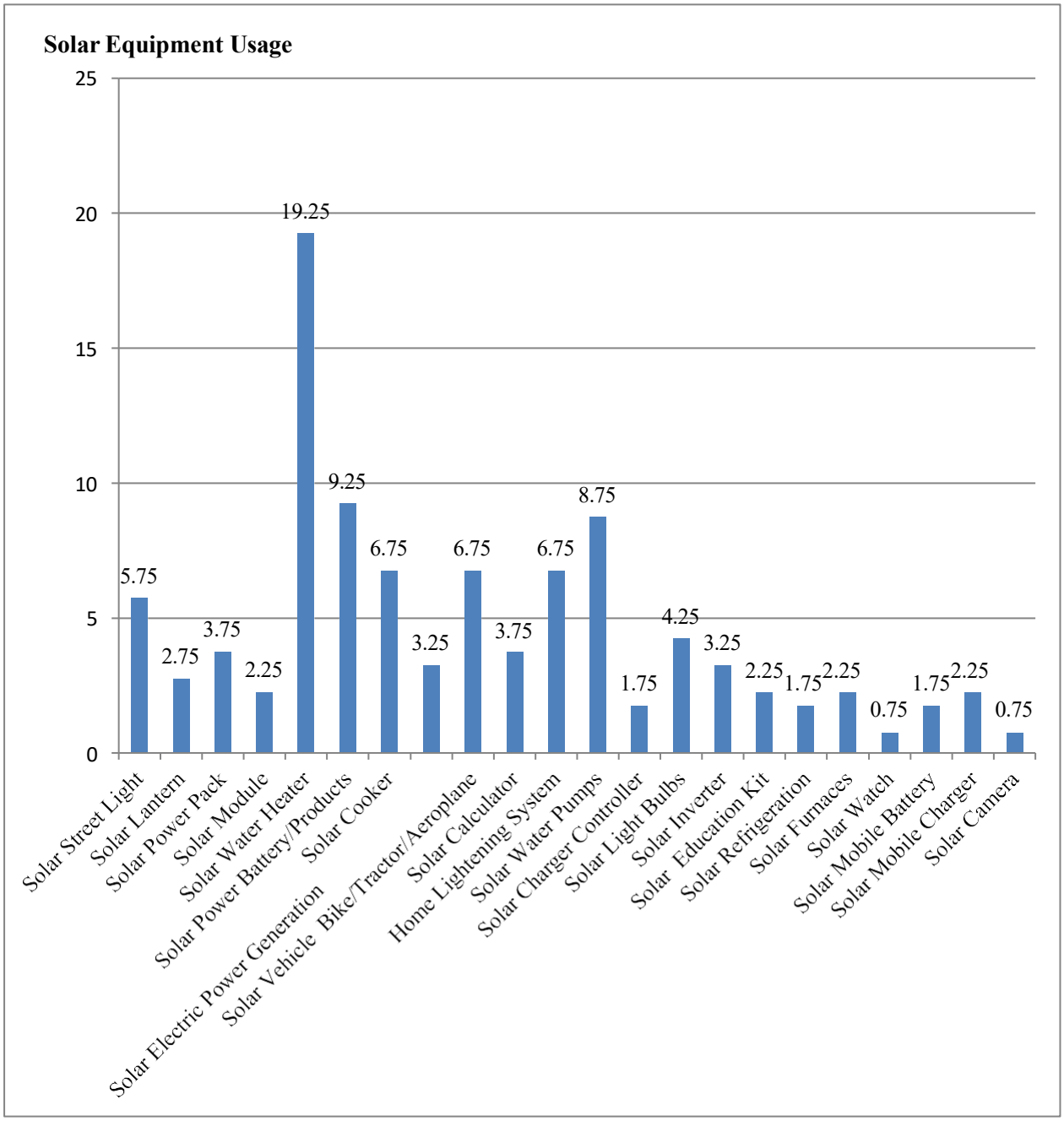
The graph makes it obvious that 98% (392) of the respondents agree that Sustainable development of Solar Photovoltaic Cell is important, whereas the remaining 2% (8) think that it is not necessary.

Table 2 : To study Solar Appliance/ Equipment used in India

	Solar Equipment Usage	Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Solar Street Light	23	5.75	06	5.75
	Solar Lantern	11	2.75	03	8.50
	Solar Power Pack	15	3.75	04	12.25
	Solar Module	9	2.25	02	14.50
	Solar Water Heater	77	19.25	19	33.75
	Solar Power Battery/Products	37	9.25	09	42.50
	Solar Cooker	27	6.75	07	49.25
	Solar Electric Power Generation	13	3.25	03	52.50
	Solar Vehicle Bike/Tractor/Aeroplane	27	6.75	07	59.25
	Solar Calculator	15	3.75	04	63
	Home Lightening System	27	6.75	07	69.75
	Solar Water Pumps	35	8.75	09	78.50
	Solar Charger Controller	7	1.75	02	80.25
	Solar Light Bulbs	17	4.25	04	84.50
	Solar Inverter	13	3.25	03	87.75
	Solar Education Kit	9	2.25	02	90
	Solar Refrigeration	7	1.75	02	91.75
	Solar Furnaces	9	2.25	02	94
	Solar Watch	3	0.75	01	94.75
	Solar Mobile Battery	7	1.75	02	96.50
	Solar Mobile Charger	9	2.25	02	99.25
	Solar Camera	3	0.75	01	100
	Total	400	100	100	

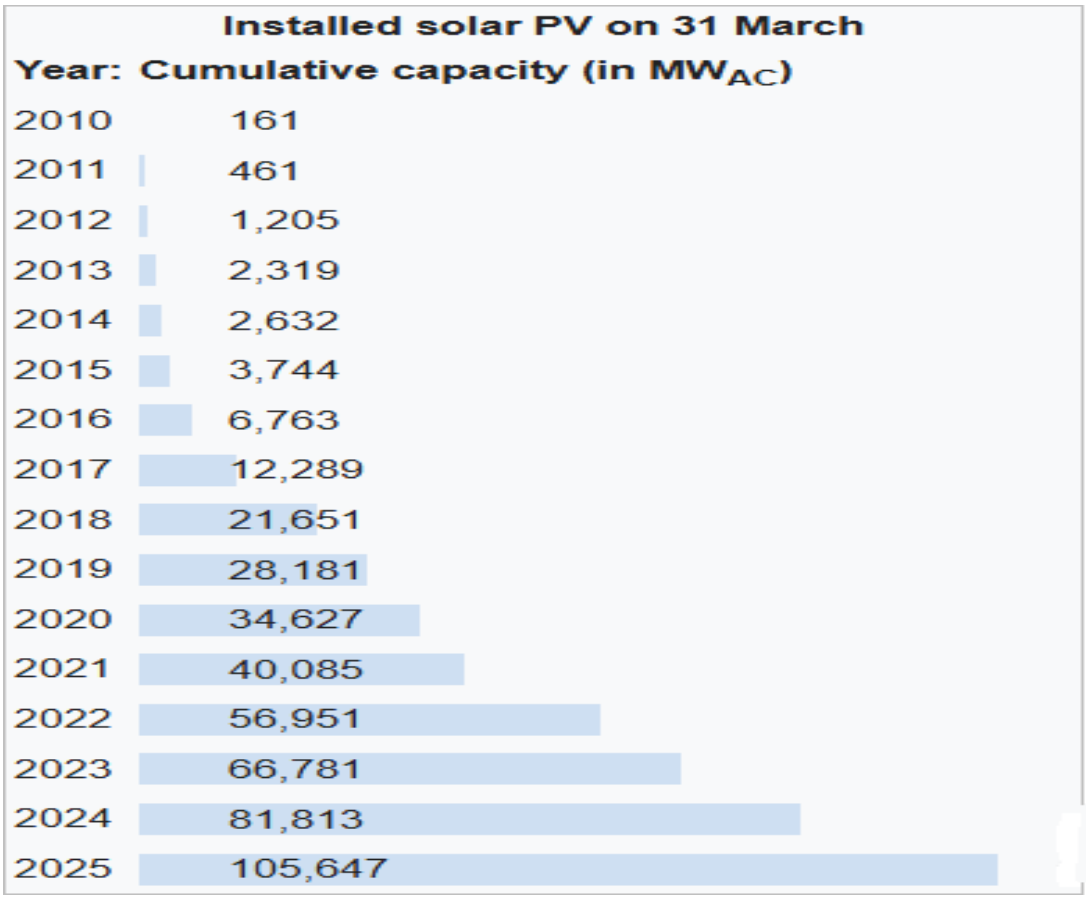
Source: Primary Source

Figure 2


Solar Equipment Usage
25
20
15
10
5
0
5.75
2.75
3.75
2.25
19.25
9.25
6.75
3.25
6.75
3.75
6.75
8.75
1.75
4.25
3.25
2.25
1.75
2.25
0.75
1.75
2.25
0.75
Solar Street Light
Solar Lantern
Solar Power Pack
Solar Module
Solar Water Heater
Solar Power Battery/Products
Solar Cooker
Solar Electric Power Generation
Solar Vehicle Bike/Tractor/Aeroplane
Solar Calculator
Home Lightening System
Solar Water Pumps
Solar Charger Controller
Solar Light Bulbs
Solar Inverter
Solar Education Kit
Solar Refrigeration
Solar Furnaces
Solar Watch
Solar Mobile Battery
Solar Mobile Charger
Solar Camera

The majority of the consumers claim to use Solar Water Heaters regularly to warm-up water. Then, the sequence is begun with solar calculator, Solar Street Light, Solar, Power Battery, Solar Stove, Solar Lamp/ Flashlight, Solar Timepiece, Solar Oven, Solar Camera. People are knowledgeable and at ease with the decisions to include solar equipment in their routine daily schedules. At the beginning, Solar Illumination systems, Solar Energy generation, Solar Vehicles, Solar Energy unit, Solar Inverters, Solar Learning Kits, Solar Coolers, Solar Heaters as well as solar water pumps must be implemented into everyday life at a lesser rate The current Scenario of Solar Power in India.

Figure 3



Graph Installed Solar PVC on March 2025

Hypothesis:-

Hypothesis 1 Solar photovoltaic (PV) technology is vital for sustainable development.

H0: Solar photovoltaic (PV) technology is not vital for sustainable development.

H1: Solar photovoltaic (PV) technology is vital for sustainable development

Table 3

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.0725	1.03
Variance	0.067412281	0.029172932
Observations	400	400
Pearson Correlation	0.629017482	
Hypothesized Mean Difference	0	
df	399	
t Stat	4.208346797	
P(T<=t) one-tail	1.59026E-05	
t Critical one-tail	1.648681534	
P(T<=t) two-tail	3.18052E-05	
t Critical two-tail	1.965927296	

Based on the outcomes displayed by the paired t-test: An outline of what was discovered. Both the two variables in question have 400 measures. The value of variable 1 is about 1.0725 and the value of variable 2 is about 1.03. Variance (variable 1) is 0.0674 and variance (variable 2) is 0.0292

The Pearson Correlation is approximately 0.629 so that casts an indication of moderate level of positive relationship.

Hypothesized Mean Difference: 0 (test on whether mean difference is equal to 0). The data set has 399 Degrees of Freedom.

t-Stat: approximately 4.208. p-Values:

One tailed p-value is approximately 1.59 x 10 -5

Two-tailed p-value: approximately 3.18 x 10 -5.

Interpretation:

that Solar photovoltaic (PV) technology plays a great role in getting sustainability.

Hypothesis 2:-

Solar Photovoltaic cell is Eco Friendly energy source for Adoption.

H0: Solar Photovoltaic cell is not Eco Friendly energy source for Adoption. (μ=0)

H1: Solar Photovoltaic cell is Eco Friendly energy source for Adoption. (μ=0) The test of difference between the means of the Variable 1 and Variable 2 was undertaken using observations of 400 pairs of variables with the help of t-test. The results that you will obtain after going through the process are the following ones:

Table 4

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.0725	1.0575
Variance	0.067412281	0.054329574
Observations	400	400
Pearson Correlation	0.883448421	
Hypothesized Mean Difference	0	
df	399	
t Stat	2.464983191	
P(T<=t) one-tail	0.007061116	
t Critical one-tail	1.648681534	
P(T<=t) two-tail	0.014122233	
t Critical two-tail	1.965927296	

Their p-values are so small to insignificance level of 0.05 and thus are significant in proving that the null hypothesis is strongly rejected. It knows

The variance between sample means. X 1-X 2 = 0.015 X 1-X 2 = 0.015

t-Statistic: The degrees of freedom are 399 and the formula t=2.465t = 2.465

Two-tailed p-Value.

The likelihood will be p= 0.0141

Pr -Critical t-value assuming P=0 in a t-test.
tcrit=+- 1.966tcrit = \pm1.966
Given that:

p 0.0141 <0.05p = 0.0141 < 0.05

The t value is 2.465 and this is greater than the value of 1.966. We will not take the null hypothesis that both means are equal.
Interpretation:
It can be determined through statistics that the average of Variable 1 does not equal (it is a bit bigger than) the average of Variable 2. Since the correlation of the two variables (r = 0.8834) is quite strong, it would be advisable to match up the two variables and the test is valid. So, since the null hypothesis was not accepted, it was concluded that Solar Photovoltaic cells is Eco Friendly and there should be promotion of Solar Photovoltaic cells.

Solar Energy and Sustainable Development –

Passive methods and active methods are the two main uses for solar energy in sustainabl development. Passive solar energy uses heat and light as they are, without being converted into other forms. On the other side, it means capturing or saving solar energy for different uses. The active use of solar energy is generally categorized as photovoltaic (PV) or solar thermal.

As solar radiation triggers semiconductors, photovoltaic technology changes the radiation into electrical energy. Unlike solar photovoltaic, solar thermal uses the sun's heat to produce electricity and provides heat for home or building warm-up. Solar thermal systems can be sorted into non-electric and electric varieties.

Among solar thermal non-electric technologies are solar water heaters, solar air heaters, solar cooking systems, solar cooling systems and others. This uses solar energy to make steam that can produce electricity. The technique used here is called Concentrated Solar Power (CSP). Several CSPs are sold in the market such as the Power Tower, Fresnel Mirror, Solar Dish Collector and Parabolic Trough.

How solar energy is used in India at the moment.

In 2023, India generates more solar power than most countries except China and the USA. Last year, India got 5.8% of its electricity from solar power.
India increased its installed power capacity by 18 Terawatt hours, after China (+156 TWh), the United States (+33 TWh) and Brazil (+22 TWh).

By September 2024, Indian solar energy has gone up to 90.76 GW which is 30 times higher than what it was nine years earlier.

Problems in the Manufacturing of Solar Photovoltaic Cell in India:-

Having A Small-Scale Solar Project Is

Still More Costly Than Other Options, Even Though Solar Power Prices Are Declining.

Solar parks of a large scale struggle with land access and worry about big transmission losses and difficulties in joining the grid because solar power is not always available.

Projects for large solar parks are put on hold in Rajasthan and Gujarat because some endangered species could be disturbed.

Even though the amount of solar energy installed has grown, it still plays a minor role in electricity generation; expansion of rooftop solar is also very slow, far below its intended goal (18%).

Absence of Innovative financing options makes it difficult and costly for residential consumers and small businesses to choose rooftop solar.

High initial expenses are a problem for residential consumers and SMEs, since they do not have important innovations in how solar can be financed.

India imports most of its solar equipment since it does not produce solar wafers or polysilicon at home and it mainly relies on China for its trade ($76.62 billion in 2021-22).

There will be 1.8 million tonnes of solar waste by 2050; however, e-waste rules now do not make manufacturers responsible for recycling or disposal.

Legal problems at the WTO prevent India from enforcing its requirement for locally made solar cells and modules.

Actions taken to promote Solar Energy in India:-

PM-KUSUM was created with the purpose of solar grid pump incentive and loan schemes connected to agricultural water pumps.

Through **Suryamitra Programme**, NISE offers solar project installation, operation and maintenance training.

Atal Jyoti Yojana: Brings solar street lights for public areas where electricity is not available.

SRISTI Scheme: Gives financial support to encourage people to install solar panels on their roofs.

The Green Energy Corridor Scheme: New transmission lines and sub-stations will be used to evacuate renewable energy.

Solar Parks Policy was introduced in 2014 to help create big solar parks.

Collaborating with the World: Joined the International Solar Alliance (ISA) and promotes the idea of combining solar energy from all countries into one system.

Worldwide Largest Solar Energy Generating Countries in 2024:-

Figure 4

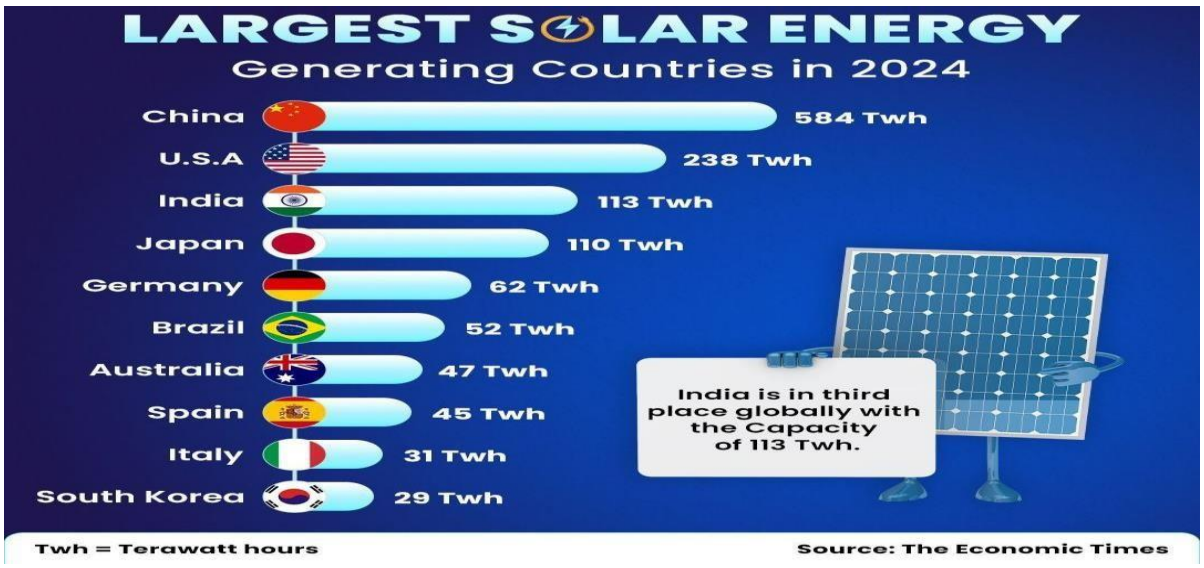
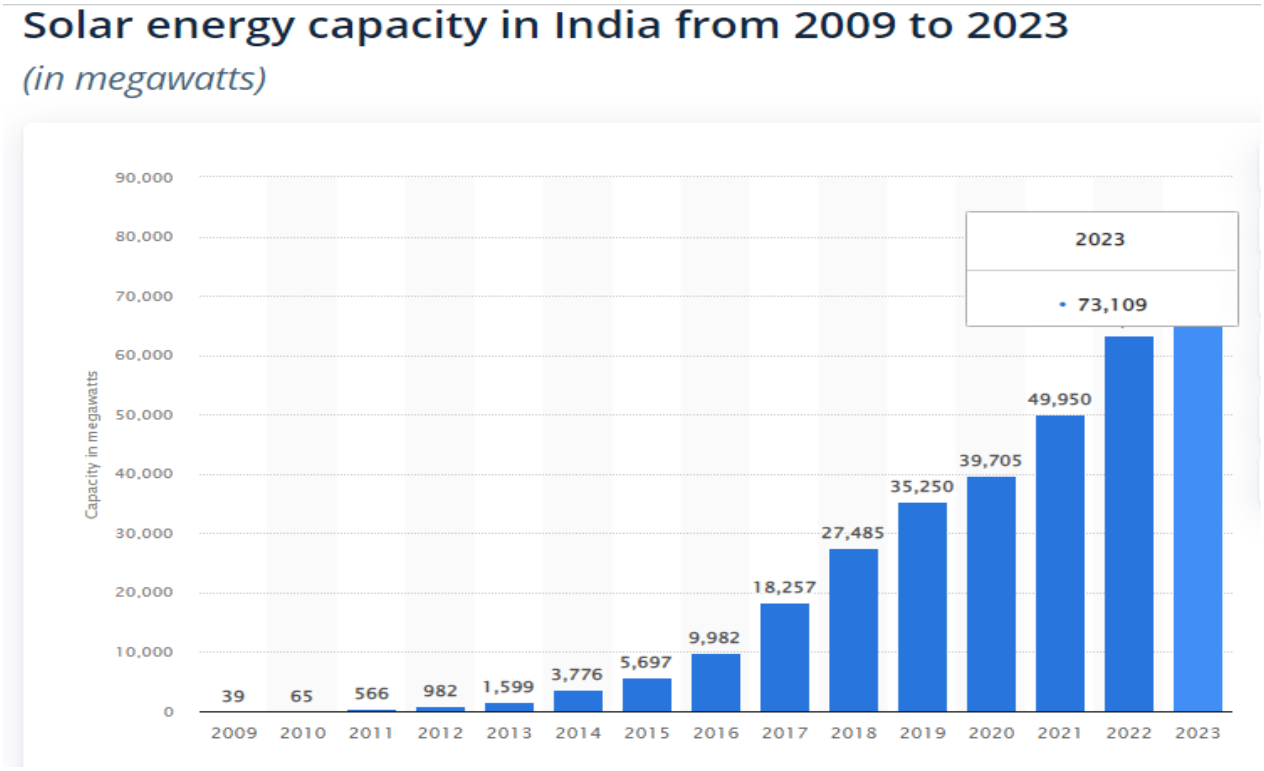


Figure 5



The government has introduced a number of steps designed to encourage solar energy in the country.

One measure is giving automatic permission for up to 100 percent Foreign Direct Investment (FDI). Additionally, there is no Inter State Transmission System (ISTS) fees charged on solar and wind energy sold across states for these projects that will be operational by June 30, 2025. A Renewable Purchase Obligation (RPO) plan has been set by the government for the years 2029-30. They have also issued guidelines to explain what is required for setting up solar photovoltaic systems/devices.

A Project Development Cell has been formed to motivate and back investments. To help prompt payment of renewable energy producers by distribution companies, the government needed documentation like a letter of credit (LC) or advance payment.

Implementation of the 'Electricity (Late Payment Surcharge and Related Matters) Rules 2002 (LPS Rules)' and Open Access to Green Energy Rules 2022 announced for promoting renewable energy.

To help sell solar energy from renewables more easily, the government set up the Green Term Ahead Market (GTAM).

Table 5 Using Solar Power Appliances Innovatively in Daily Living

Solar air conditioning	Solar-powered fan	Solar chimney
Solar-powered waste compacting bin	Solar cooker	Solar dryer
Solar charger (Strawberry Tree)	Solar inverter	Solar furnace
Solar keyboard	Solar lamp	Solar pond
Solar-powered Stirling engine	Solar road stud	Solar street light
Solar traffic light	Solar Tuki	Solar-powered flashlight
Solar-powered calculator	Solar-powered desalination unit	Solar-powered pump
Solar-powered radio	Solar still	Solar roadway
Solar-powered refrigerator	Solar balloon	Solar vehicle
Solar Spark Lighter	Solar-powered watch	Solar boat
Planet Solar	Solar sail	Solar golf cart
Solar bus	Solar-pumped laser	Solar Turanor
Solar car Stella (solar vehicles)	Solar panels on spacecraft	Solar thermal rocket

Solar Lighting

One of the most common and growing areas using solar power is for lighting. It can also be put to good use in lights for streets, in gardens, in restaurants with solar umbrellas and in palm tree lighting at institutes and industries.

Chargers That Run On Solar Energy

Solar chargers for phones and iPads are a very small way to make use of solar energy.

Especially since millions in India use mobile phones, this will reduce the amount of energy needed to keep them charged. It is quite a minor application, but it still works very effectively.

Parking Area with Solar Energy

In a Solar Car parking, cars are parked under solar panels placed at a height above the ground. Larger arrays spread over the parking area can create a larger amount of energy.

Restaurant in the Solar Kitchen

The main goal of the solar kitchen restaurant is to encourage using solar energy. All cooking at Solar Kitchen Restaurant happens through solar energy. The restaurant will centre on a solar kitchen, helping to make eating there both interesting and enjoyable. Using solar energy for cooking gives each dish a special and positive effect, making the meal taste and feel different in an interesting way.

Solar-Powered Advertising Billboard

In some situations, no electricity exists nearby or the nearest source is quite far which means billboards still need to be erected. Installation of a LED billboard using solar energy is considered a cheaper option rather than digging up the street for new cables or calling an electrician.

A Solar Bill Board

At times, billboards have to be put up in places without electricity close by or where the closest power is quite far. Having a LED billboard powered by solar energy avoids the expensive process of excavating trenches and employing electricians.

Solar Canal

Narmada Canal, Gujrat part of India, has witnessed the launch of the Canal Solar Power Project.

Sun-Linked Space Power Station

People refer to this concept as the solar space power station. Study on this has been conducted since the early 1970s.The Solar Space Power Station transforms sunlight into microwaves above the atmosphere, avoiding both the power losses and the momentary break caused by the Earth's rotation.

Solar Energy Used for Transportation

Many areas of transportation use solar energy in different ways. Solar-powered cars interest a lot of researchers at this time. When a solar vehicle draws electricity from solar power, it becomes 100% solar

vehicle.

Examples of solar vehicles are solar car, solar tracking bus, solar rail, solar boat, solar aircraft and solar space craft. Solar energy is used for supplying power to vehicles, especially for the ventilation system and vehicle cooling fans.

CONCLUSION: -

Solar Power reported a considerable rise in its business for Solar Photovoltaic Cell off-grid and On-Grid systems in India. Application of this technology has helped by supplying Solar vehicles, Railways, Boats, Planes and for on road vehicles to help move towards sustainability in India. Sustainable development innovations in India involve lighting and charging by solar energy, solar parking, solar restaurants, solar ads, solar irrigation systems throughout the country, solar stationed in outer space and solar elements used in constructions.

In the solar power sector, the problems include reducing manufacturing expenses, expanding R&D, educating consumers, no common standards and difficulties with financing. It is necessary to conquer. Fast growth and widespread adoption of technology raise these issues.

To help with research and solar energy development, it is important that the private sector plays a big role. Setting up the infrastructure for new solar projects will generate lots of new jobs. Promoting jobs created by clean energy, along with refunds for environmental and energy services, will give more weight to clean energy policies and gain people's support.

If things go as intended, India would be able to compete globally in solar energy.

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WHEN GOVERNANCE MEETS FINANCE: PATHWAYS TO CLIMATE RESILIENCE IN EMERGING ECONOMIES - A PANEL QUANTILE APPROACH

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BACKGROUND AND LITERATURE

Climate change has shifted from being a distant threat to an immediate reality, manifesting in floods, droughts, wildfires, and rising sea levels that threaten human well-being and economic stability. While global awareness has increased, countries vary greatly in their ability to adapt to these shocks. This disparity results from differences in institutional quality, financial development, and governance systems. Some countries have the financial and institutional strength to manage risks, while others remain structurally vulnerable. This raises an urgent research question: what determines a nation's capacity to withstand and adapt to climate shocks, and how resilient are these countries? Finance is widely recognized as a double-edged sword in the climate resilience discussion.

On one side, financial markets mobilize capital for clean technologies, green bonds, and socially responsible investments, and can help reduce emissions when governance is strong (He, Liu, Zhong, Wang, & Xia, 2019; Richardson, Cowtan, Hawkins, & Stolpe, 2016). On the other side, in many developing nations, finance often worsens emissions and vulnerability by channeling funds into carbon-intensive industries (Imamoglu, 2021). Similarly, the literature is divided on the role of financial institutions: some studies show banks and insurers worsen emissions by funding polluting sectors (Petrović & Lobanov, 2022; Saidi & Mbarek, 2017), while others emphasize their role in fostering low-carbon innovation and sustainability (Habiba & Xinbang, 2022; Tao, Sheng, & Wen, 2023).

This tension highlights the dual nature of finance. Financial institutions like banks and insurers, with long- term investment horizons and regulatory oversight, may align with sustainability goals. In contrast, financial markets, prone to speculation and short-termism, may divert capital from long-term adaptation unless guided by effective governance (Engle, Giglio, Kelly, Lee, & Stroebel, 2020; Hong, Li, & Xu, 2019). However, despite this growing body of literature, there is limited cross-country empirical evidence linking governance, financial development, and climate resilience. Most existing studies are country specific or focus on emissions rather than resilience and adaptation.

This study addresses this gap by examining how financial institutions and financial markets influence climate resilience across

low- and middle-income countries, moderated by governance quality. It utilizes the Notre Dame Global Adaptation Index (ND-GAIN) to measure resilience and combines it with global financial development indices and World Bank governance indicators, providing a more comprehensive view of the determinants of adaptation capacity.

RESEARCH QUESTIONS:

- How do financial institutions influence climate resilience in low- and middle-income countries?
- What is the role of financial markets in shaping resilience outcomes?
- To what extent does governance quality (regulatory quality, control of corruption, government effectiveness, and political stability) condition the relationship between finance and resilience?

EMPIRICAL STRATEGY

Data and Variables:

Dependent Variable: Climate resilience, measured by the ND-GAIN Index, which evaluates vulnerability to climate risks and readiness to adapt.

Key Explanatory Variables: Financial Institutions Index (FII), Financial Markets Index (FMI), Governance indicators (World Governance Indicators: Government Effectiveness, Regulatory Quality, Control of Corruption, Political Stability).

Control Variables: GDP per capita, inflation, trade openness, population density, renewable energy share, and gross fixed capital formation.

Sample: 30 low- and middle-income countries, including Angola, Bangladesh, Benin, Bhutan, Bolivia, Burkina Faso, Burundi, Cambodia, Cameroon, Chad, Ghana, Guinea, Honduras, India, Jordan, Kenya, Lebanon, Mali, Morocco, Nepal, Nicaragua, Niger, Pakistan, Philippines, Rwanda, Senegal, Sierra Leone, Sri Lanka, Togo, Tunisia, Uganda, Vietnam, and Zambia.

Econometric Methods:

This study applies Panel Quantile Regression (Fixed-effects Quantile Regression – FQR) to explore heterogeneous effects of financial development across the conditional distribution of climate resilience. Unlike mean-based estimators, FQR captures how the role of finance differs between countries at low, median, and high levels of resilience (Koenker & Bassett, 1978). This approach is particularly suitable in cross-country settings characterized by significant heterogeneity and skewness in resilience outcomes.

To address potential cross-sectional dependence and endogeneity, robustness checks are implemented using bootstrapped standard errors and lagged instruments within the quantile regression framework (Canay, 2011). Interaction terms are included to assess the moderating role of governance on the finance–resilience nexus. All analyses are conducted in Stata, with robustness checks confirming stability of results across quantiles.

This rigorous methodology allows us to assess whether financial institutions and markets contribute differently to climate resilience at different points in the distribution, thereby offering richer insights than traditional mean-based models.

Expected Outcomes

The Financial Institutions Index (FII) demonstrates a positive and statistically significant relationship with climate resilience, an effect that becomes stronger under high governance quality, particularly with strong regulatory oversight and effective control of corruption.

Financial institutions play a crucial role by providing long-term lending and project finance for climate- resilient infrastructure, renewable energy, and climate-smart agriculture, thereby acting as key vehicles for adaptation. In contrast, the Financial Markets Index (FMI) shows a weaker or even negative effect on resilience, especially in contexts of weak governance, where negative interactions with control of corruption and political stability indicate that market development can undermine resilience by channeling capital into speculative or short-term activities rather than long-term adaptation projects.

Governance thus emerges as a critical moderator: strong institutions amplify the positive impact of financial institutions, while weak governance exposes the fragility of financial markets, underscoring that finance cannot be divorced from institutional quality and that governance reforms are a precondition for finance-driven resilience. Moreover, financial institutions are found to enhance readiness (adaptive capacity) rather than directly reducing vulnerability, highlighting the importance of complementary policies that target vulnerability while financial institutions strengthen adaptive readiness.

Policy Relevance

Governments should prioritize strengthening financial institutions such as banks, ensuring they have both the capacity and incentives to provide long-term funding for climate-resilient projects, as direct lending and project finance are more effective for adaptation than speculative market mechanisms.

Market liberalization and development should only be pursued once governance meets minimum thresholds of effectiveness, regulatory quality, and political stability, since premature market development under weak governance can misallocate resources and increase volatility.

Regulators need to integrate climate resilience into financial regulations by embedding climate risk assessments into prudential norms and ensuring that banks and insurers channel finance toward sustainable, resilient projects rather than carbon-intensive sectors.

Finally, global and regional cooperation is critical, as international organizations and development banks should first support governance reforms and institutional capacity building before channeling large-scale market-based finance into emerging economies, recognizing the asymmetric roles of financial institutions and markets across different governance contexts.

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DOES CIRCULAR ECONOMY AND RECYCLING-FOCUSED WASTE MANAGEMENT STRATEGY PROMOTE SUSTAINABLE GROWTH IN THE FOOTWEAR INDUSTRY?

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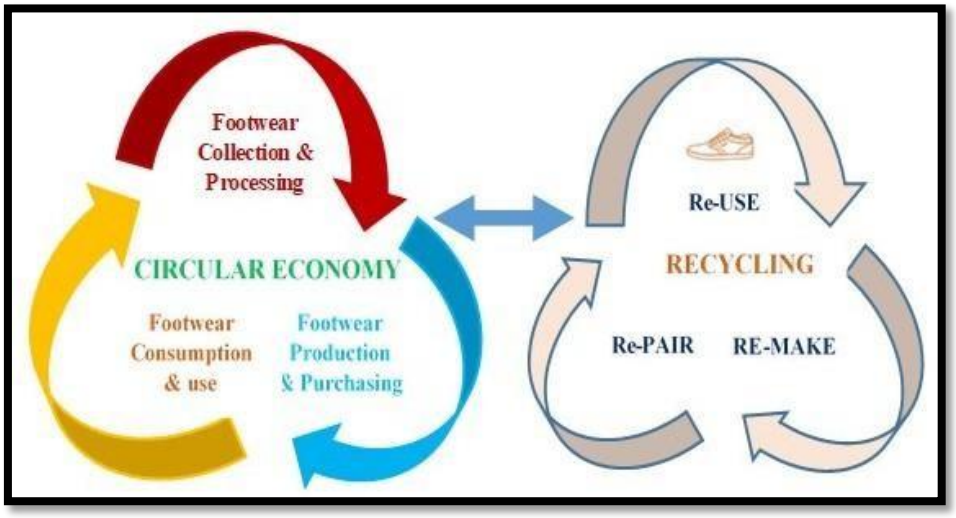
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Graphical Abstract

ABSTRACT

This research reveals a strategic approach on how circular economy approach and recycling strategy plays a crucial role in tackling and prioritizes the most effective solutions to footwear waste management for creating sustainable value chain. This article highlights the significance of recycling and its impact on the waste management strategies within the footwear industry, emphasizing the production of high-quality footwear that supports healthcare benefits and promotes a circular economy as an innovative approach. The footwear industry faces significant environmental and social challenges, particularly concerning the disposal of excess and waste shoes, which is frequently overlooked.

Extended Abstract

To address the most effective pollution

alleviation strategy of footwear waste management, the present research attempts to reveal the importance of recycling and circular economy approach that influence on footwear industry's waste management strategy. Currently, circular economy is considered as a novel approach of producing quality footwear that ensures sustainable growth overtime and focusing on healthcare benefit. Footwear has a large environmental as well as social impact, which presents a challenge to the footwear industry due to the disposal of surplus and waste shoes mainly rubber and plastic soles that is often disregarded. This article seeks to highlight the significance of recycling and circular economy approach in footwear industry's waste management strategy that fosters interdisciplinary research for breakthrough science and dissemination of related knowledge, focusing on the sustainability and prosperity of the footwear industry. Furthermore, this conceptual article offers insights into the circular economy by outlining the necessary conditions for recycling footwear waste materials. Its aim is to mitigate resource waste by advocating for promotion, reduction, reuse, recovery, and recycling.

Moreover, it is important to emphasize that footwear is an essential component of human attire that should not be disregarded. Concurrently, the role of the footwear industry today extends well beyond simply fulfilling a basic human need (Gustafsson and Lazzaro, 2021). On the other hand, the rising demand for footwear made of organic leather, and emergence of smart shoes, will be some of the other factors impacting the on the global fashion market growth. Consequently, today the commitment of the footwear industry to promote a circular economy has emerged as a significant strategy for achieving sustainable development (European Commission, 2020). Similarly, it can be argued that the changing views on recycled shoe manufacturing could improve the sustainable value chain in the footwear sector, as consumers become more aware of the negative impacts of their various shopping habits related to footwear (Saha et al. 2024).

In addition, it is mandatory to point out that currently footwear waste management strategy move to quality footwear manufacturing strategy that mainly focusing on healthcare benefit. For example, vegan shoes, plastic running shoes, handcrafted organic cotton shoes, therapeutic medicated shoes and sustainable sneakers from recycled and renewable materials (Yadav et al. 2022). Consequently, the outcome of this study in the long-run identifies the importance of the recycled footwear's sustainable value that is produced in our linear economy via the re-use, re-make and re-pair of resources.

Keywords – Circular economy, footwear industry, environmental impacts, global challenges, recycling process, sustainable value chain, waste management.

Purpose:

The objective of this article is to provide a vibrant overview about the recycling and circular economy approach of waste management for the footwear industry-that considers the waste hierarchy with the purpose of preventing resource waste through promotion, minimization, reuse, and recycling.

- To reveal the coherent strategic approach of recycling and circular economy conception of waste management for the footwear industry that considers the waste hierarchy with the purpose of preventing resource waste through promotion, minimization, reuse, and recycling (Urbinati and Chiaroni, 2017).
- To highlight the primary objective of this study that emphasize the potential solutions for recycling of footwear products that envisioned two key areas of discussion, i.e. sustainable footwear by circular economy and sustainable footwear by recycling – where, the development of an economically sustainable recycling process is required for the footwear industry (Rossi et al. 2024).
- Conversely, **to emphasize that circular economy strategy is one of the essential building block components of managing footwear waste.** As it reflects on following certain conditions of footwear waste management strategy. Such as "design-for- manufacturing", "Cradle to Cradle" and "Cradle to Grave" model.

RESEARCH HIGHLIGHTS:

- Firstly, carry out a **systematic study and identify crucial elements** within the footwear industry that emphasize the importance of waste management in relation to recycling and circular economy of footwear industry.

- Secondly**, identify the gap by demonstrating**
  - Challenges unique to the material.
  - Structural and socio-economic obstacles.
  - Challenges focused on innovative design.
  - Value chain analysis, value proposition, and business models are how fundamentally connected to the circular economy and recycling
- Thirdly, exploring the study relevant from technological up gradation point of view as well as from the socio-economic benefit point of view
- Sustainable footwear by circular economy – dealing with the green deal, initiation about the sustainable footwear industry based on the circular economy, life-cycle assessment, and energy efficiency.
- Sustainable footwear by recycling-intentions to highlight from the point of view of the production and disposal of footwear human health and nature must be considered.

Finally, the research assumptions of this study emphasize the importance of recycling and the circular economy as critical factors in waste reduction, which separates sustainable value from material consumption in several ways. For instance, we can help the planet by maintaining our resources within a cycle of reducing, reusing, recovering, retrieving, and remanufacturing (the 5 R's). This approach not only minimizes environmental degradation and the scarcity of ecological resources in our society but also creates distinct opportunities for managing footwear waste.

ACKNOWLEDGMENT

This work was conducted within the framework of Project Grant no:101139988 AEQUALIS4TCLF - ERASMUS-EDU-2023-PI-ALL-INNO "Addressing Skills Gaps in the European Textile, Clothing, Leather and Footwear Industries, Emphasizing Equality, Innovation, and Resilience." AEQUALIS4TCLF (https://aequalis4tclf.eu/), and Project Garnt no: 2025-1-PT01-KA220-HED-000361174, “Advanced Education for Recycling and Circular Economy in the Shoe Industry”.Also, the first author dedicated this work to her only beloved son “Kanishka Binayak Saha”, and the first & second author dedicated this work to their beloved father “Chittaranjan Saha”.

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E+HEALTH A UNIQUE FRAMEWORK FOR APPLICATION OF AI IN HEALTHCARE-EXTENDED ABSTRACT

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PROLOGUE

In February 2004, the Author J.L.Gandhi, in his capacity as Director, Asian Business School, was invited by the Organizing Committee of the 4th National Conference on Medical Records MEDRECON 2004 organized jointly by the Medical Records Association and the Medical Records Dept. Of National Institute of Mental Health and Neuro Sciences (NIMHANS) Bangalore, to deliver the keynote address on February 20, 2004, which was titled "Transforming Healthcare Through Electronic Health Records". (scanned copy of the keynote address enclosed at the end of this abstract)

At that time, Electronic Health Records were a relatively new concept and the keynote address delivered by the author, although well-received by the assembled audience consisting of Doctors, Medical Administrators, Medical Records Officers, and support staff of leading hospitals, was very visionary and spelt out a number of prophetic predictions including the emergence of "a new era of human evolution created by the fusion of carbon-based and silicon-based intelligence or ***bionic convergence*** the convergence of biological revolution with the information revolution, of biology with electronics."

In early 2008, the 53-nation Commonwealth launched the world's first international e-health initiative across countries and continents, in an attempt to harness its members' evidentially extraordinary appetite for high-tech with health-friendly governance, potentially offering fast-track opportunities to poor people spread across the Commonwealth through the e-health focus. According to Mr. Ernest Massiah, the Head of Health at the London-headquartered Commonwealth secretariat, which organizes health ministers' annual meetings in Geneva, India with its universally acknowledged techie skills can play role to foster south-south cooperation in the health sector. (source TOI May 17, 2008)

Despite the early efforts of many countries across the world to adopt e-health as a means of inter-country cooperation in the health sector, namely a coordinated response to outbreaks of infectious diseases and timely preventive measure to vulnerable sections of the population, a disaster of un-imaginable proportions occurred in the year 2019-2020 referred by the Covid-19 pandemic which created a Global crisis resulting in the shutdown of travel and tourism for a period of more than 2 years and tremendous loss of life; as of 15 October 2025, there have been reported 7.1 million confirmed COVID-induced deaths worldwide and it is now widely accepted that COVID-19 pandemic is the worst worldwide calamity experienced on a large scale in the 21st Century, making the Covid-19 death toll the highest seen on a global scale since the Spanish flu and

World War 1.

Present status of e-health adoption in India is quite impressive with almost all states having created E-health initiatives and the adoption of UHID (Unique Health Id) being issued to all patients registered with hospitals and healthcare agencies. Under the E-health initiative, the Ministry of Health and Family Welfare, Govt. Of India has launched the Ayushman Bharat Digital Mission (ABDM) which aims to develop the backbone necessary to support the integrated digital health infrastructure of the country. It will bridge the existing gap among different stakeholders of the Healthcare ecosystem through digital highways.

What is eHealth?

The term eHealth stands for electronic health. In other words, electronic (health) care. This is a catch-all term by which we mean all forms of digital care. We are not talking about EHR (Electronic Health Record), but mainly about innovative applications with digital tools.

In addition, the term mhealth is also becoming more familiar. This stands for mobile health and refers to digital care by means of mobile devices. So this is part of eHealth.

Types of eHealth applications in hospitals

Most eHealth applications are mobile apps and Web applications. Apps are downloaded onto a mobile device and web applications are opened from the browser. The use of robotics is not included in eHealth.

Much of eHealth is patient-centered: asking questions, informing and monitoring. But there are also applications that support the work of hospital staff. Think, for example, of eHealth applications that help with diagnosis or step-by-step plans: these apps provide (standardized) suggestions or tasks for the next step in the care process. This saves a lot of time.

EHealthplus Initiative of Hongkong SAR (Special Administrative Region) Govt. The Hongkong SAR (Special Administrative Region) has rolled out a five-year plan of eHealth+ with a new commitment of HK$1.4 billion in July 2024 for implementing a plan to transform eHealth from a health record sharing system into a comprehensive healthcare information infrastructure that integrates multiple functions of healthcare data sharing, service support and care journey management with four strategic directions:

- One Health Record
- One Care Journey
- One Digital Front Door to Empowering Tool
- One Health Data Repository

The eHealth+ will incorporate an integrated service platform to facilitate care coordination, cross-sector collaboration, health management and health surveillance through the following nine core functions:

- eBooking/eReferral
- eIdentification/eAuthentication
- eImaging/eLaboratory Report
- eMedication
- eMedical Certificate
- Portable eHealth Record

- eHealth Manager
- eHealth Tracker
- eHealth Life

In addition, a chatbot service "Ah Kin" is provided on the eHealth website, which helps to handle simple enquiries from the general public, supporting the use of English, Traditional Chinese and Simplified Chinese.

All these actions are intended to support every key stage or touchpoint of the care journey from building health awareness and scheduling appointments to receiving follow-up care as well as continued monitoring consistent with patient-centric principle and the four strategic directions laid out earlier.

EHealth Exchange USA

eHealth Exchange USA (ehealthexchange.org) headquartered in Virginia, USA, is a "Network of Networks" facilitating exchange of health information among providers, regional and state HIEs (Health Information Exchanges), public health authorities, payers, and federal agencies, including optional onramps to Carequality and TEFCA™ (Trusted Exchange Framework and Common Agreement) catering specifically to following Use Case Scenarios:

- Treatment/Care Coordination
- Encounter Alerts
- Task Based Exchange
- Clinical Data Exchange CDex
- Prior Authorizations
- Payer Data Exchange PDex
- HEDIS (Healthcare Effectiveness Data and Information Set) Reporting
- Public Health Reporting
- Electronic Case Reporting ECR
- Electronic Case Investigations ECI
- Adverse Event Exchange
- Electronic Lab Reporting ELR
- Syndromic Surveillance Notifications
- Prescription Drugs Monitoring Program PDMP
- Immunization Notifications
- Research
- Social Security Benefits Determination
- Individual Access to Health Information
- Life Insurance Applications
- Image Share

WORLD HEALTH ORGANIZATION (WHO) GUIDANCE REPORT 2021

Ethics and governance of artificial intelligence for health: WHO guidance. Geneva: World Health Organization; 2021

The WHO guidance on Ethics & Governance of Artificial Intelligence for Health is the product of eighteen months of deliberation amongst leading experts in ethics, digital technology, law, human rights, as well as experts from Ministries of Health. While new technologies that use artificial intelligence hold great promise to improve diagnosis, treatment, health research and drug development and to support governments carrying out public health functions, including surveillance and outbreak response, such technologies, according to the report, must put ethics and human rights at the heart of its design, deployment, and use.

The report identifies the ethical challenges and risks with the use of artificial intelligence of health, six

consensus principles to ensure AI works to the public benefit of all countries. It also contains a set of recommendations that can ensure the governance of artificial intelligence for health maximizes the promise of the technology and holds all stakeholders – in the public and private sector – accountable and responsive to the healthcare workers who will rely on these technologies and the communities and individuals whose health will be affected by its use.

Key ethical principles for the use of AI for health

The six principles for the use of AI for health are summarized below:

- Protecting Human Autonomy
- Promoting Human Well Being and Safety and the Public Interest
- Ensuring transparency, explainability and intelligibility
- Fostering responsibility and accountability
- Ensuring inclusiveness and equity
- Promoting AI that is responsive and sustainable

Overview of the report

This report is divided into nine sections and an annex.

Section 1 explains the rationale for WHO's engagement in this topic and the intended readership of the report's findings, analyses and recommendations. Sections 2 and 3 define AI for health through its methods and applications.

Section 2 provides a non-technical definition of AI, which includes several forms of machine learning as a subset of AI techniques. It also defines "big data," including sources of data that comprise biomedical or health big data.

Section 3 provides a non-comprehensive classification and examples of AI technologies for health, including applications used in LMIC (Low & Medium Income Countries), such as for medicine, health research, drug development, health systems management and planning, and public health surveillance.

Section 4 summarizes the laws, policies and principles that apply or could apply to the use of AI for health. These include human rights obligations as they apply to AI, the role of data protection laws and frameworks and other health data laws and policies. This section describes several frameworks that commend ethical principles for the use of AI for health, as well as the roles of bioethics, law, public policy and regulatory frameworks as sources of ethical norms.

Section 5 describes the six ethical principles that the Expert Group identified as guiding the development and use of AI for health.

Section 6 presents the ethical challenges identified and discussed by the Expert Group to which these guiding ethical principles can be applied: whether AI should be used; AI and the digital divide; data collection and use; accountability and responsibility for decision-making with AI; autonomous decision-making; bias and discrimination associated with AI; risks of AI to safety and cybersecurity; impacts of AI on labour and employment in health care; challenges in the commercialization of AI for health care; and AI and climate change.

The final three sections (7,8, and 9) of the report identify legal, regulatory and non-legal measures for promoting ethical use of AI for health, including appropriate

Governance frameworks. Recommendations are provided.

Section 7 examines how various stakeholders can introduce ethical practices, programmes and measures to anticipate or meet ethical norms and legal obligations. They include: ethical, transparent design of AI technologies; mechanisms for the engagement and role of the public and demonstrating trustworthiness with providers and patients; impact assessment; and a research agenda for ethical use of AI for health care.

Section 8 is a discussion of how liability regimes may evolve with increasing use of AI for health care. It includes how liability could be assigned to a health-care provider, a technology provider and a health-care system or hospital that selects an AI technology and how the rules of liability might influence how a practitioner uses AI. The section also considers whether machine-learning algorithms are products, how to compensate individuals harmed by AI technologies, the role of regulatory agencies and specific aspects for LMICs (Low- & Medium-Income Countries).

Section 9 presents elements of a governance framework for AI for health. "Governance in health" refers to a range of functions for steering and rule-making by governments and other decision-makers, including international health agencies, to achieve national health policy objectives conducive to universal health coverage. The section analyses several governance frameworks either being developed or already matured. The frameworks discussed are: governance of data, control and benefit sharing, governance of the private sector, governance of the public sector, regulatory considerations, the role of a policy observatory and model legislation and global governance of AI. Finally, the report provides practical advice for implementing the WHO guidance for three sets of stakeholders: AI technology developers, ministries of health and healthcare providers. The considerations are intended only as a starting-point for context-specific discussions and decisions by diverse stakeholders. While the primary readership of this guidance document is ministries of health, it is also intended for other government agencies, ministries that will regulate AI, those who use AI technologies for health and entities that design and finance AI technologies for health.

In summary, AI systems should be designed to minimize their environmental consequences and increase energy efficiency. That is, use of AI should be consistent with global efforts to reduce the impact of human beings on the Earth's environment, ecosystems and climate. Sustainability also requires governments and companies to address anticipated disruptions in the workplace, including training for health-care workers to adapt to the use of AI systems, and potential job losses due to use of automated systems.

EMPLOYEE ATTRITION PREDICTION USING MACHINE LEARNING APPROACHES

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ABSTRACT

Recent industry reports, including EY's Future of Pay 2024, reveal that the average attrition rate for employees across various industries in India reached around 18.3 % in 2023. This ongoing challenge adversely affects profit manage- ment, workforce stability, and operational efficiency. In the past, understanding why employees leave largely depended on lengthy HR processes like surveys and interviews. Machine learning en- ables organizations to move beyond these traditional approaches, offering quicker, data-informed, and more reliable forecasts of attrition. This study addresses these gaps by conducting a comprehensive, comparative analysis of nine machine learning classifiers which are Logistic Regression, Decision Tree, Random Forest, Gradient Boosting, AdaBoost, Na¨ıve Bayes, K-Nearest Neighbors (KNN), XGBoost, and CatBoost in a dataset of 1,470 employees with 35 diverse attributes. The aim is to identify all the factors that contribute to attrition and to evaluate it using performance metrics. The results of the research imply that CatBoost achieved the highest accuracy (92.71%), while XGBoost showed the best class separation (ROC-AUC 0.968). This approach aims to enhance decision-making in HR analytics by assisting HR teams to predict employee turnover effectively, minimize attrition costs, and help to design work-life balance strategies, competitive pay structures, and customized career development programs.

Keywords : Employee Attrition, HR Analytics, Human Re- sources, Profit Management, Workforce Stability

INTRODUCTION

Employee attrition, often described as workforce turnover, represents a significant barrier for organizations by disrupting operational flow, diminishing productivity, and increasing fi- nancial strain. Being able to anticipate which employees might exit the organization allows businesses to design timely inter- ventions, control costs, and

maintain team unity [1]. Industry reports highlight the magnitude of this concern. According to a 2023 Work Institute analysis, voluntary turnover accounted for more than $600 billion in annual costs for companies in the United States, with over 40 million employees leaving within a single year. Main reasons included insufficient career growth prospects (22%), challenges in work-life balance (12%), and Non-competitive remuneration (9%). Beyond direct hiring and training costs, attrition also impacts team morale and obstructs ongoing projects. To counteract these challenges, many firms have turned to engagement tools like Qualtrics and Culture Amp, which offer mechanisms for gathering real- time employee feedback. However, these platforms mostly offer descriptive summaries and lack the predictive capability needed to plan ahead and reduce employee turnover. Motivated by these gaps, this study examines how machine learning can be utilized to forecast employee turnover. The dataset used encompasses of 1,470 records with 35 diverse attributes covering demographic, role-specific, and organizational di- mensions. Out of which 34 attributes are independent variables and there is only one dependent variable ”attrition” which contains categorical values like yes or no. A total of nine supervised learning algorithms including Logistic Regression, Na¨ıve Bayes, K-Nearest Neighbours (KNN), Decision Tree, Random Forest, Gradient Boosting, AdaBoost, XGBoost, and CatBoost are evaluated, complemented by techniques like SMOTE for handling class imbalance and feature scaling. This work emphasizes the growing need for data-centric decision- making in human resources, moving beyond intuition to evidence-backed strategies. Organizations are under growing pressure to spot possible attrition early and take specific measures to keep key employees as they ask not only for money but also for growth, flexibility, and job satisfaction [2]. This study helps them reduce turnover risks and build a stable workforce for the long term. This research offers several significant contributions, which include:

- Highlighting deficiencies in current HR analytic tools regarding predictive insights.
- Establishing a comparative framework using multiple algorithms and extensive features for attrition forecasting.
- Presenting an interpretable, data-driven approach to sup- port strategic retention efforts.

LITERATURE REVIEW

Existing literature emphasizes various approaches, datasets, and methodologies aimed at understanding the causes and factors that mitigate workforce turnover. Researchers have explored various machine learning techniques to better predict turnover. [3] applied data mining to detect early behavioral indicators of attrition. [4] evaluated multiple models, finding Decision Trees and Random Forests balanced performance with interpretability. Several studies focused on comparative model evaluations. [5] showed SVM outperforming Logistic Regression in both accuracy (86% vs. 78%) and precision. [6] developed an AI framework combining Gradient Boosting, De- cision Trees, and Logistic Regression, with Gradient Boosting yielding an F1 score above 0.9. [7] created a pipeline using KNN, Random Forest, and XGBoost, with XGBoost achieving nearly 90% accuracy and an AUC of 0.93.

Several studies explored domain-specific applications and actionable insights. [8] surveyed churn methodologies across employee and customer contexts, highlighting ML flexibility in HR. [9] documented the shift from traditional statistics to scalable ML in workforce analytics. [10] applied predictive models in education, stressing domain-specific variables for retention. [11] linked job satisfaction and pay to turnover, while [12] combined data-driven analysis with HR policy recommendations. In general, these works highlight the im- portance of combining technical models with practical insights so that companies can make smarter decisions and reduce the employee turnover.

Numerous previous studies focused on limited

demographic and compensation variables, employed fewer models, and omitted organizational elements and interpretability within the prediction of employee turnover. The gaps in previous research are mitigated through our work, which blends 35 distinctive features, utilizes nine classifiers, and applies explainable arti- ficial intelligence tools for visualization. This accuracy yields enhanced explanatory power, fostering improved decision-making. Our research aids in effective employee retention by reinforcing proactive intelligent workforce strategy manage- ment and shifting the HR focus from reactive to responsive practices

METHODOLOGY

In order to precisely forecast employee attrition, a robust and systematic approach was undertaken. This approach tra- verses various steps, ranging from data collection to prepro- cessing, analysis, training of the model, and evaluation. Each step is crucial to guaranteeing the validity and reliability of the predictive model. The steps followed are outlined below.

Data Collection and Initial Assessment

The method starts with the gathering of a holistic dataset containing both current and past employee data. This is done to ensure that the inherent patterns and trends pertaining to attrition are properly captured. The dataset forms the basis of all the subsequent steps.

An initial check is then performed on the dataset to assess its structure as well as quality. The following steps are carried out:

- Dataset dimensions: The number of rows and columns are analyzed to determine the extent of the data.
- Statistical summary: Simple statistical values like mean, median, standard deviation, and variance are calculated for every numerical feature to get an overall picture.
- Column classification: All features are categorized into numerical and categorical categories for proper treatment in the next steps.
- Duplicate records: The data set is scanned for any dupli- cate records, which, if present, are eliminated to ensure data integrity.
- Missing data evaluation: Every attribute is scanned for missing values. The number of and percentage of missing values for each column are computed.
- Distinct category values: Categorical variables are checked for distinct values. For instance, the 'Attrition' variable contains two values—'Yes' and 'No'. Remain- ing categorical fields are 'Department' (Sales, Research and Development, Human Resources), 'Education Field' (Medical, Life Sciences, Technical Degree), and 'Gender' (Male, Female).

The dataset had no null or undefined values, and there were no duplicate records found.

Exploratory Data Analysis

Exploratory Data Analysis is essential in understanding the structure, relationships, and hidden patterns of the dataset. The EDA process includes:

- Attrition distribution: The general distribution of employees who have remained and those who have left is represented using pie charts and histograms.
- Percentage analysis: Pie charts are used to illustrate the percentage of workers in each attrition group so the imbalance if any can be visualized.
- Feature-based insights: Numerical and categorical variables are examined in-depth. Inter-variable relationships are explored to determine the features with maximum chances of impacting attrition.

These insights inform the feature selection and identify possible issues like imbalance or correlation that may affect model performance.

Data Preprocessing

Several preprocessing operations are carried out to get the dataset ready for training models:

- Label encoding is used on binary categorical variables such as 'Gender'.
- One-hot encoding is used on multi-category variables such as 'Business Travel', 'Department', 'Education Field', 'Job Role', and 'Overtime'. This is done to make sure all categories are treated equitably without adding artificial ordinal relations.
- Highly correlated features like 'JobLevel', 'MonthlyIn- come', 'YearsAtCompany', and 'YearsInCurrentRole' are recognized and dropped. These attributes contribute to redundancy and multicollinearity, which hinder specific models by overstating the importance of some features and making them less interpretable.

Variable Selection and Handling Class Imbalance

Once preprocessing is done, the dataset is split into:

- Independent variables (X): All the features that are per- tinent and could have an impact on employee attrition.
- Dependent variable (y): The 'Attrition' column, where 1 represents an employee who left and 0 represents an employee who remained.

There is a class imbalance, with many more employees labeled 'no attrition' than 'attrition'. To counteract this, the Synthetic Minority Oversampling Technique (SMOTE) is uti- lized. SMOTE generates synthetic samples of the minority class (attrition) in order to have balanced class distribution. This step is important since imbalanced datasets may bias the model towards predicting the majority class, hence minimizing performance in correctly predicting attrition cases.

Feature Scaling

After balancing the dataset, feature scaling is done to nor- malize the range of independent variables. This is especially crucial for algorithms that use distance calculations or are sensitive to feature magnitude.

Min-max scaling is used to scale features into a consistent scale, typically between 0 and 1. Alternatively, standardization (z-score normalization) can also be employed based on the re- quirements of the algorithm. Standardizing the data accelerates training convergence and improves model performance.

Model Training and Evaluation

Having preprocessed, balanced, and scaled the data, it is now ready for model training and evaluation.

- Data splitting: The dataset is split into a training set and a test set, usually with an 80:20 ratio. The training set is used to train the models, and the test set is used to measure model performance on unseen data.
- After preprocessing, balancing, and scaling, the dataset is divided into training and test sets (80:20 split). Various classification algorithms, including Logistic Regression, KNN, Naive Bayes, Decision Tree, Random Forest, Ad- aBoost, Gradient Boosting, and CatBoost, are applied. To evaluate these models, several performance metrics are used: Accuracy, which measures the proportion of correct predictions; Precision, indicating the model's abil- ity to correctly identify relevant instances; Recall, which assesses the model's capability to find all relevant cases; F1-score, the harmonic mean of precision and recall; and ROC-AUC score, which evaluates the model's capacity to distinguish between the attrition and non-attrition classes.

The model with the highest performance based on these metrics is selected and integrated into the HR analytics system. This facilitates data-driven

strategies to reduce attrition and enhance employee retention.

PURPOSE

Employee attrition is a serious and persistent issue to modern-day organizations, with direct implications on operational continuity, team performance, and bottom-line performance. Since the average rate of attrition in India stands at close to one-fifth of the total workforce, organizations are increasingly under pressure to control the risks of employee attrition. Replacing experienced people not only costs a lot to recruit and induct but also leads to the loss of company- specific knowledge and the loss of productivity in the team. All these organizational concerns having been identified, fore- casting and explaining employee attrition has emerged as an imperative research area, especially within strategic human resource management.

Historically, HR professionals have depended on past meth- ods like exit interviews, employee satisfaction surveys, and reviews at regular intervals to comprehend the reason behind attrition. Although the above-mentioned methods can offer qualitative results, they are not good at predicting turnover in advance. They gather subjective views after an employee has made up his or her mind to exit, therefo limiting intervention in a timely manner. In addition, these traditional tools tend to be non-scalable, especially in large organizations with complex workforce dynamics. This calls for a change from reactive, survey-based attrition monitoring to data-driven, predictive approaches. The overall aim of this research is to create a machine learning-based framework capable of precisely predicting employee attrition as well as determining the root causes of the same. The objective is to enable organizations to forecast which employees are most likely to leave, identify why they are disengaged, and institute preventive measures to drive retention. In an effort towards this aim, the study employs a dataset of 1,470 employee records with 35 different features such as demographic information, job functions, satisfaction with work environment, compensation levels, and performance metrics.

One of the main contributions of this study is its comparative analysis of nine supervised machine learning models: Logistic Regression, Decision Tree, Random Forest, Gradient Boosting, AdaBoost, Naıve Bayes, K-Nearest Neighbors, XGBoost, and Cat Boost. Through systematic benchmarking and comparison of each model on accuracy, precision, re- call, F1-score, and ROC-AUC metrics, the research seeks to identify which algorithms provide the most accurate and interpretable predictions in human resource analytics. The comparative benchmarking enables a better picture of various machine learning approaches' performance against workforce attrition data. The research also seeks to determine the most significant factors driving attrition. These findings will not only enhance the model's predictive validity but also offer actionable intelligence for HR professionals. Job satisfaction, work-life balance, overtime, and levels of compensation are anticipated to emerge as prominent predictors, providing a

basis for targeted managerial action. Understanding these variables helps decision-makers segment the workforce based on attrition risk and craft customized interventions that align with employee needs.

MAJOR RESEARCH FINDINGS

In this proposed system, we utilized a dataset available through IBM Watson Analytics, which includes information about IBM data scientists. The dataset comprises HR-related data from 1,470 employees, featuring 35 key attributes. Among these employees, 1,233 were categorized as active, labeled with 'no' for attrition, while the remaining 237 were former employees, classified under 'yes' for attrition in our analysis The

dataset used in this study comprises a total of 35 columns, categorized into numerical and categorical data. Specifically, there are 26 numerical columns, which capture quantitative aspects of the employees' HR information. "Null" or "un- defined" values and duplicate records are identified, as these could potentially impact the accuracy of the model training and lead to erroneous predictions. Fortunately, the dataset contained no null or undefined values, and no duplicate entries were found. Exploring Unique Values of Categorical Attributes involves analyzing the diversity within categorical variables to better understand their distribution and potential impact on analysis. For example, the Attrition variable has two distinct values: Yes and No, representing employees who left and those who stayed. Business Travel includes three categories: Travel Rarely, Travel Frequently, and Non-Travel, reflecting the travel frequency of employees. Similarly, The Department attribute is categorized into Sales, Research '&' Development, and Human Resources, while the Education Field catergorizes as Medical, Life Sciences, and Technical Degree. Gender is represented by male and Female. There are other features which includes categorical data like this. Understanding and summarizing these unique values provides meaning insights into the categorical variables as catergorical values cannot be analyzed like numerical values. Exploratory Data Analysis (EDA) plays a crucial role in understanding and uncovering underlying patterns and trends in the dataset. For better understanding employee attrition, we begin by visualizing the distribution of employees with and without attrition, using pie charts or histograms to illustrate the count of employees in each category. Additionally, pie charts are used to display the percentage distribution of attrition, offering a clear view of the overall attrition rate. Further, EDA involves a detailed feature- based analysis, not only for categorical variables but also for numerical features. In the data preprocessing phase, categorical features are transformed into numerical representations to facilitate model training. For binary categorical variables such as gender, label encoding is applied, assigning numeric values to each category. For multi-category variables, such as Busi- ness Travel, Department, Education Field, Job Role, Marital Status, and Overtime. One-Hot Encoding is employed to create binary columns for each category, ensuring that each category is appropriately represented without introducing any ordinal relationships. Further to improve the efficiency of the model and reduce multicollinearity ,highly correlated features are identified and removed. Features with hign correlation, such as Job Level, Monthly Income, Years At Company and YearsInCur- rent Role are dropped from the dataset to minimize redundancy. In the next step, the dataset is first split into independent and dependent variables, where the independent variables (X) include all features except the target variable "Attrition", while the dependent variable (Y) represents the "Attrition" status. The dependent variable is chosen in such a way that this depends on the other independent variables. To address the class imbalance in the dataset, where the majority class (no attrition) is significantly higher the minority class (attrition), the Synthetic Minority Oversampling Technique (SMOTE) is employed. SMOTE generates synthetic samples for the minority class, so that there is an equal distribution of "attrition" and "no attrition" classes. By removing imbalance in the data set, the model does not become biased towards predicting the majority class. Following the balancing of the dataset, feature scaling is applied to standardize the independent variables, which is particularly important for models sensitive to the scale of input data, such as distance based algorithms. Either min- max scaling or standardization can be used. By standardizing the features, we improve the

model's convergence rate during training and thereafter its overall performance. The dataset is now balanced and scaled and is ready for the next steps in model development. The results of EDA are shown for the most important features which lead to employee attrition. The results of EDA are shown for the most important features which lead to employee attrition.

The chart in Fig. 1 shows that the employee attrition rates peak among those aged 28 to 32. As employees get older, the chances of them leaving the organization tend to decrease, because they prioritize job stability and family obligations more during this phase of their careers. In contrast, younger employees, especially those between 18 and 20, are more inclined to leave the company as they often seek different career opportunities for their individual growth and success.

Fig. 1: Correlation between employee age and attrition rates

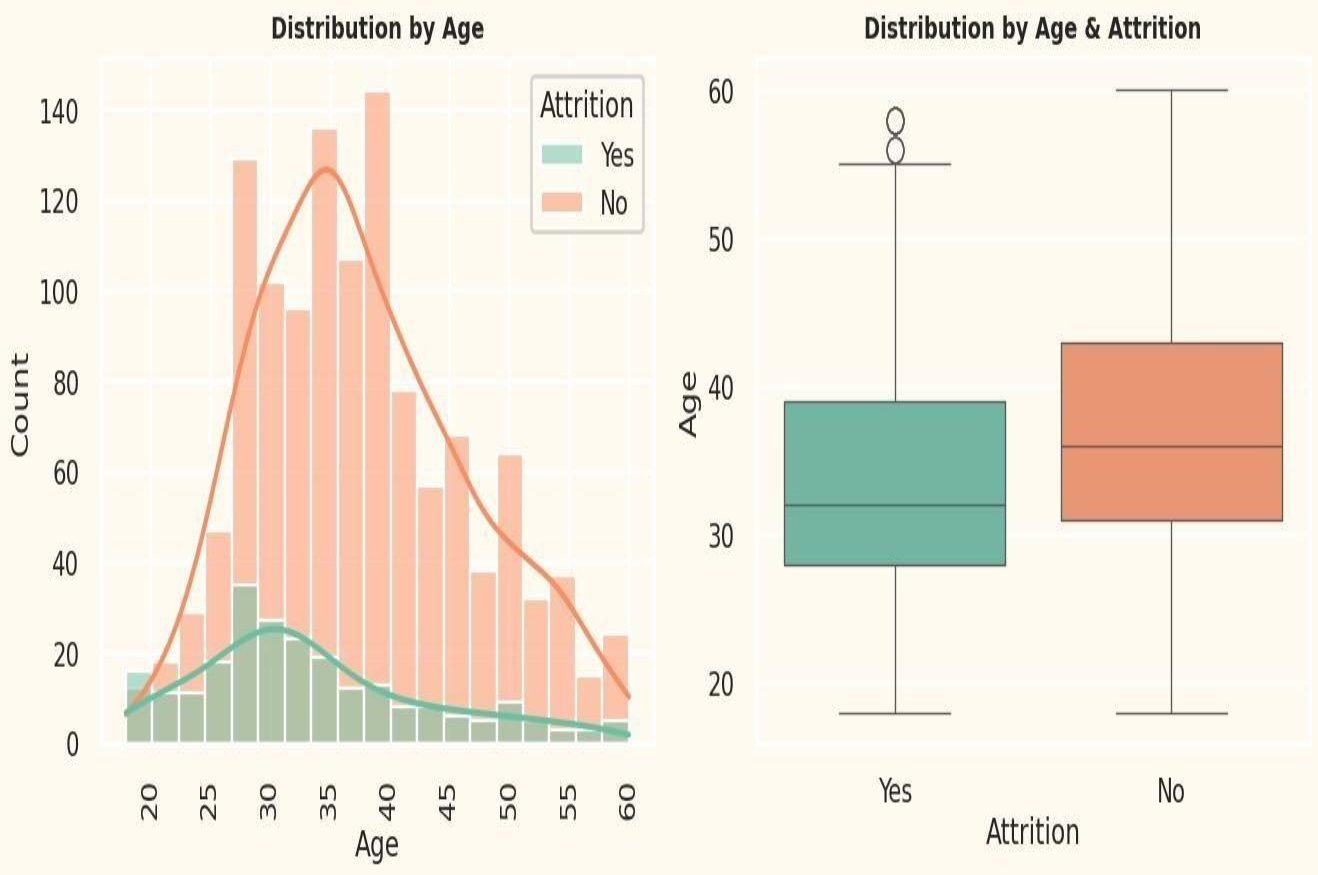
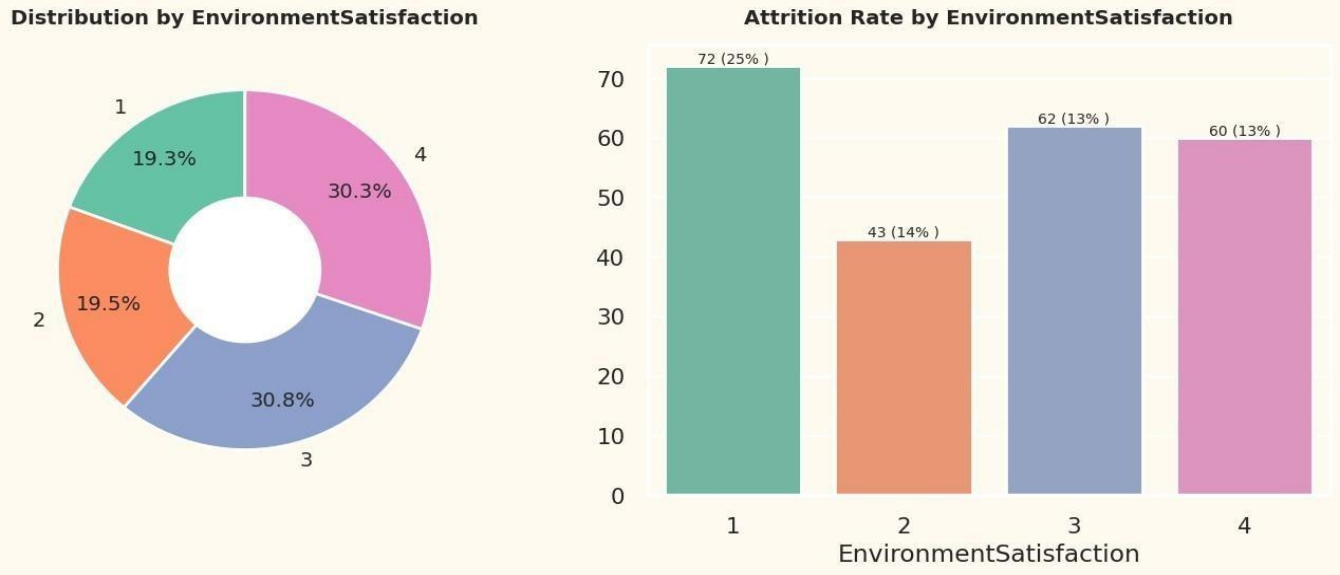


Figure. 2: Employee attrition across levels of environmental satisfaction



The distribution of employees across different levels of environmental satisfaction is presented in Fig. 2. The majority of employees report either high satisfaction (Level 4, 30.3%) or moderate satisfaction (Level 3, 30.8%). In contrast, Levels 1 and 2 represent a smaller portion of the workforce. Attrition rates, as depicted in the corresponding bar chart, show a clear trend: employees with the lowest environmental satisfaction (Level 1) experience the highest attrition rate at 25%, followed by Level 2 at 14%. Meanwhile, those reporting moderate (Level 3) and high (Level 4) satisfaction have comparatively lower attrition rates, both at 13%.

The analysis of job satisfaction, illustrated in Fig. 3, highlights a clear link between satisfaction levels and attrition. Most employees report high (Level 4, 31.2%) or moderate (Level 3, 30.1%) satisfaction, while fewer fall into the lower levels (Levels 1 and 2). The bar chart shows that attrition is highest at Level 1 (22%) and Level 2 (16%), whereas Levels 3 and 4 exhibit significantly lower attrition rates (both at 11%). These findings confirm a strong negative correlation between job satisfaction and attrition: higher satisfaction is associated with lower turnover.

Figure. 3: Employee attrition across levels of job satisfaction

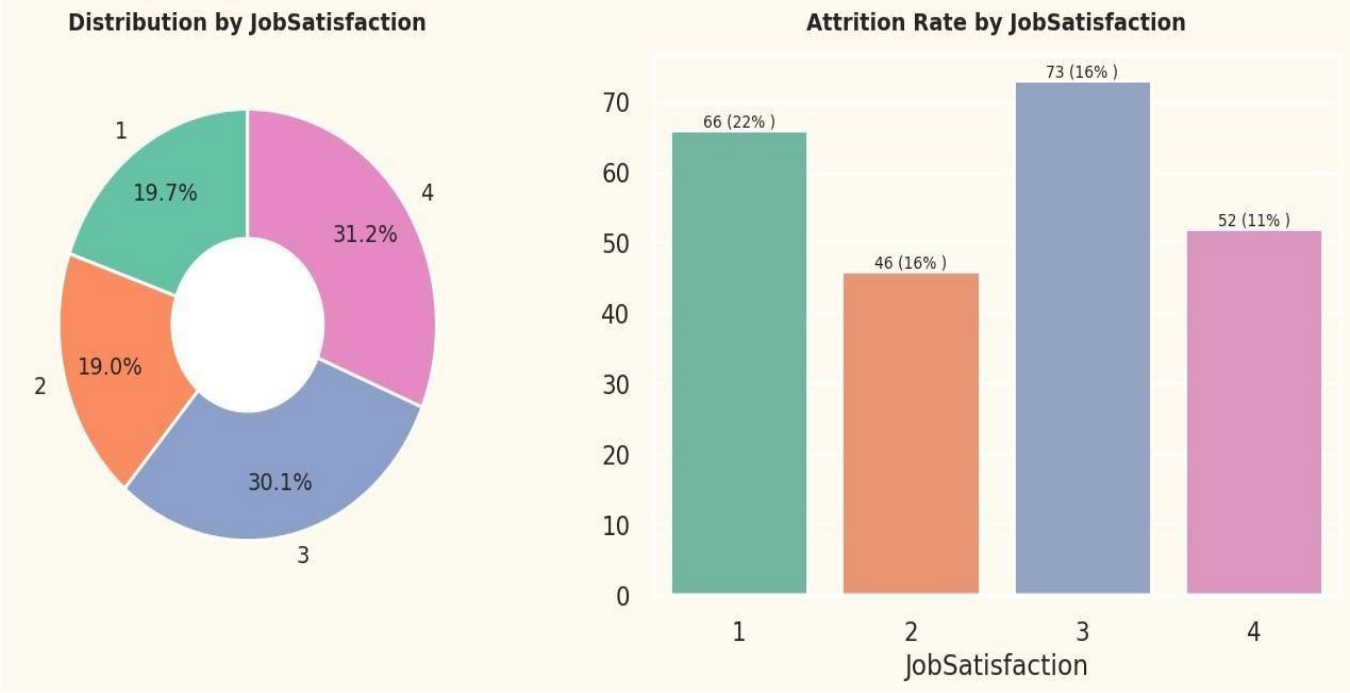


Figure. 4: Trends in attrition with varying educational qualifications

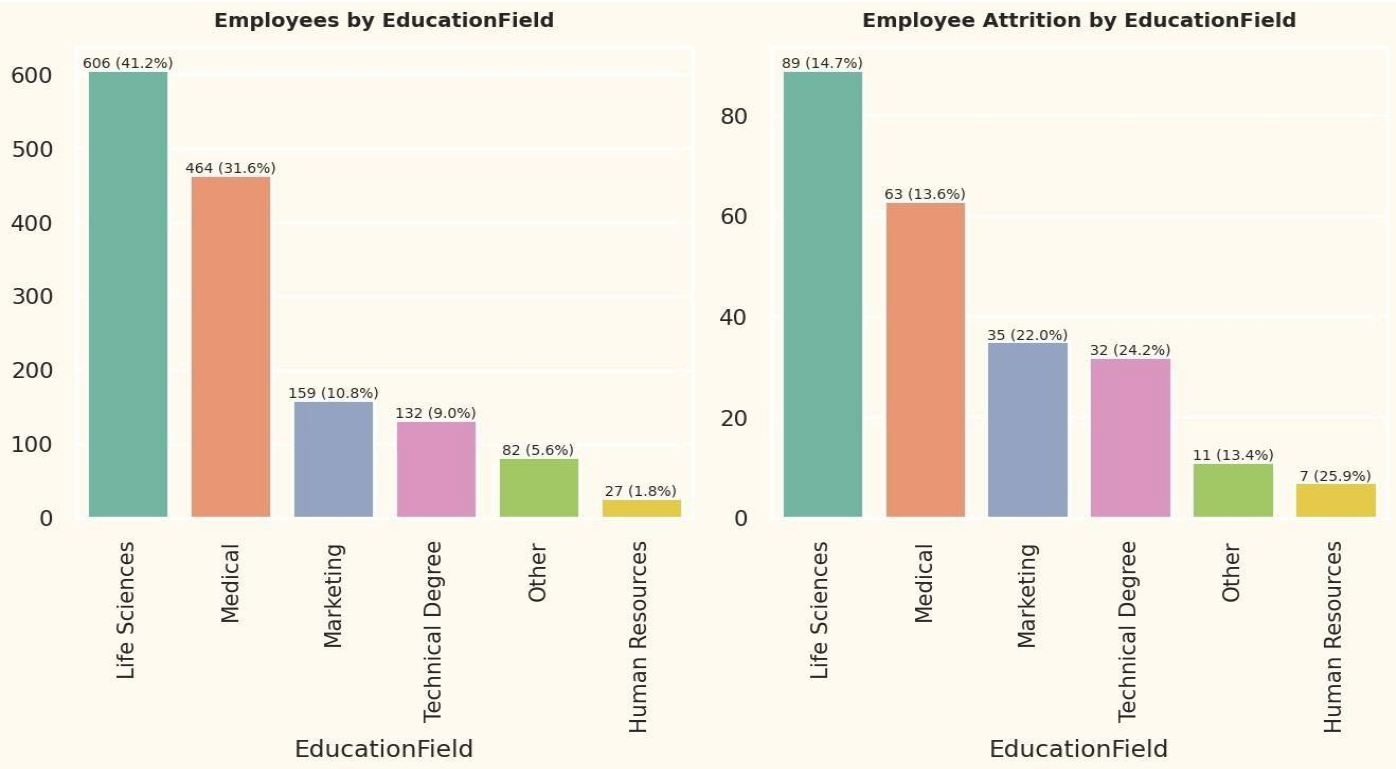


Figure. 5: Impact of relationship satisfaction on attrition levels

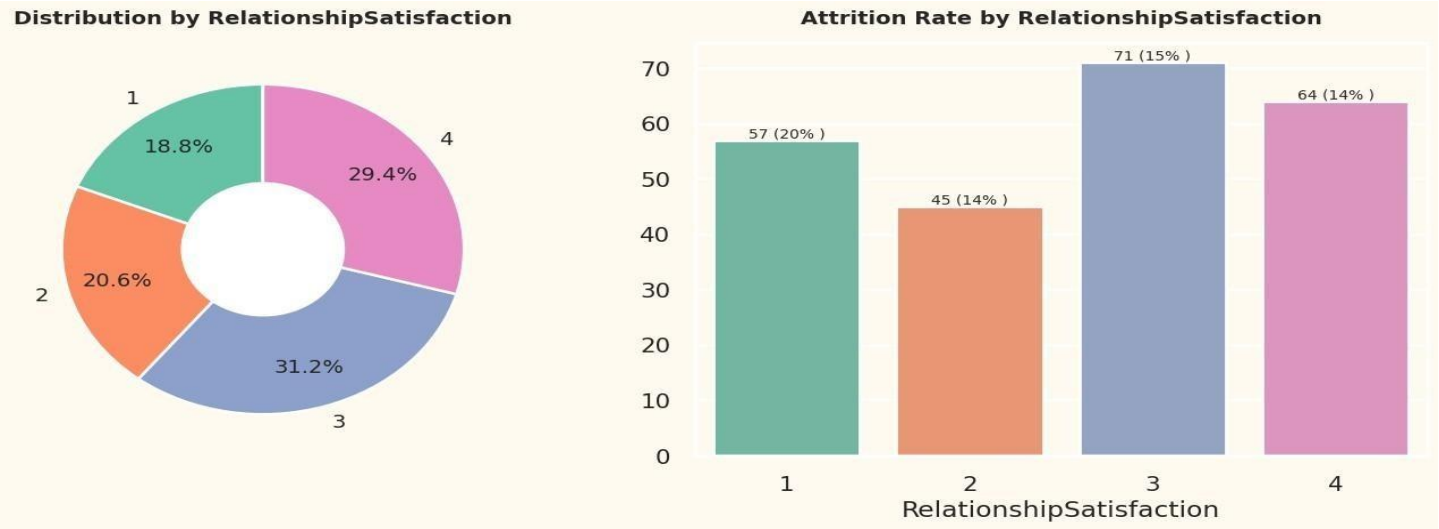
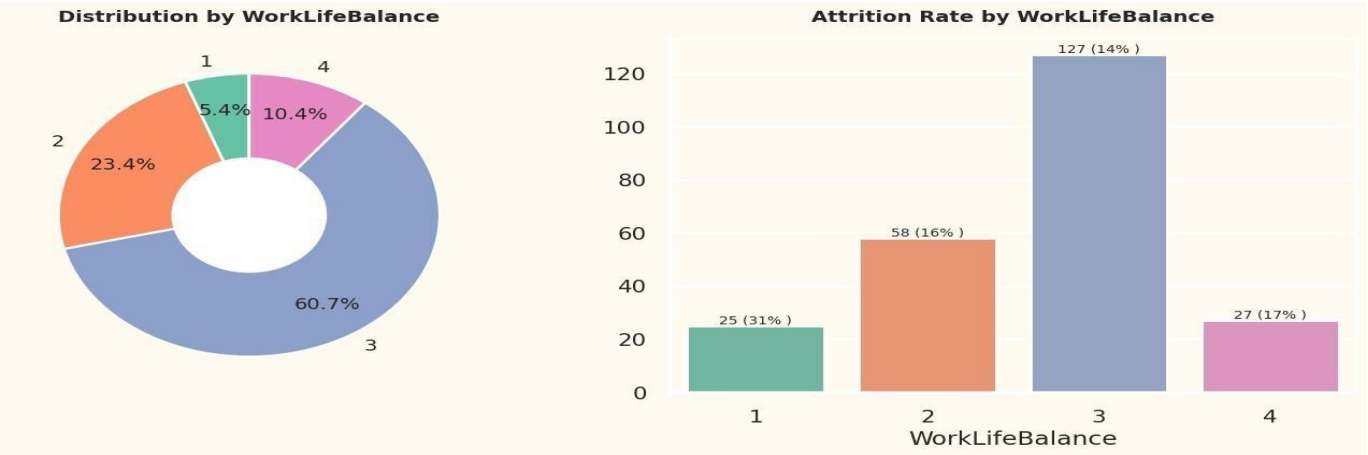


Fig. 5 illustrates the distribution of relationship satisfac- tion among employees, with the majority reporting moderate 31.2% or high 29.4% satisfaction. Lower satisfaction levels

1 and 2 account for a smaller share. The attrition data reveals that employees at level 1 have the lowest attrition rate 10%, followed by level 2 at 14%. Those with moderate and high satisfaction levels 3 and 4 also show relatively low attrition rates of 14% and 15%, respectively. This indicates a moderate negative correlation between relationship satisfaction and attrition—employees with higher satisfaction tend to have slightly lower turnover rates.

Figure. 6: Effect of work-life balance satisfaction on employee turnover



In Fig. 6 shows that employees reporting high work-life balance (60.7%) have the lowest attrition rate at 14/%. In contrast, those with poor balance face a much higher rate (31%), while the moderate group is at 16%. This pattern suggests that inadequate work-life balance, due to long hours or low flexibility, may drive turnover. Supporting a healthy balance is therefore important for retention and employee well- being

The chart Fig. 7 indicates that 71.7% of staff members never work overtime and 28.3% of staff members work overtime. Matching attrition statistics indicate that a mere 10% of non-overtime employees quit the company, while a significantly greater 30% of overtime workers did. This shows that overtime workers are almost three times more likely to quit than employees who work standard hours.

Figure. 7: Effect of overtime on employee retention rates

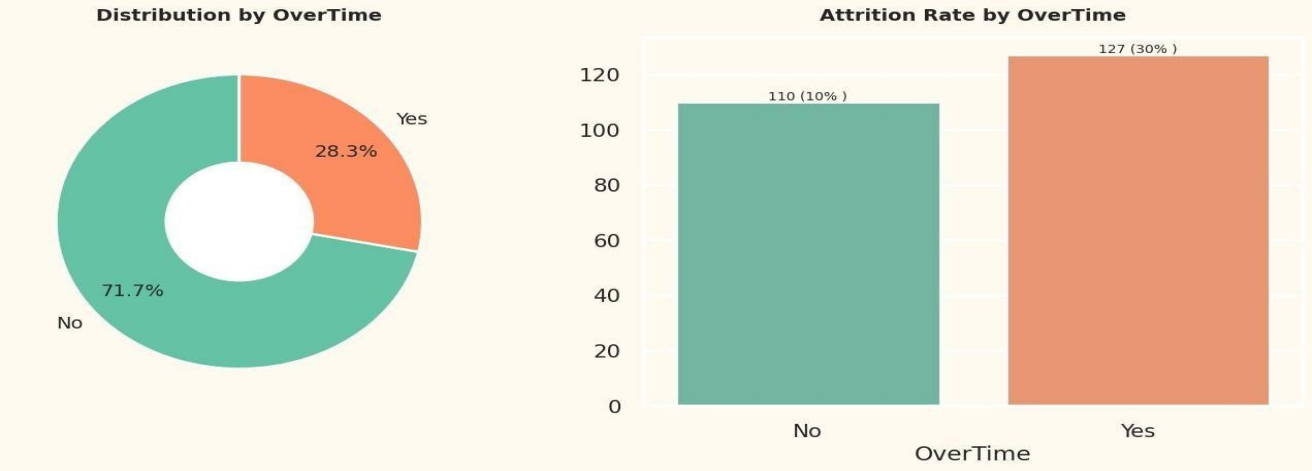
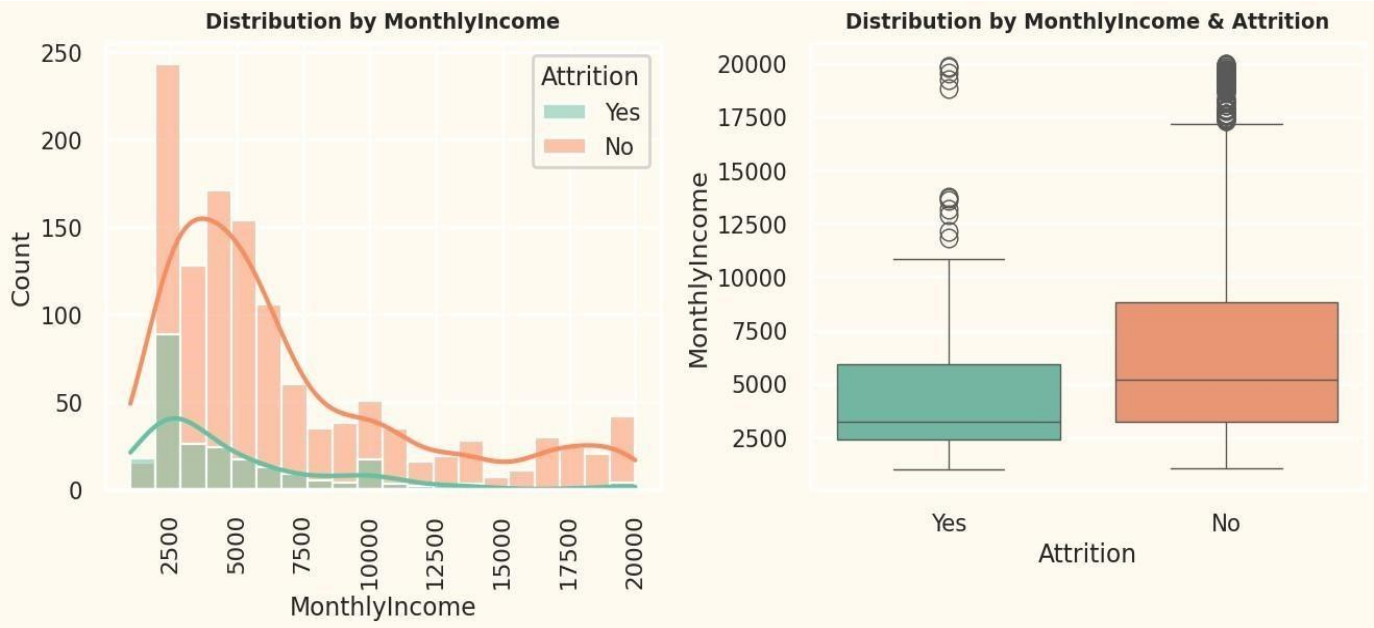


Figure. 8: Influence of monthly income on employee retention



The density plot in Fig. 8 indicates that the employees who remained with the company have a wider income distribution, peaking at 2500. Their counterparts who departed the organization are predominantly in lower income groups. The boxplot also reinforces the pattern of significantly lower median income for the ones who departed, as well as a narrower interquartile range and less high-income presence. These findings imply that reduced monthly earnings could be one of the causes of worker turnover

The distribution of pay in Fig. 9 increases is slightly skewed towards pay increases between 12% and 14 %. Surprisingly, departing employees had slightly higher median pay increases than those who remained. Nevertheless, the overall trend indicates that low pay increases might result in higher turnover. Though greater increases may serve as a motivating force, lower-increase recipients are likely to look for opportunities elsewhere.

Figure. 9: Salary hike distribution showing attrition versus retention trends

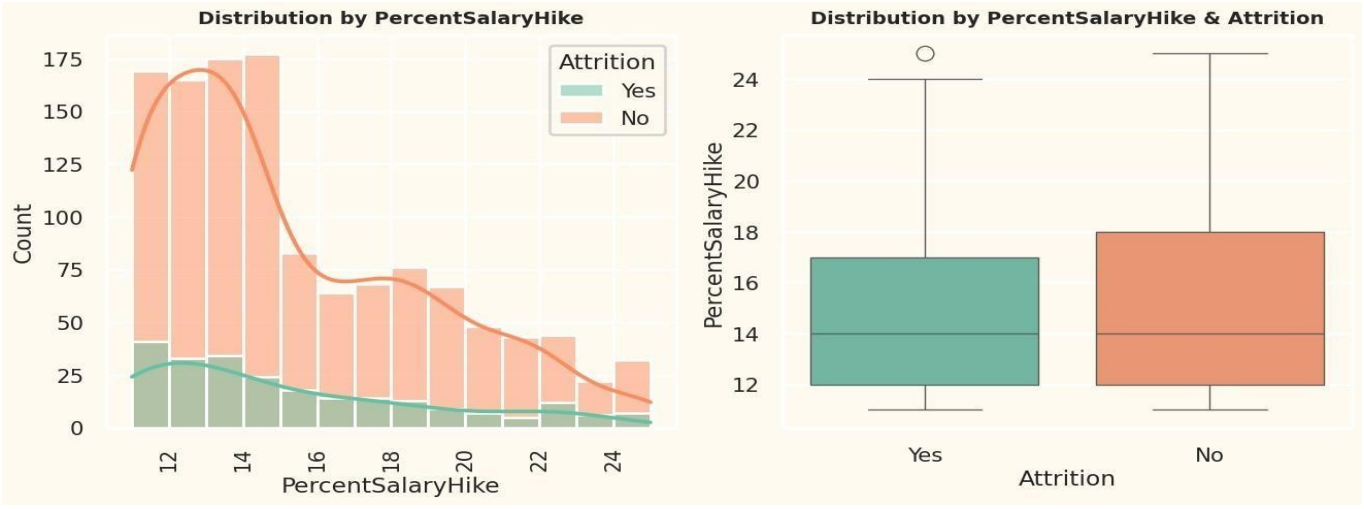


Figure. 10: Impact of total working years on employee turnover rates

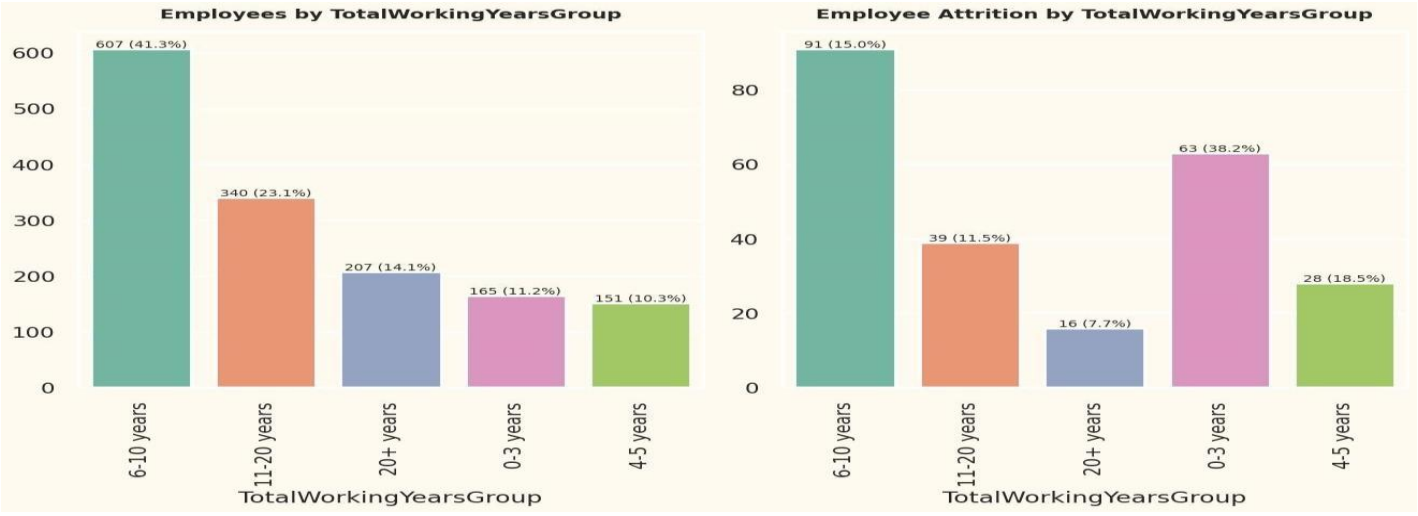


Fig. 10 indicates 41.3% of staff members have been in the company for 6 to 10 years, and 23.1%

for 11 to 20 years, thus forming the two biggest groups. The greatest attrition is among the staff members with 0 to 3 years of experience, standing at 15%. This indicates that new staff members are more likely to exit the company, perhaps as a result of unrealized expectations or adaptation problems. As workers gain more experience, they seem to be more apt to remain, perhaps because of improved pay, familiarity with the job, or more solid workplace relationships.

Fig. 11, the majority of employees, approximately 43%, reside between 0 and 5 kilometers from the workplace. The attrition rate in this category is lowest, at 13.8%. As the dis- tance from the workplace increases, the number of employees gradually decreases, while the attrition rate rises. Employees living more than 20 kilometers away experience the highest attrition rate at 22.1%. These findings indicate that longer commuting distances may contribute to increased stress and dissatisfaction, which in turn affects employee retention.

Fig. 12 shows the distribution of employees shows that a significant majority (71%) rarely travel for business, while 18.8% travel frequently and 10.2% do not travel at all as shown in Figure 13. This travel pattern correlates with attrition rates: frequent travellers face the highest attrition rate at 24%, suggesting that the demands of regular travel might lead to stress and work-life imbalance, contributing to their decision to leave the company. In contrast, those who travel rarely experience a moderate attrition rate of 14%, and non-travellers have the lowest rate at 8%.

Figure. 11: Attrition rates based on distance from workplace

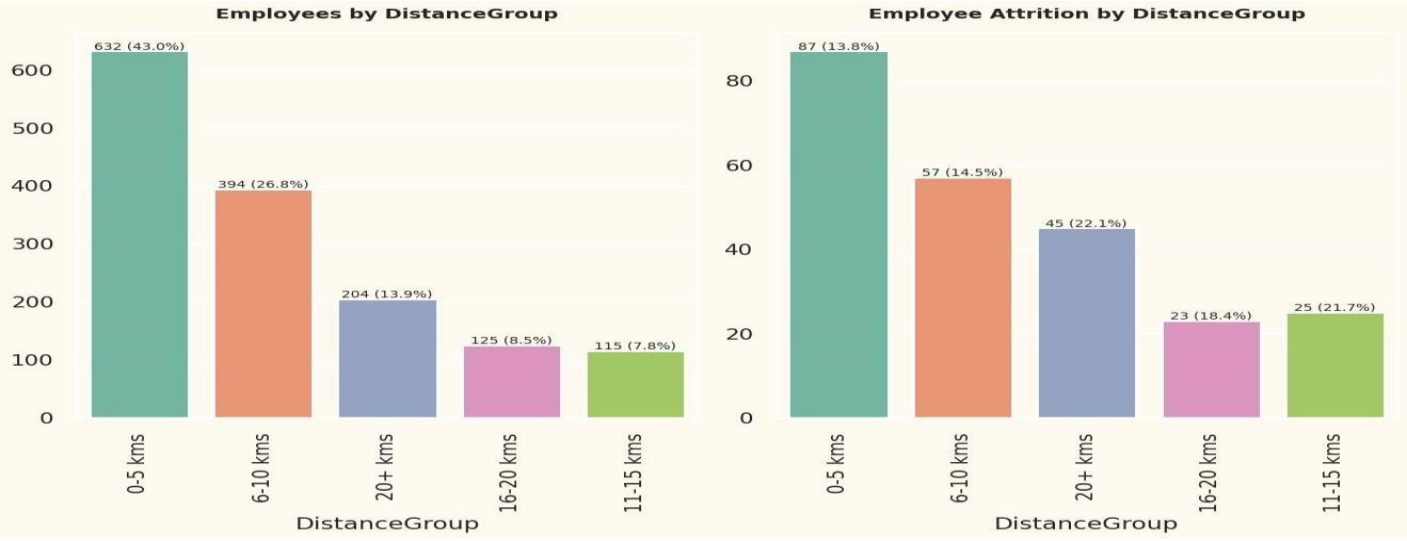
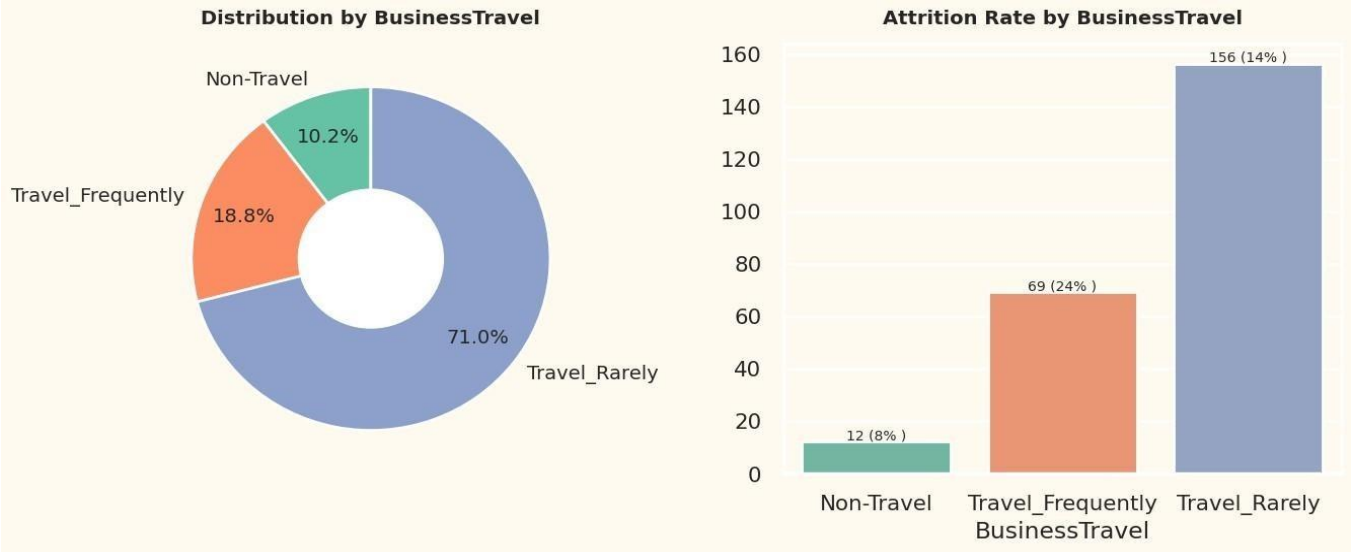


Figure. 12: Employee attrition rates by frequency of business travel.



This could indicate that frequent travellers may be less satisfied with their job roles or work-life balance, and the company's culture and support for its travelling employees could significantly impact their retention. Addressing these concerns could improve job satisfaction and lower turnover rates.

Lastly, the distribution of employees by marital status reveals that 45.8 % are married, 32% are single, and 22.2% who are divorced. The single employees experience the highest turnover at 25%, compared to 12% for divorced employees and a notably lower rate of 10% for married employees. These trends can be interpreted in several ways: married employees may exhibit greater stability and commitment to the company due to their financial security and family obligations, while single employees, particularly those in younger demographics, may prioritize career advancement and personal growth, lead- ing to their higher attrition. Additionally, divorced employees might encounter unique challenges in managing their work-life balance, contributing to their elevated turnover rates.

Model Building

After establishing our objectives and thoroughly preparing and analyzing the dataset, we moved forward with designing a prediction model aimed at identifying employees who may be at risk of leaving the company. During the model construction phase, we recognized the importance of utilizing a training set that includes instances from a previously classified population. This would enable us to train the model effectively to classify new observations, which will constitute our test set, where the class attribute is absent. To enhance the model's predictive capabilities, it is crucial to train it on a substantial and consistent number of observations. By utilizing a larger dataset during training, we can significantly improve the precision of the machine learning algorithms employed. Therefore, the original dataset was split into two parts with an 80:20 ratio. Training Set: 80% of the total dataset was used for training. The model learned the relationships within this data. Test Set: The remaining 20% observations were done using the test set, used for testing and validating each model's performance. Here the predicted results were compared against actual outcomes. This split encourages effective evaluation and fine-tuning of the model, so that the model can give a good performance when encountered with unknown data. The training dataset has used different classification models on training set. These

models are:

Logistic Regression: A widely used linear model for binary classification-related applications that estimates the probability of an event based on input features. It works well when the relationship between independent and dependent variables is linear.

K-Nearest Neighbors (KNN): A memory-based, flexible model that classifies data points according to the majority class among *K* nearest neighbours. It is effective for smaller datasets but may become computationally expensive when working with larger datasets.

Naive Bayes: A probabilistic model based on Bayes' Theorem, effective for applications like text classification. It works on the assumption of feature independence and normal distribution.

Decision Tree Classifier: This model divides data by making decisions on the basis of feature values. It can handle both categorical and numerical data but might perform poorly if it gets overfit without proper pruning or regularization.

Random Forest Classifier: This model creates multiple decision trees and combines their predictions. It helps reduce overfitting and enhances generalization, making it a robust choice for diverse datasets.

AdaBoost Classifier: This model integrates multiple weak classifiers into a stronger one by adjusting the weights of misclassified data points in successive iterations. It is popular for improving model accuracy in challenging tasks.

Gradient Boosting Classifier: In this model, classifiers are built iteratively, each correcting the errors of the previous one. While it is highly effective for complex datasets, improper regularization may lead to overfitting.

CatBoost Classifier: This model efficiently handles cate- gorical features without requiring extensive pre-processing. It focuses on reducing overfitting while achieving high perfor- mance, especially on large datasets with mixed data types.

RESULTS

In this phase, Table 1 and Table 2 show the effectiveness of the selected models was assessed. For each algorithm, the outcomes of the predictions were organized into a con- fusion matrix. This matrix displays the predicted values in the columns and the actual values of each instance from the test set in the rows. By analyzing the confusion matrix, key performance metrics, namely accuracy, precision, recall, and F1-score, and the results were analyzed to identify the model that achieved the best predictive performance.

TABLE I: Comparison of models based on accuracy and precision

Model	*Accuracy (Train)*	*Accuracy (Test)*	*Precision*
Logistic Regression	85.44	84.00	0.848
KNN	90.87	87.85	0.808
Naïve Bayes	76.41	75.50	0.699
Decision Tree	100.00	86.23	0.846
Random Forest	100.00	92.51	0.968
AdaBoost	93.05	90.49	0.923
Gradient Boosting	96.55	92.31	0.960
XGBoost	100.00	92.51	0.956
CatBoost	99.65	92.71	0.954

TABLE II: Comparison of models based on Recall, ROC-AUC, and F1 Score

Model	*Recall*	*ROC-AUC*	*F1 Score*
Logistic Regression	0.823	0.910	0.836
KNN	0.987	0.961	0.889
Naïve Bayes	0.885	0.867	0.781
Decision Tree	0.881	0.863	0.860
Random Forest	0.877	0.976	0.930
AdaBoost	0.881	0.955	0.910
Gradient Boosting	0.881	0.965	0.930
XGBoost	0.889	0.968	0.921
CatBoost	0.885	0.971	0.930

MANAGERIAL IMPLICATIONS AND PRACTICAL IMPLICATIONS

The findings from this research have important managerial implications, especially for decision-making in the Human Resources function. As attrition continues to affect organiza- tional stability and profitability, managers are under growing pressure to detect early warning signs and introduce pre- ventive measures. Machine learning models provide a more structured and data-driven method of interpreting employee behavior. Managers can use predictive insights to identify patterns and trends indicating likely turnover, enabling them to target resources and assistance to those places where they are most urgently required. This requires a change in culture for organizations as well, when HR is no longer just a support function but a strategic partner facilitated through advanced analytics. Implications in terms of practical implementation, the usage of high-performance models like XGBoost and CatBoost creates a revolutionary moment for HR functioning.

The above models can easily be plugged into existing HR IT systems to keep track of the risks of attrition in real time. In this manner, HR teams

can segment their employees by how likely they are to leave and probe the individual drivers of such risk—be it dissatisfaction with pay, absence of recognition, lack of career progression, or inadequate work-life balance. This degree of granularity makes it possible to have intervention at a point of specificity, eliminating over-reliance on time-consuming traditional practices like exit interviews and one-size-fits-all employee satisfaction surveys. Additionally, the application of machine learning supports the effectiveness of HR departments and enables them to act proactively instead of reactively.To effectively restrain attrition, businesses must engage in a holistic strategy that combines machine learning insights with people-centric programs. Firstly, they need to incorporate models such as CatBoost and XGBoost into their HR infrastructure to get high-risk employees automatically flagged. These predictive systems can be used to construct in-depth employee profiles, exposing key drivers of disengage- ment or dissatisfaction. With risks discovered, businesses can implement customized responses such as providing flexible working times, raising compensation transparency, and designing customized development plans. Further, by building a culture of internal mobility where workers are urged to try out new jobs within the organization, voluntary turnover can also be lessened. To maintain this strategy, organizations need to create ongoing feedback loops where actual-world results feed into the predictive models so that they become increasingly accurate with time. Of comparable significance is empowering HR staff through data literacy and model interpretation training, so that not only are insights created but also interpreted and translated into action. When predictive analytics are combined with human intuition and empathy, organizations are in a position to better retain high-performing talent, increase employee engagement, and create long-term organizational success.

RESEARCH LIMITATIONS

One of the main restrictions is in the consistency of model performance between algorithms. While ensemble models like CatBoost and XGBoost performed better in accuracy and ROC-AUC, other more basic models like Na¨ıve Bayes and K-Nearest Neighbors were unable to cope with the complication and skew in the dataset. The class distribution was also dominated by non-attrition cases, which was a concerning aspect for classification algorithms and may have biased their predictions. Even with the use of the SMOTE method to balance the class distribution, some models continued to underperform in detecting minority class instances, hence inhibiting their capability to reflect actual attrition risks in real- world deployment.

Overfitting was also a concern in some models, such as Decision Trees. These models performed virtually flawlessly on the training set but suffered a significant performance loss on the test set. This difference between training and test metrics indicates that some models learned patterns specific to the training set instead of generalizable knowledge. Overfitting in this manner decreases the strength and dependability of predictions in real-world operating environments, where the model needs to generalize to novel and unknown data. In order to address this issue, further implementations would be aided by more comprehensive cross-validation processes, regularization methods, and iterative retraining from new data inputs.

Another limitation lies in the lack of generalizability due to the character of the dataset employed. Data used for this research came from one organization alone IBM, which had special culture-related, structure-specific, or policy-related characteristics different from those of other firms or sectors. Accordingly, the results and model behaviors obtained from this dataset may not be applicable as-is to other corporate

settings. Some of the features involved in this analysis, e.g., internal job positions or certain satisfaction metrics, might not be available elsewhere, thereby limiting portability and scalability of resulting models. The interpretability of the machine learning models is also a limitation, particularly for ensemble algorithms such as CatBoost and XGBoost. Although these models provided high predictive performance, their internal mechanisms are usually unclear to non-technical users. This transparency can limit the acceptance and real usage of model outputs within human resource departments, where decision-makers may need explainable justifications for predictive recommendations.

From the point of view of data governance, feature avail- ability and privacy concerns also restrict the study's real-world utility. Some of the data that is utilized to train the models, like detailed performance scores, individual demographics, and satisfaction metrics, would not be easily accessible in every organization because of legal, ethical, or practical reasons. Additionally, the utilization of employee sensitive information also poses privacy issues that need to be resolved through proper anonymization and adherence to data protection laws. These demands can require adjustments to the model or its input parameters, possibly impacting its reliability or accuracy in usage.

Lastly, it must be emphasized that no predictive platform could possibly supplant the sophisticated judgment of sea- soned human resource professionals. Although the models formulated in this research yield useful advance warnings and data-driven observations, their efficacy hinges on being incorporated within a more encompassing strategic process that integrates managerial judgement, policy redesign, and ongoing employee participation. Predictive analytics must be viewed as a decision support system, not as a sole intervention.

ORIGINALITY

While several prior studies have explored employee attrition using various demographic and compensation variables, our work distinguishes itself by not only integrating 35 features across demographic, job-related, and organizational dimen- sions and benchmarking nine supervised learning algorithms (from Logistic Regression to XGBoost and CatBoost), but also by employing a diverse set of visualizations such as box plots, histograms, bar charts and pie chart which translate complex model outputs into actionable recommendations for HR teams. These graph-based presentations clarify which factors most strongly drive turnover risk, enabling practitioners to locate and prioritize selective measures more effectively than in earlier, less interpretable frameworks.

CONCLUSION AND FUTURE RESEARCH WORK

In this research, several loopholes were filled by including 35 unique features and using nine various machine learning classifiers. EDA helped to visualize the results, to make the findings precise and understandable. This approach enables organizations to identify high-risk segments of employees at an early stage and implement timely and focused measures to enhance retention and overall employee satisfaction. Out of the comparative study of machine learning models under different evaluation metrics (Accuracy, Precision, Recall, ROC_AUC, and F1 Score), the CatBoost Classifier is always among the best-performing models. It has very high test accuracy at 92.71%, good precision (0.954), and good recall (0.885), with superior ROC_AUC (0.971) and F1 Score (0.930). The XGBoost Classifier is also competitive, equalling CatBoost in both training accuracy and test accuracy, and having similar measurements in the other metrics. On the opposite end, the Na¨ıve Bayes model has the lowest test accuracy (75.50%), precision (0.699),

and lowest F1 Score (0.780) among all the models considered. The Linear Regressor, although compar- atively stable, also lags behind the ensemble approaches in most performance indicators. Ensemble learning algorithms, especially CatBoost, XGBoost, and Gradient Boosting, always perform better than more basic models such as Na¨ıve Bayes, KNN, and Decision Trees. This suggests that boosting-based solutions are better suited to the problem in question, most probably because they can minimize bias and variance by iteratively refining the model. Future work can build on this study by adding more types of data, such as real-time employee feedback, health and wellness information, or trends from the wider industry. This would help create stronger, more adaptable models to predict attrition. Research could also look at designing customized retention plans by using more detailed risk profiles and improving how easily we can understand model results, for example through new explanation tools. Testing these methods across different industries and cultures would show how well they work in various settings. Finally, there is potential to expand this approach for long-term predic- tions and to link it directly with employee growth platforms, so companies can better spot possible turnover and respond in a more focused, culturally aware way\

ACKNOWLEDGMENT

The authors of the paper acknowledge the support of the Department of Electrical Engineering, Techno International New Town and the Department of Information Systems & Business Analytics, Indian Institute of Management Ranchi, to accomplish the presented work.

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EFFECTS OF INSPECTION ON RETAILER'S ORDERING POLICY FOR A DETERIORATING ITEM WITH WEIBULL DISTRIBUTION DETERIORATION, TIME-DEPENDENT DEMAND UNDER INFLATIONARY CONDITION

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ABSTRACT

For an unstable supply inventory model, the received lots may carry a random proportion of damaged products characterized by a known distribution.Accordingly, inspection of the lot is essential in nearly every case.The Weibull distribution with two parameters specifically represents the time to deterioration.Defective units are presumed to be retrieved as a single batch following inspection.For many consumer goods, it is also noted that the price and demand increase linearly with time, especially in inflationary circumstances.Since demand and price change over time, this study looks at how merchants' ordering procedures for deteriorating items are impacted by defective items under inflation. The proposed model aims to maximize the order quantity and the retailer's expected profit. An example is provided to illustrate the outcomes.

Keywords

Inventory, Inspection, Time-dependent demand, Inflation, Weibull distribution.

INTRODUCTION

This research concentrates on designing an EOQ model for deteriorating goods, integrating Weibull deterioration, time- varying demand, and inflation. For the derating items, a number of economic order quantity (EOQ) models have been developed thus far. The following models are:

- Porteus (1986): Optimal Lot Sizing, Process Quality Improvement and Setup Cost Reduction,
- Lee and Rosenblatt (1987): Simultaneous determination of production cycles and inspection schedules in a pro- duction system,
- Salameh and Jaber (2000): Economic Production Quan- tity model for items with imperfect quality,
- Ghosh and Chaudhuri (2004): An order level inventory model for a deteriorating item with Weibull distribution deterioration, time-quadratic demand and shortages,
- Convert and Philip (2007): An EOQ model for items with Weibull distribution deterioration,
- Jaggi, Mittal, and Khanna (2013),
- Mittal, Khanna, and Jaggi (2017): Retailer's ordering policy for deteriorating imperfect quality items when demand and price are time-dependent under inflationary conditions and permissible delay in payments,
- Alshanbari, Rashid (2021): Economic order quantity model with Weibull distributed deterioration under a mixed cash and prepayment scheme,

- Yadav, Chand, and Sarkar (2023): Smart production sys- tem with random imperfect process, partial backordering, and deterioration in an inflationary environment,
- Rajawat, Mittal, and Sarkar (2025, March): Inventory optimization for deteriorating products using exponential demand forecasting and machine learning with carbon emission constraints,
- Rajawat, Mittal, and Rana (2025, January): A compara- tive analysis of 3PL logistics for deteriorating products: a CNN approach to demand and carbon emission predic- tion.

Driven by this consideration, this article discusses the inven- tory model used by retailers for Weibull deteriorating, subpar products in inflationary environments where price and demand are time dependent. Product where demand and price fluctuate linearly over time, such as crops (paddy, wheat, potato, onion, ginger, etc), benefit greatly from this model. The model further considers that customer demand is covered by screened non- defective units, since the screening process operates faster than the demand rate. The model is designed to achieve simultaneous maximization of the retailer's expected profit and optimization of the order quantity. A numerical example is used to examine the effects of deterioration, inflation, and the expected number of poor-quality items on order quantity and overall profit.

NOTATIONS

The symbols applied in constructing the model are listed as follows:

$I(t)$	The quantity of stock present at any point in time$t > 0$.
$B(t)$	Instantaneous demand rate at time $t > 0$.
$F_p(t)$	Pricing per unit at time t.
K	Value of money represented by the discount rate.
l	Rate of inflation per unit of time.
N	Net inflation rate, $N = (K - l)$.
C	Price per unit.
C_1	Inventory storage cost per unit per unit time.
C_3	Order placement cost.
T	Duration of a cycle.
B_0	Demand at the initial time.
F_0	Per-unit selling price at the start.
m	Rate of variation of the unit selling price with respect to$t$.
n_1	Demand rate gradient with respect to t.
P_s	Salvage value assigned to each defective item, $P_s < C$.
d	Rate of screening of units.
μ_1	Screening period.
δ	Fraction of faulty units.
$f(\delta)$	Probability density function of δ.
$E_p(\cdot)$	Mean value operator.
$E_p(\delta)$	Average defective fraction, $E_p(\delta) = \int_{\lambda_1}^{\lambda_2} \delta f(\delta) d\delta,\ \lambda_1 \leq \delta \leq \lambda_2$.
$I_1(t)$	Inventory level during $0 \leq t \leq \mu_1$.
$I_2(t)$	Stock level during $0 \leq t \leq \mu_2$.
$I_3(t)$	Inventory quantity during $0 \leq t \leq T$.
$I_{eff}(\mu_1)$	Usable inventory at μ_1 after removing defectives.
$\Pi(T)$	Net present value of total profit.
$E_p[\Pi(T)]$	Expected present value of total profit.
$Z(t)$	$\alpha\beta t^{\beta-1}$, instantaneous deterioration rate for Weibull distribution with parameters $\alpha > 0$, $\beta > 0$.

MATHEMATICAL MODEL

For this study, B(t) is modeled as a function of time, staying constant until t = µ1, after which it grows linearly with time. In crops (such as paddy, wheat, potatoes, onions, ginger, etc.), this kind of demand pattern is frequently observed. Since the businesspeople initially stock the commodities in warehouses or cold stores, the market's demand for them stays steady for a certain amount of time (0,µ1). Following that specific time frame (0,µ1), the market's demand naturally rises since all consumers must buy their necessities because of the harvested item's decline. The pricing of these goods has a similar behavior. Fp(t) rises over time because the selling price rises in response to the demand rate. As a result, we define B(t) and Fp(t) as follows:

$$B(t) = B_0 + n_1(t - \mu_2)G(t - \mu_2) \quad (1)$$

$$F_p(t) = F_0 + m(t - \mu_2)G(t - \mu_2) \quad (2)$$

where

$$G(t) = \begin{cases} 1, & t \geq \mu_2 \\ 0, & t < \mu_2 \end{cases} \quad (3)$$

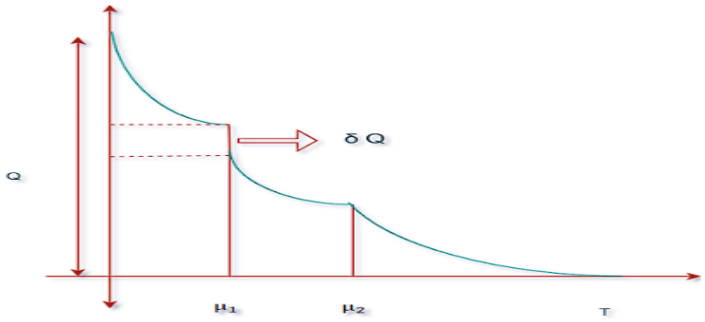


Fig. 1. The predicted total profit function is concave.

Initially, Q goods are purchased. It is assumed that some defective goods may be present in every lot. With the probability density function $f(\delta)$, computable from past data, let δ be the proportion of defective items. From 0 to μ_1, all units are subjected to screening at a per-unit time rate, presumed to exceed the demand rate $B(t)$. Demand arises concurrently with the screening process and is satisfied by the high-quality merchandise.

Upon completion of inspection at time μ_1, all defective units are offered for sale in bulk at a reduced price. At $t = \mu_1$, the effective inventory falls to $I_{\text{eff}}(\mu_1)$. The demand remains constant until μ_2, after which it increases linearly with time. Moreover, Fig. 1 shows that the inventory level diminishes to zero by time T, primarily influenced by demand and partially by deterioration.

Now, the screened lot must exceed the demand during μ_1 to prevent shortages during the screening period:

$$(1 - E_p[\delta])Q \geq B_0\mu_1 \quad \Rightarrow \quad E_p(\delta) \leq 1 - \frac{B_0}{d} \quad (4)$$

where δ is a uniformly distributed random variable with values between d_1 and d_2, and its expected value is $E_p(\delta)$. The time spent on screening is

$$\mu_1 = \frac{Q}{d} \quad (5)$$

ASSUMPTIONS

The model is constructed considering the following assumptions:

- **Deterioration rate depends on time**
- **Demand rate varies with time.**
- **The per-unit selling price changes as time progresses.**
- **There is no lead time.**
- **Stockouts are prohibited.**
- **The analysis accounts for inflation as well as the time value of money.**

Let $I_1(t)$ represent the inventory level at any given time t, where $0 \leq t \leq \mu_1$. The differential equation describing the instantaneous behaviour of $I_1(t)$ in the interval $(0, \mu_1)$ is given by

$$\frac{dI_1(t)}{dt} + Z(t)I_1(t) = -B_0, \quad 0 \leq t \leq \mu_1 \tag{6}$$

At $t = 0$, under the boundary condition, $I_1(0) = Q$, where $Z(t) = \alpha\beta t^{\beta-1}$.

This represents a first-order linear differential equation, and its integrating factor is

$$\exp\left[\alpha\beta \int t^{\beta-1} dt\right] = \exp\left[\alpha t^{\beta}\right].$$

Multiplying both sides of (6) by $\exp[\alpha t^{\beta}]$ gives

$$\left(\frac{dI_1(t)}{dt} + \alpha\beta t^{\beta-1} I_1(t)\right) \exp[\alpha t^{\beta}] = -B_0 \exp[\alpha t^{\beta}].$$

Assuming the boundary condition $I_1(0) = Q$, the solution is

$$I_1(t) = -B_0 \left[\sum_{n=0}^{\infty} \frac{\alpha^n t^{\langle n\beta+1\rangle}}{(n\beta+1)n!}\right] \exp[-\alpha t^{\beta}] + Q \exp[-\alpha t^{\beta}] \tag{7}$$

The inventory level at time μ_1, including the defective items, is

$$I_1(\mu_1) = -B_0 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_1^{(n\beta+1)}}{(n\beta+1)n!}\right] \exp[-\alpha\mu_1^{\beta}] + Q \exp[-\alpha\mu_1^{\beta}] \tag{8}$$

After screening, δQ faulty units remain at time μ_1; therefore, the effective inventory level is

$$I_{\text{eff}}(\mu_1) = -B_0 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_1^{\{n\beta+1\}}}{(n\beta+1)n!}\right] \exp[-\alpha\mu_1^{\beta}] + Q \exp[-\alpha\mu_1^{\beta}] - \delta Q \tag{9}$$

Once more, the inventory level at any given moment (μ_1, μ_2) is provided by

$$\frac{dI_2(t)}{dt} + Z(t)I_2(t) = -B_0, \quad \mu_1 \leq t \leq \mu_2 \tag{10}$$

with the boundary condition $I_2(\mu_1) = I_{\text{eff}}(\mu_1)$. Its solution is

$$I_2(t) = -B_0 \left[\sum_{n=0}^{\infty} \frac{\alpha^n t^{\langle n\beta+1\rangle}}{(n\beta+1)n!}\right] \exp[-\alpha t^{\beta}] + Q \exp[-\alpha t^{\beta}] - \delta Q \exp\left[\alpha(\mu_1^{\beta} - t^{\beta})\right] \tag{11}$$

Additionally, during (μ_2, T), the inventory level is

$$\frac{dI_3(t)}{dt} + Z(t)I_3(t) = -B_0 + n_1(t - \mu_2\rangle, \quad \mu_2 \leq t \leq T \tag{12}$$

with boundary condition $I_3(\mu_2) = I_2(\mu_2)$. Its solution is

$$\begin{aligned} I_3(t) = {} & (B_0 - n_1\mu_2) \left[\sum_{n=0}^{\infty} \frac{\alpha^n t^{(n\beta+1)}}{(n\beta+1)n!}\right] \exp[-\alpha t^{\beta}] \\ & - n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n t^{(n\beta+2)}}{(n\beta+2)n!}\right] \exp[-\alpha t^{\beta}] \\ & + Q \exp[-\alpha t^{\beta}](1 - \delta \exp[-\alpha\mu_1^{\beta}]) \\ & - n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_2^{(n\beta+2)}}{(n\beta+2)n!}\right] \exp[-\alpha t^{\beta}] \end{aligned} \tag{13}$$

Since $I_3(T) = 0$, the order quantity Q is obtained as

$$\begin{aligned} Q = {} & (1 - \delta \exp[\alpha\mu_2^{\beta}]) \Bigg\{ (B_0 - n_1\mu_2) \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{\langle n\beta+1\rangle}}{(n\beta+1)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{(n\beta+2)}}{(n\beta+2)n!}\right] + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_2^{(n\beta+2)}}{(n\beta+2)n!}\right] \Bigg\} \end{aligned} \tag{14}$$

Since $Q = d\mu_1$, we obtain

$$\begin{aligned} \mu_1(1 - \delta \exp[\alpha\mu_2^{\beta}]) = \frac{1}{d} \Bigg\{ & (B_0 - n_1\mu_2) \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{\{n\beta+1\rangle}}{(n\beta+1)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{(n\beta+2)}}{(n\beta+2)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_2^{\{n\beta+2\rangle}}{(n\beta+2)n!}\right] \Bigg\} \end{aligned} \tag{15}$$

Neglecting second and higher order terms of $\alpha\mu_2^{\beta}$ (assuming $\alpha\mu_2^{\beta} < 1$), the Taylor expansion yields

$$\begin{aligned} \mu_1[1 - \delta - \delta\alpha\mu_2^{\beta}] = \frac{1}{d} \Bigg\{ & (B_0 - n_1\mu_2) \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{(n\beta+1)}}{(n\beta+1)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{(n\beta+2)}}{(n\beta+2)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_2^{(n\beta+2)}}{(n\beta+2)n!}\right] \Bigg\} \end{aligned} \tag{16}$$

Since $\delta \in [0, 0.1]$, the term $\alpha\mu_2^{\beta}$ is negligible. Thus,

$$\begin{aligned} \mu_1 = \frac{1}{d(1-\delta)} \Bigg\{ & (B_0 - n_1\mu_2) \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{\langle n\beta+1\rangle}}{(n\beta+1)n!}\right] \\ & + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n T^{\langle n\beta+2\rangle}}{(n\beta+2)n!}\right] + n_1 \left[\sum_{n=0}^{\infty} \frac{\alpha^n \mu_2^{(n\beta+2)}}{(n\beta+2)n!}\right] \Bigg\} \end{aligned} \tag{17}$$

For one cycle, the retailer's profit is given by

$$\pi(T) = \text{Sales Revenue} - \text{Ordering Cost} - \text{Purchasing Cost} - \text{Screening Cost} - \text{Holding Cost} \tag{18}$$

Moreover, under inflationary conditions, the present value of sales revenue is given by

$$\begin{aligned}\text{Revenue} =& P_s \delta Q e^{-N\mu_1} + \int_0^{\mu_2} F_0 B_0 e^{-Nt}\, dt \\ &+ \int_{\mu_2}^{T} \{B_0 + n_1(t-\mu_2)\}\{F_0 + m(t-\mu_2)\} e^{-Nt}\, dt\end{aligned} \tag{19}$$

Evaluating the above integrals, we obtain

$$\begin{aligned}\text{Revenue} =& P_s \delta Q e^{-N\mu_1} + F_0 B_0 \left(\frac{1-e^{-NT}}{N}\right) \\ &+ (B_0 m + F_0 n_1)\frac{e^{-N\mu_2} - e^{-NT}}{N^2} \\ &- (T-\mu_2)\frac{e^{-NT}}{N} + m n_1 \frac{(T-\mu_2)^2 e^{-NT}}{N^2} \\ &+ \frac{2e^{-NT} - 2e^{-N\mu_2}}{N^3}\end{aligned} \tag{20}$$

The current ordering cost is simply

$$\text{Ordering Cost} = C_3 \tag{21}$$

(The ordering cost is unaffected by inflation because the order is placed at $t = 0$.)

The current purchase cost is

$$\text{Purchase Cost} = CQ \tag{22}$$

The current screening cost is

$$\text{Screening Cost} = hQe^{-N\mu_1} \tag{23}$$

The holding cost associated with the present replenishment cycle is

$$\begin{aligned}\text{Holding Cost} = C_1 \Bigg[&\int_0^{\mu_1} I_1(t) e^{-Nt}\, dt + \int_{\mu_1}^{\mu_2} I_2(t) e^{-Nt}\, dt \\ &+ \int_{\mu_2}^{T} I_3(t) e^{-Nt}\, dt \Bigg]\end{aligned} \tag{24}$$

Substituting (19)–(23) into (18) gives the present value of the total profit $\Pi(T)$:

$$\begin{aligned}\Pi(T) =& F_0 B_0 \left(\frac{1-e^{-NT}}{N}\right) \\ &+ (B_0 m + F_0 n_1)\frac{e^{-N\mu_2} - e^{-NT}}{N^2} \\ &- (T-\mu_2)\frac{e^{-NT}}{N} + m n_1 \frac{(T-\mu_2)^2 e^{-NT}}{N^2} \\ &+ \frac{2e^{-NT} - 2e^{-N\mu_2}}{N^3} + P_s \delta Q e^{-N\mu_1} \\ &- C_3 - CQ - hQe^{-N\mu_1} \\ &- C_1 \Bigg[\int_0^{\mu_1} I_1(t) e^{-Nt}\, dt + \int_{\mu_1}^{\mu_2} I_2(t) e^{-Nt}\, dt \\ &+ \int_{\mu_2}^{T} I_3(t) e^{-Nt}\, dt \Bigg]\end{aligned} \tag{25}$$

Since δ follows the probability density function $f(\delta)$, the expected present value of profit is

$$\begin{aligned}E_p[\Pi(T)] =& F_0 B_0 \left(\frac{1-e^{-NT}}{N}\right) \\ &+ (B_0 m + F_0 n_1)\frac{e^{-N\mu_2} - e^{-NT}}{N^2} \\ &- (T-\mu_2)\frac{e^{-NT}}{N} + m n_1 \frac{(T-\mu_2)^2 e^{-NT}}{N^2} \\ &+ \frac{2e^{-NT} - 2e^{-N\mu_2}}{N^3} \\ &+ P_s E_p[\delta] Q e^{-N\mu_1} \\ &- C_3 - CQ - hQe^{-N\mu_1} \\ &- C_1 \int_0^{\mu_1} I_1(t) e^{-Nt}\, dt - C_1 \int_{\mu_1}^{\mu_2} I_2(t) e^{-Nt}\, dt \\ &- C_1 \int_{\mu_2}^{T} I_3(t) e^{-Nt}\, dt\end{aligned} \tag{26}$$

where

$$N = k - l$$

V. Solution Procedure

To achieve the maximum of the expected total profit $E_p[\Pi(T)]$, the optimal cycle time $T = T^*$ must be identified, and the following conditions must be met:

$$\frac{d}{dT}E_p[\Pi(T)] = 0 \tag{27}$$

$$\frac{d^2}{dT^2}E_p[\Pi(T)] < 0 \tag{28}$$

We have,

$$\begin{aligned}\frac{d}{dT}E_p[\Pi(T)] = {} & F_0B_0\left(\frac{1-e^{-NT}}{N}\right) \\ & + (B_0m + F_0n_1)\frac{e^{-N\mu_2} - e^{-NT}}{N^2} \\ & - (T-\mu_2)\frac{e^{-NT}}{N} + mn_1\frac{(T-\mu_2)^2e^{-NT}}{N^2} \\ & + \frac{2e^{-NT} - 2e^{-N\mu_2}}{N^3} + P_sE_p[\delta]Qe^{-N\mu_1} \\ & - C_3 - CQ - hQe^{-N\mu_1} \\ & - C_1\left[\int_0^{\mu_1} I_1(t)e^{-Nt}\,dt + \int_{\mu_1}^{\mu_2} I_2(t)e^{-Nt}\,dt \right. \\ & \left. + \int_{\mu_2}^{T} I_3(t)e^{-Nt}\,dt\right] = 0 \end{aligned} \tag{29}$$

Through the solution of (26), the optimal value T^* can be determined.

Concavity of the expected total profit function is ensured only if the following condition is fulfilled:

$$\frac{d^2}{dT^2}E_p[\Pi(T)] < 0 \tag{30}$$

The mathematical proof of concavity for $E_p[\Pi(T)]$ is difficult due to the complexity of its second derivative. Therefore, a graphical representation of the concavity of $E_p[\Pi(T)]$ is used (see Fig. 2).

VI. Numerical Example

The data listed below has been used to validate the model:

$C_3 = 230$ /cycle, $B_0 = 4000$ units/year, $F_0 = \$35$, $C = \$15$, $m = 0.22$, $n_1 = 3.5$, $k = 0.12$, $l = 0.06$, $N = 0.08$, $C_1 = \$10$ $P_s = \$12$, $\mu_2 = 1.2$, $\lambda_1 = 0$, $\lambda_2 = 0.8$, $E[\delta] = 0.04$, $h = 0.35$ /unit, $d = 12{,}000$ units/year, $\alpha = 0.002$, $\beta = 1.5$.

To make sure there are no shortages during the screening process, we first verify the condition provided by Equation (4) for the given data:

$$E[\delta] \le 0.983$$

Because Equation (27), which yields $T^* = 1.4$ years, may be solved to determine the ideal value of T.

When we substitute T^* into Equations (18), (15), and (26), we obtain:

$$\text{Sales Revenue} = \$186{,}094.33$$

$$\text{Holding Cost} = \$17{,}417.02$$

$$\text{Purchase Cost} = \$84{,}959.44$$

$$\text{Screening Cost} = \$1{,}975.26$$

$$\mu_1^* = 0.4721 \text{ years}, \quad Q^* = 5663.96 \text{ units}$$

$$E_p[\Pi(T^*)] = \$81{,}512.61$$

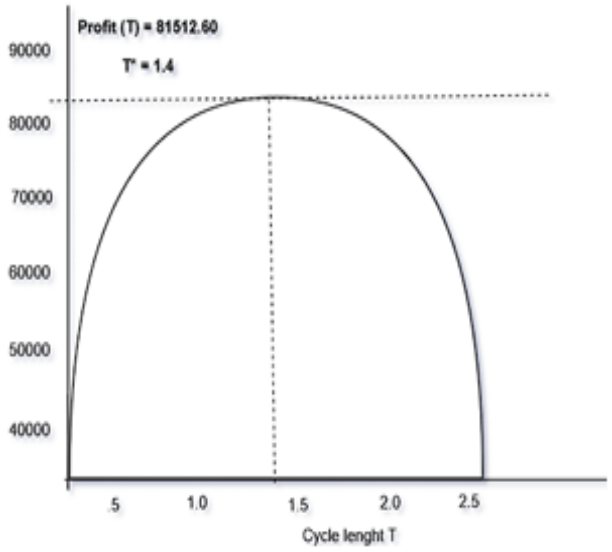


Fig. 2. The predicted total profit function is concave.

CONCLUSION

This article develops inventory models for imperfect-quality items with time-dependent selling price and demand, con- sidering the push-and-pull effects of inflation and Weibull deterioration. All units are inspected, and it is expected that the screening rate exceeds the demand rate. Its significance increases when objects are naturally degrading. Additionally, it has been noted that, particularly in inflationary environments, the price and demand for some consumer goods—such as wheat, paddy, etc.—increase linearly with time. When devel- oping an inventory replenishment strategy for these products, it is vital to consider both inflation and the time value of money. Consumable items and other products that are likely to have these qualities can benefit greatly from the suggested model in the retail sector.

The results have ultimately been verified through a nu- merical case study. The results unmistakably provide retailers with crucial managerial insights for choosing the best ordering strategy in a variety of scenarios, including: (a) The presence of more defective units in the ordered lot should encourage the retailer to exercise greater caution when ordering. (b) Placing more frequent orders for items that are deteriorating rapidly; and (c) Placing large orders in an extremely inflationary market to boost profits.\

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"BEHAVIOURAL INSIGHTS IN GREENING DECISIONS UNDER COBB DOUGLAS DEMAND: EXPLORING OVERCONFIDENCE IN CENTRALIZED AND DECENTRALIZED SUPPLY CHAINS"

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Abstract. This study explores how a manufacturer's overconfidence can shape decision-making strategies and overall performance in green supply chains, especially in the context of growing global demand for sustainable practices. Departing from the traditional assumption of rational behaviour, it introduces behavioural bias into supply chain modeling to understand how inflated perceptions of greening investment efficiency influence outcomes. Demand is sensitive to both greening and price, captured through a Cobb–Douglas-type differential demand function. The research seeks to bridge behavioural operations management with sustainability-focused supply chain design. The paper employs a Stackelberg game-theoretic framework where the retailer acts as the leader, setting the retail price, and the manufacturer acts as the follower, choosing the greening effort and wholesale price. The model is categorized under two structures centralized and decentralized decision-making structures. Overconfidence is mathematically modeled as an upward bias in the manufacturer's perception of greening return. Analytical expressions for equilibrium decisions and profits are derived, comparing outcomes under both rational and overconfident scenarios. The analysis reveals that overconfidence does not change the optimal decision values. However, it increases profit for both the manufacturer and retailer and the market demand. This counterintuitive result emerges because the overconfident manufacturer invests more in greening, which enhances perceived sustainability and thus attracts more consumers. The model shows that behavioural bias—often considered a liability—can, under certain conditions, improve overall supply chain performance.

Implication of Study: The findings provide novel managerial and theoretical insights. From a behavioural operations perspective, the results show that mild overconfidence can be beneficial, leading to higher profits and sustainability without requiring changes to contract structures. It highlights the value of integrating behavioural traits into green supply chain models, especially when designing incentive- compatible contracts.

This contributes to the

developing field of behavioural green supply chain management, offering a foundation for future research that blends cognitive bias, sustainability, and decentralized decision-making under uncertainty.

Keyword: Green Supply Chain, Overconfidence, Differential Demand, Cobb-Douglas Demand, Stackelberg Game

INTRODUCTION

In the last few years, the design of sustainable and environmentally responsible operations has become a core concern in green supply chain management, providing growth to the concept of green supply chains. Day by day the green supply chain is a rapidly growing topic in both academia and industry (Ma et al., 2024; Fahimnia et al., 2015; Ghosh and Shah, 2012). Green supply chains have been widely studied as mechanisms to integrate environmental concerns into traditional supply chain operations, particularly through greening investments and eco- friendly practices (Li & Shan, 2023; Srivastava et al., 2022). A green supply chain integrates environmental considerations—such as greening investments, carbon reduction, and eco-friendly practices—into traditional logistics and production decisions.

Overconfidence is a belief that a decision-maker's knowledge is more valuable or precious than reality (Camerer & Lovallo, 1999; Fahimnia, Pournader, Siemsen, Bendoly, & Wang, 2019; Li, 2019), While classical models assume rational decision-making, growing evidence suggests that behavioural factors, especially overconfidence, play a significant role in shaping managerial choices. Overconfidence may cause decision makers to systematically overestimate the benefits of greening efforts, thereby influencing both prices and investment levels in unexpected ways. Beyond fairness concern, overconfidence is another commonly explored form of irrational behaviour. Psychological studies have shown that individuals often show excessive overconfident in real world economic (Moore & Healy, 2008). So, in this context, overconfidence is a belief that a decision-maker's knowledge is more valuable or precious than reality (Liu, Shen, & Wang, 2018).

To better reflect the complexity of demand in such contexts, many studies have employed differential demand structures, which allow demand to be jointly influenced by prices, greening levels, and other market signals. Among these approaches, the Cobb–Douglas demand model provides a particularly flexible and analytically. Such demand functions is widely applied in the economics, operations management, and marketing literature (Ma et al.,2013; Moon et al.,2018; Wang et al.,2013). By capturing both price sensitivity and greening responsiveness in multiplicative form, it provides a useful tool to analze how overconfident perceptions of greening efforts reshape demand outcomes and, consequently, profitability across the supply chain.

Decision- making structures play a crucial role in supply chain outcomes. In centralized supply chains, the manufacturer and retailer cooperate to maximize total profit of the system, on the other hand in decentralized supply chains, each party pursues individual optimization, often leading to inefficiencies. To bridge these contrasting setups, game-theoretic models such as the Stackelberg game are widely applied (Cachon, 2003). In this hierarchical framework, one party (often the retailer) assumes a leadership role by

setting retail prices, while the manufacturer responds with decisions on wholesale pricing and greening investment. The presence of overconfidence in such Stackelberg interactions creates new dynamics that affect equilibrium outcomes in both centralized and decentralized contexts.

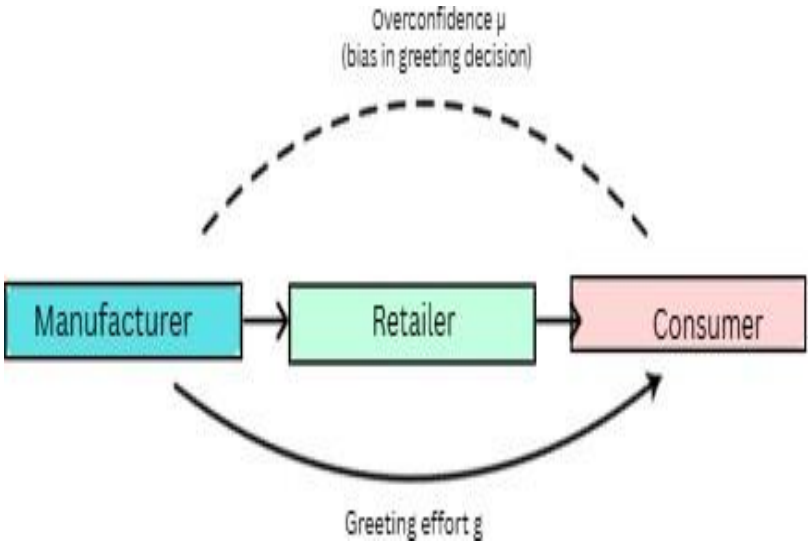
This paper investigates how behavioral biases— specifically overconfidence— interact with Cobb– Douglas differential demand structures in green supply chains, comparing results under centralized and decentralized decision frameworks. By embedding these considerations within a Stackelberg game setting, the study seeks to uncover novel insights into how cognitive biases influence optimal strategies, market demand, and profitability. The findings contribute to both theory and practice by extending the literature on behavioral operations and offering guidance for sustainable supply chain contract design in uncertain and behaviorally influenced environments.

Most existing research assumes fully rational firms. In reality, firms often display behavioral biases, especially overconfidence in the returns from greening investments. This study aims to find the answers to the following research questions:

- What are the comparative effects of centralized and decentralized decision- making on profits, demand, and greening effort under overconfidence?
- Can overconfidence mitigate the inefficiencies of decentralized structures?
- How does manufacturer overconfidence regarding greening returns affect optimal price, wholesale price, and greening effort in a supply chain governed by Cobb– Douglas demand?

None of researchers have worked on a Cobb Douglas demand with overconfidence in greening and Stackelberg game approaches to understand their impact on pricing, greening decisions, demand and overall supply chain performance using centralized and decentralized approaches. This paper consists of section 1, the introduction and literature review. Section 2 consists of notations and assumptions. Section 3 consists of mathematical formulation, centralized and decentralized model. section4 consists of numerical and sensitivity analysis. Section 5 consists of the conclusion.

Figure1 Green supply chain



Notations And Assumptions

Following are the assumptions and notation given below in Table 1.

Table 1. The following are the symbols/notations

p: Retailer price per unit
g: Greening cost per unit
w: Wholesale price per unit
c: Unit production cost
a: Elasticity of price, $a > 1$
b: Elasticity of greening cost, $0 < b < 1$
k: Demand scaling constant
μ: Overconfidence factor of greening, $\mu \geq 0$
$D(p, g)$: Demand function
$D^*(p, g)$: Demand with overconfidence factor
TP_C : Centralized profit ($)
TP_R : Retailer's profit ($)
TP_M: Manufacture's profit ($)
TP: Total Profit ($)
$TP_M{}^*$: Profit of the manufacturer with overconfidence factor
$TP_R{}^*$: Retailer's profit with overconfidence

Notations

Following is the notations

Assumptions

In the formation of the mathematical model, following assumptions are considered

- There is one manufacturer and one retailer in this supply chain model.
- Demand depends on price and the greenness of the product.
- No lead time and no shortages.

Mathematical Model Development

To analyze the sustainable supply chain with the effects of overconfidence, we use a game-theoretic modelling approach. In this supply chain modal, demand is influenced by both the retail price and the level of greening effort with a single manufacturer and a single retailer. Demand is represented by a Cobb–Douglas functional form: $D(p,g) = kp{-}agb$ (Ghoshel.al., 2024) (1) where g is the greening effort,p denotes the retail price, $k > 0$ captures the market potential, $b > 0$ represents the elasticity of demand with respect to greening, and $a > 0$ represents the price elasticity of demand. Within the sustainable supply chains framework, the upstream manufacturer may inaccurately assess its greening cost by overestimating it, thereby misjudging value and giving wrong results. The higher the value of μ, $\mu \geq 0$ the higher the overestimation degree of the manufacturer's efforts. Also, when $\mu = 0$,showing a fully rational and unbiased behavior.

$D^{*}(p, g) = kp^{-a}((1 + \mu)g)^{b}$

Methodology

We begin by developing a centralized benchmark model in which the manufacturer and retailer cooperate to maximize the total profit of the supply chain, jointly determining the retail price and greening level. We develop decentralized models under a Stackelberg framework, in which the retailer takes the role of leader by determining the retail price, while the manufacturer, as the follower, chooses the wholesale price and level of green investment. To capture behavioral distortions, we incorporate an overconfidence parameter μ, $\mu \geq 0$, representing the extent to which the manufacturer overestimates the effectiveness of its greening effort. Equilibrium solutions are derived through backward induction, yielding the optimal price, wholesale price, and greening effort under both rational and biased settings. Finally, we conduct sensitivity and comparative statics with respect to the key parameters a, b, c, μ allowing us to assess when overconfidence mitigates inefficiencies such as double marginalization.

Mathematical Formulation of Model

Centralized Modal

To develop a centralized benchmark model in which the manufacturer and retailer cooperate to maximize the total channel profit, jointly determining the retail price and greening level.

$TP_C = (p - c - g)kp^{-a}g^b$ (2)

$\frac{\partial TP_C}{\partial p} = kp^{-a}g^b + (p - c - g)k(-a)p^{-a-1}g^b$ (3)

$\frac{\partial TP_C}{\partial g} = (-1)kp^{-a}g^b + (p - c - g)kbp^{-a}g^{b-1}$ (4)

Putting $\frac{\partial TP_C}{\partial p} = 0$, $\frac{\partial TP_C}{\partial g} = 0$ to get optimal values from equation (3) and (4)

$\frac{\partial TP_C}{\partial g} = -kp^{-a}g^b + (p - c - g)kbp^{-a}g^{b-1} = 0$

$\frac{\partial TP_C}{\partial p} = kp^{-a}g^b + (p - c - g)k(-a)p^{-a-1}g^b = 0$

$p = \frac{a(c+g)}{a-1}, g = \frac{b(p-c)}{b+1}$ solving both to get the optimal value of p and g

$p^* = \frac{ac(A+b)}{(a-1)A}, g^* = \frac{bc}{A}$ where $A = a - b - 1$

Centralized profit with overconfidence Factor

This is a centralized model an overconfidence factor μ in greening in which the manufacturer and retailer cooperate to maximize the total channel profit, jointly determining the retail price and greening level.

$TP_C{}^* = (p - c - g)kp^{-a}(1 + \mu)^b g^b$ (5)

As $(1 + \mu)^b$ is a constant so it does not affect the optimal values so all the optimal values are same as above $p^* = \frac{ac(A+b)}{(a-1)A}, g^* = \frac{bc}{(a-b-1)}$

Decentralized Model

To construct decentralized models usin Stackelberg framework, where the retailer acts a leader by setting the retail price, and manufacturer, as the follower, decides the whol price and greening effort.

$TP_R = (p - w)(kp^{-a}g^b)$ (

$TP_M = (w - c - g)kp^{-a}g^b$ (

Differentiate equation (6) with respect to p

$\frac{\partial TP_R}{\partial p} = kp^{-a}g^b + (p - w)k(-a)p^{-a-1}g^b$ (

Putting $\frac{\partial TP_R}{\partial p}$ =0 so from equation (8)

$\frac{\partial TP_R}{\partial p} = kp^{-a}g^b + (p - w)k(-a)p^{-a-1}g^b =$ (

$p^* = \frac{aw}{(a-1)}$ (9)

Putting the value of p in equation (7)

$TP_M = (w - c - g)k(\frac{aw}{(a-1)})^{-a}g^b$ (10)

Now differentiate equation (10) w.r.t. g and w

$\frac{\partial TP_M}{\partial g} = k(\frac{aw}{(a-1)})^{-a}[-g^b + (w - c - g)bg^{b-1}$ (11)

$\frac{\partial TP_M}{\partial w} = kg^b \left(\frac{a}{(a-1)}\right)^{-a}[(w - c - g)(-a)w^{-a-1} + w^{-a}]$ (12)

Putting $\frac{\partial TP_M}{\partial g} = 0$, $\frac{\partial TP_M}{\partial w} = 0$ so from equations and (12)

$g^{b-1}k(\frac{aw}{(a-1)})^{-a}[-g + (w - c - g)b] = 0$

$w^{-a-1}kg^b \left(\frac{a}{(a-1)}\right)^{-a}[-a(w - c - g) + w] =$

Implies that $g = \frac{(w-c)b}{(1+b)}, w = \frac{a(c+g)}{(a-1)}$

$g = \frac{(w-c)b}{(1+b)}, w = \frac{a(c+g)}{(a-1)}$ on solving both to g optimal values of g and w

$w^* = \frac{ac}{(a-b-1)}, g^* = \frac{cb}{(a-b-1)}$

Now putting the values of w^* and g^* in equatic

$p^* = \frac{aw}{(a-1)} = \frac{a}{(a-1)}[\frac{ac}{(a-b-1)}]$

Decentralized Model with Overconfidence

To capture behavioral distortions, we incorporate an overconfidence parameter μ, representing the extent to which the manufacturer overestimates the effectiveness of its greening effort. Where the retailer acts as the leader by setting the retail price, and the manufacturer, as the follower, decides the wholesale price and greening effort using the Stackelberg framework in this decentralized modal.

$$D^*(p,g) = kp^{-a}((1+\mu)g)^b \quad (13)$$

$$TP_R{}^* = (p-w)(kp^{-a}((1+\mu)g)^b \quad (14)$$

$$TP_M{}^* = (w-c-g)kp^{-a}((1+\mu)g)^b \quad (15)$$

As $(1+\mu)^b$ is a constant so it does not affect the optimal values so all the optimal values are same as above$g^* = \frac{cb}{(a-b-1)}, w^* = \frac{ac}{(a-b-1)}, p^* = \frac{a}{(a-1)}[\frac{ac}{(a-b-1)}]$

Numerical Validation And Concavity

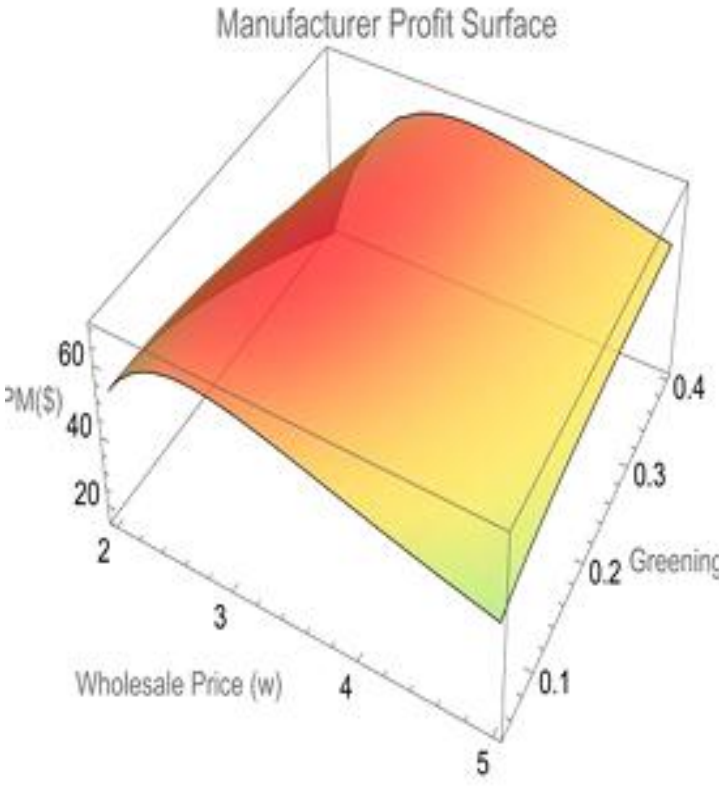


Fig-2. Concavity of manufacturer prof

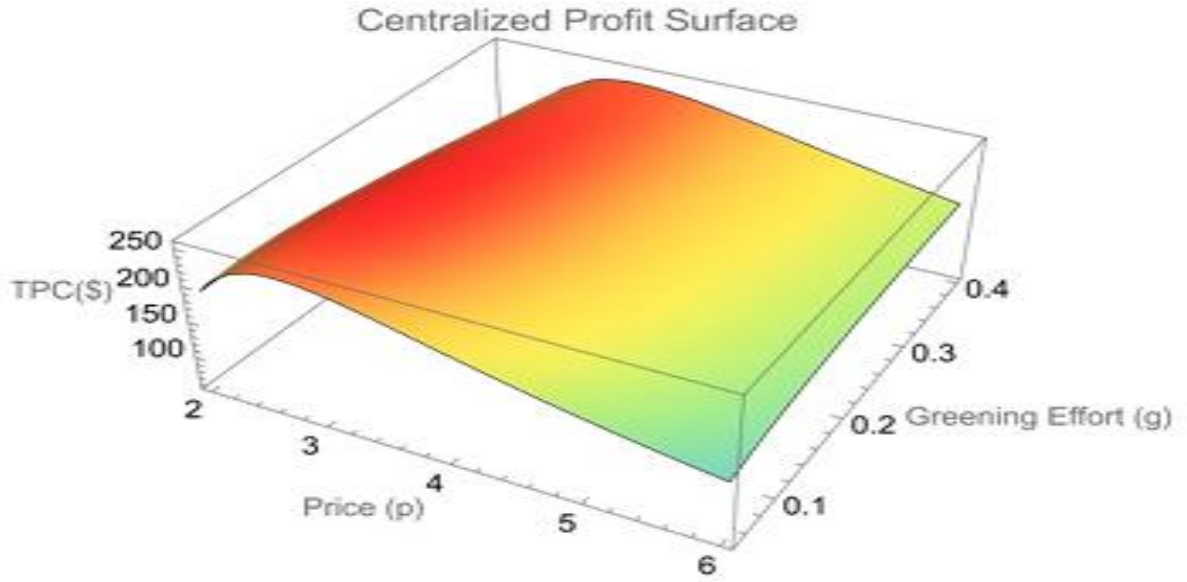


Fig-3. Concavity of centralized profit

Concavity

Figure 2 presents the manufacturer's profit $TP_M\ (w, g)$ surface as a function of wholesale price w and greening effort g, while figure 3 illustrates the centralized profit $TP_C\ (p, g)$ surface in terms of retail price p and greening effort g. In both cases, the surfaces exhibit a clear concave shape with a single peak, confirming that profit functions are strictly concave. This means that there exists a unique optimal combination of decision variables that maximizes profit. The curvature of the plot forms a dome-like shape, which also indicates concavity. The profit reaches its highest value near this point. Overall, both graphs visually confirm the concavity of the respective profit functions with respect to the decision variables.

Numerical Comparison

Validation of model by taking the values from previous literatures and some values taken hypothetically for optimal values and profit functions: $a = 2.4, b = 0.15, c = 1.5, k = 3500, \mu = 0.4$. (Ghosh et al., 2024)

Table 2. Optimal values and profit values

Variables	Centralized model	Centralized model with overconfidence	Decentralized model	Decentralized modal with overconfidence
p	2.88	2.88	4.93	4.93
g	0.18	0.18	0.18	0.18
w			2.88	2.88
D	213.70	224.76	58.82	61.86
$TP_M(\$)$			65.87	69.28
$TP_R(\$)$			125.28	131.77
$TP_C(\$)$	256.44	269.72		
$TP(\$)$			191.16	201.06

Sensitivity Analysis

Following are the graphs of the sensitivity analysis.

Fig-4. Profit with respect to a

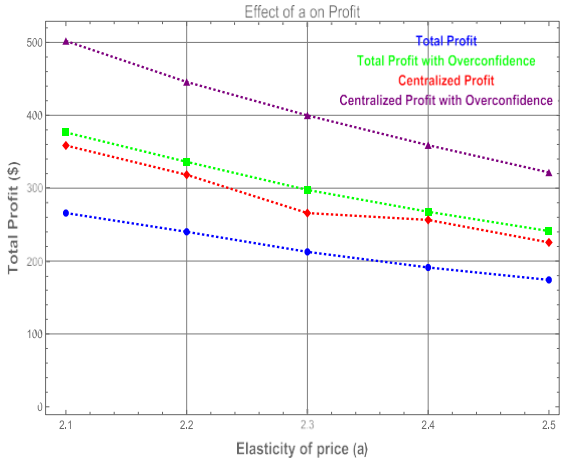


Fig-5. Fig-4. Profit with respect to b

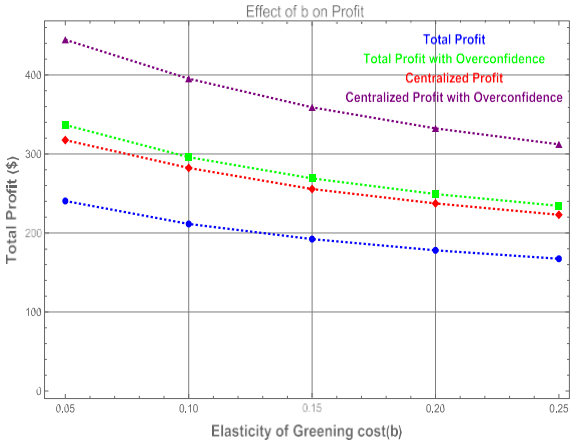


Fig-6. Fig-4. Profit with respect to c

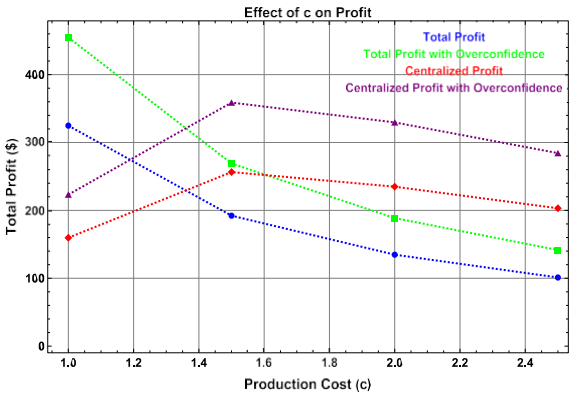


Fig-7. Fig-4. Profit with respect to μ

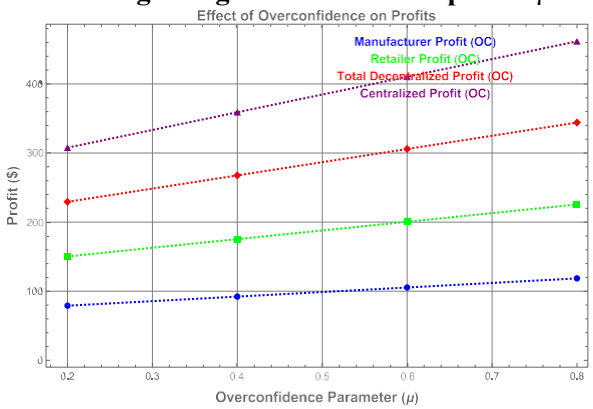


Figure 4 shows that as the elasticity of price , a increases, all profit values decline steadily. This is expected, as a higher a implies greater price sensitivity — meaning the demand drops more sharply with price. Overconfidence significantly improves both total and centralized profits, but the relative decline across all curves suggests that price sensitivity strongly influences profitability regardless of coordination strategy.

Figure 5 shows that as the elasticity of greening cost, b increases, profits decrease across all scenarios. This is because higher b makes sustainability investment less cost-effective, thereby reducing net gains. Overconfidence still leads to noticeably higher profits, especially in centralized settings. The pattern indicates that systems are vulnerable to increasing greening costs unless behavior-driven optimism is leveraged.

Figure 6 reveals a sharper decline in profits with increasing c, particularly for total profit under the standard model. Interestingly, centralized profit with overconfidence maintains a relatively stable trend,

highlighting its resilience. The benefit of overconfidence becomes more pronounced at higher production costs, suggesting it can act as a buffer against cost-induced performance drops.

Figure 7 shows that all profit measures increase with the overconfidence parameter , μ Manufacturer profit rises steadily but at a slower rate, while retailer profit grows more sharply, reflecting the retailer's stronger benefit from overconfidence. As a result, total decentralized profit increases almost linearly, demonstrating that overconfidence can actually enhance overall supply chain performance. Centralized profit exhibits the steepest growth, indicating that coordination amplifies the positive effects of overconfidence. Overall, the results reveal that higher μ improves profits across all

cases, with the greatest gains achieved under centralized decision-making.

CONCLUSION AND FUTURE SCOPE

This study examined how manufacturer overconfidence shapes decision-making and performance in green supply chains under centralized and decentralized structures. The findings provide clear answers to the research questions and highlight several key insights.

First, centralized coordination offers superior alignment between economic and environmental objectives. However, the presence of overconfidence changes this dynamic. Even though the optimal decision variables—such as retail price, wholesale price, or greening effort—remain unchanged, overconfidence increases the perceived effectiveness of greening, which in turn raises demand and profitability. This effect occurs in both coordination structures but is more pronounced in centralized systems due to stronger joint decision-making.

Second, the results indicate that overconfidence, though typically seen as a behavioral bias, can partially offset inefficiencies in decentralized supply chains. While it does not completely resolve coordination problems, it improves financial outcomes for both the manufacturer and the retailer, thereby narrowing the gap between decentralized and centralized performance.

Finally, under the Cobb–Douglas demand framework, overconfidence does not alter the form of the optimal solutions but magnifies their outcomes. The manufacturer's inflated expectations of greening returns lead to stronger market responses, translating into higher realized profits and greater consumer adoption.

Overall, this study provides a counterintuitive insight: psychological biases such as overconfidence, rather than always harming performance, may under certain conditions strengthen both environmental sustainability and business profitability.

From the managerial point of view this study highlights that behavioral traits, such as manufacturer overconfidence, can unexpectedly enhance both sustainability and profitability in supply chains that integrated contracts and joint decision frameworks not only resolve pricing and investment inefficiencies but also amplify the positive effects of behavioral tendencies, enabling companies to align environmental goals with business growth.

Thus, overconfidence encourages stronger greening efforts, which raise consumer demand and improve financial outcomes, even when decision variables like price or investment appear unchanged.

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WI-FI-BASED HUMAN ACTIVITY RECOGNITION USING CSI AND MACHINE LEARNING TECHNIQUES

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1. INTRODUCTION

Human Activity Recognition has become an essential technology for applications in smart homes, healthcare monitoring, and human computer interaction. Traditional approaches rely on vision-based systems or wearable sensors, which often raise privacy concerns and may require user compliance [1]. To overcome these limitations, recent research has turned towards Wi-Fi-based sensing, which leverages the widely available wireless infrastructure to achieve contactless and device-free recognition of human activities [2].

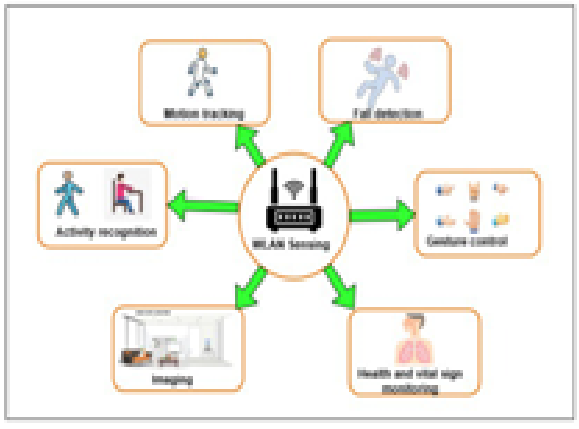


Fig. 1: Basic working representations of a WiFi-Based Human Sensing System

Fig. 1 A key enabler of Wi-Fi based HAR is Channel State Information (CSI), which captures fine grained signal variations induced by human motion in the wireless environment [3]. By analyzing these variations, it is possible to detect and classify activities such as walking, sitting, falling, and even respiration monitoring [4]. For example, Zhang et al. demonstrated the use of commodity Wi-Fi devices for non-intrusive respiration detection, showing the sensitivity of CSI to subtle body movements [4]. Similarly, Wu et al. showed that Wi-Fi can be used to detect both moving and stationary humans in indoor settings [2]. The integration of machine learning techniques has further enhanced HAR performance. Statistical modeling approaches, such as Wi Detect, provided robust motion detection under varying environments [5], while more recent advances have explored deep learning frameworks to extract spatial-temporal features directly from CSI streams [6]. Yang and Jiang proposed selective sharing modules for multitask sensing, demonstrating the adaptability of deep models for complex recognition scenarios [7]. Such progress highlights the growing synergy between wireless signal processing and artificial intelligence. In the study, we train and test the classical machine learning models such as SVM, Random Forest, and KNN and test them against the deep learning ones, a shallow neural network and a Bidirectional Long Short-Term Memory (Bi-LSTM) network. The primary contributions is a CSI-inspired modeling approach applied to the UCI HAR dataset, detailed comparison of classical and deep learning models for activity recognition and an experimental evaluation demonstrating that Bi-LSTM achieves the highest recognition accuracy.

The remainder of this paper includes section 2, which includes a brief study about Wi-Fi signal-based sensing and its applications and future. The next section is section 3, which includes the description of the dataset used and details about CSI signals. In section 4 we have the details about the methodology we have used for analysis and implementation of algorithms. The next section is section 5 with the more details of implementation and results we got after analysis. The

last section 6 we have concluded this paper with discussion on future works.

2. RELATED WORK

The rapid growth of WiFi sensing has enabled non-intrusive HAR, leveraging the ubiquity of wireless networks and the fine-grained information available in CSI. Unlike early approaches relying on Received Signal Strength (RSS) [3], CSI captures multipath propagation details, enabling more accurate recognition of diverse human activities, including both subtle respiration signals [4] and gross body movements [2]. These developments have established WiFi sensing as a promising alternative to vision-based or wearable sensing approaches, particularly in healthcare and smart home contexts. Several surveys and overview studies have mapped the progress of WiFi-based HAR. Hernandez and Bulut [8] discussed signal processing techniques and challenges in real-world edge deployments, while Ahmad et al. [6] reviewed deep learning–driven advances in WiFi sensing, highlighting unresolved challenges such as environment dependence and domain adaptation. Similarly, Ahmed [9] provided a comprehensive survey of device-free gesture recognition using CSI, underscoring its potential as a versatile, low-cost sensing modality. Collectively, these works demonstrate both the maturity and the evolving research challenges of WiFi CSI sensing. Researchers have also explored statistical and model-based approaches. WiDetect [5] introduced a statistical electromagnetic model for robust motion detection under environmental variations, while Taylor et al. [1] developed an intelligent real-time HAR system tailored for healthcare. Song et al. [10] further incorporated AI methods into contactless sensing, demonstrating improved robustness in complex settings. These works show that statistical methods remain relevant, though increasingly complemented by AI techniques.

With the rise of machine learning and deep learning, performance improvements have become evident. Yang and Jiang [7] proposed a multitask WiFi sensing framework using selective-sharing deep modules, whereas Zhu et al. [11] developed a deep learning system to distinguish human and non-human motion. Meng et al. [12] introduced Secur-Fi, a secure CSI-based sensing system on commercial WiFi devices, emphasizing privacy and robustness. Abuhoureyah et al. [13] extended the field with through-wall HAR via deep learning, demonstrating feasibility even in non-line-of-sight scenarios.

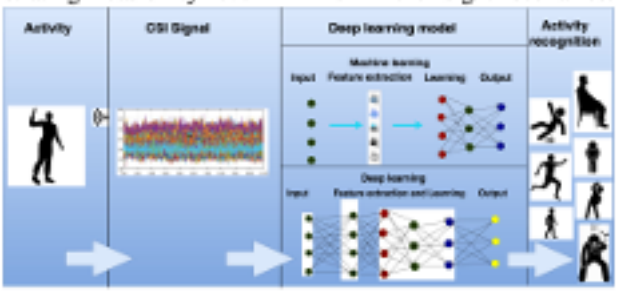


Fig. 2: Conceptual Representation of CSI-Based Activity Recognition

3. DATASET AND CSI SIGNAL OVERVIEW

The primary focus of this work is on WiFi signal–based human activity recognition, where Channel State Information provides a structured collection of wireless signals captured during various human activities [14]. CSI is obtained by leveraging the physical layer information from Wi-Fi signals [8], reflecting how wireless channels are influenced by environmental dynamics such as human motion [3], body orientation, and surrounding obstacles [2]. In this context, Wi-Fi devices operate as transmitters and receivers, while the wireless channel itself becomes a medium for sensing human activities [15]. CSI measurements, represented as complex values containing both amplitude and phase information across multiple subcarriers, provide fine-grained insight into signal variations caused by different activities [8]. However, due to the limited availability of publicly accessible CSI-based HAR datasets, this study employs the UCI HAR dataset as a benchmark for model training and evaluation. Although the UCI HAR dataset is based on wearable sensor data rather than WiFi CSI, it offers a standardized and well-annotated resource, making it an effective proxy for validating proposed approaches while keeping the broader goal of WiFi CSI–based HAR in perspective.

3.1. UCI HAR Dataset

The dataset includes recordings of common activities such as walking, sitting, standing, falling, and other movements, each of which produces distinct variations in the recorded signal patterns [14]. These variations are reflected in the sensor measurements over different axes, making it possible to differentiate between activities through signal analysis [5]. Each data trace is captured over time, resulting in a time-series dataset with multiple dimensions corresponding to sensor axes and placements [8]. Such multi-dimensionality enhances the discriminative power of the dataset, as certain activities influence specific signals more strongly than others [3]. An important characteristic of this dataset is its focus on real-world conditions, where the measurements are subject to variability, interference, and noise. These conditions make the data both challenging and realistic for machine learning applications in HAR [6]. To enable systematic experimentation, the dataset is pre-structured with labeled activity classes, allowing researchers to train and evaluate classification models effectively. The repository also provides preprocessing utilities to extract features from the raw signals, normalize the data, and prepare it for machine learning pipelines [14].

3.2. Reinterpreting UCI HAR as CSI Data

CSI data offers a rich, high-dimensional representation akin to accelerometer data in UCI HAR, but without requiring wearable sensors [1]. The overall pipeline mirrors the UCI HAR structure: activities are labeled, CSI data epochs are

captured, preprocessed, and then fed into a classification algorithm specifically, an LSTM-based deep learning model [6]. This similarity suggests that UCI HAR classification tasks can, in principle, be reinterpreted within a CSI framework, using Wi-Fi signal variations as the functional equivalent of acceleration signals [9]. The repository includes tools for CSI data extraction (sendData/recvCSI), visualization, labeling, and model training, making it possible to replicate or extend CSI experiments similarly to how UCI HAR datasets are used for benchmarking [14]. Additionally, CSI-based frameworks such as Wi-ESP demonstrate the potential of standardized tools for device-free Wi-Fi sensing and reproducible experimentation [16].

4. METHODOLOGY

The proposed methodology leverages motion sensor data to perform HAR, drawing inspiration from the framework described below. The workflow begins with sensor data collection, where accelerometers and gyroscopes embedded in smartphones capture three-axis acceleration and angular velocity signals during different activities. Each sample represents motion dynamics across multiple axes, forming a high-dimensional time-series representation of human movement [14]. Since raw sensor measurements are often noisy and irregular, preprocessing is applied to ensure robustness. This involves steps such as denoising, signal calibration, and normalization of values to minimize device-specific distortions [5].

Following preprocessing, feature extraction is carried out to capture discriminative characteristics of human activities. Both time-domain features (e.g., mean, variance, energy) and frequency-domain features (e.g., spectral entropy, dominant frequencies) can be derived from the sensor signals. In some cases, advanced transformations such as Short-Time Fourier Transform (STFT) or Wavelet Decomposition are applied to preserve temporal and spectral information. The resulting feature vectors provide a compact and informative representation of activity patterns [8].

These feature vectors are then used for model training, where supervised learning algorithms such as Support Vector Machines (SVM), Random Forests, or deep neural networks are applied to learn discriminative mappings between extracted features and activity labels. The dataset is typically split into training and testing sets, and model parameters are optimized using validation techniques. Once trained, the model can classify unseen sensor signals into activity classes with high accuracy, completing the HAR pipeline [3].

4.1. Data Preprocessing

The data processing pipeline involves extracting raw signal measurements, removing noise, computing statistical and frequency-domain features, segmenting the data streams into overlapping windows, applying appropriate transformations, and normalizing the features to prepare them for classification [14]. To ensure consistent feature distributions, we perform the following preprocessing steps: Normalization: Z-score standardization is applied to each feature. Label Encoding: Activity labels are numerically encoded. Sequence Padding: For sequence-based models such as LSTM, sequences are padded to ensure uniform length. Train-Test Split: 80% of the data is used for training and 20% for testing [5].

4.2. Feature Representation

Temporal dynamics are represented in the time-frequency domain using transformations such as STFT and complemented with statistical descriptors (mean, variance, skewness, and higher-order moments) to capture distributional characteristics of the signals. The combination of temporal, spectral, and statistical features produces a discriminative representation that preserves activity-specific signal modulations for effective classification. The original data provide a set of 561 features, including time-domain descriptors (mean, standard deviation, energy) and frequency-domain descriptors (FFT coefficients, spectral entropy). To incorporate temporal dependencies, feature vectors are reshaped into a sequence of shape (time, steps, features), particularly when using sequence-based deep learning models such as Bi-LSTM [11].

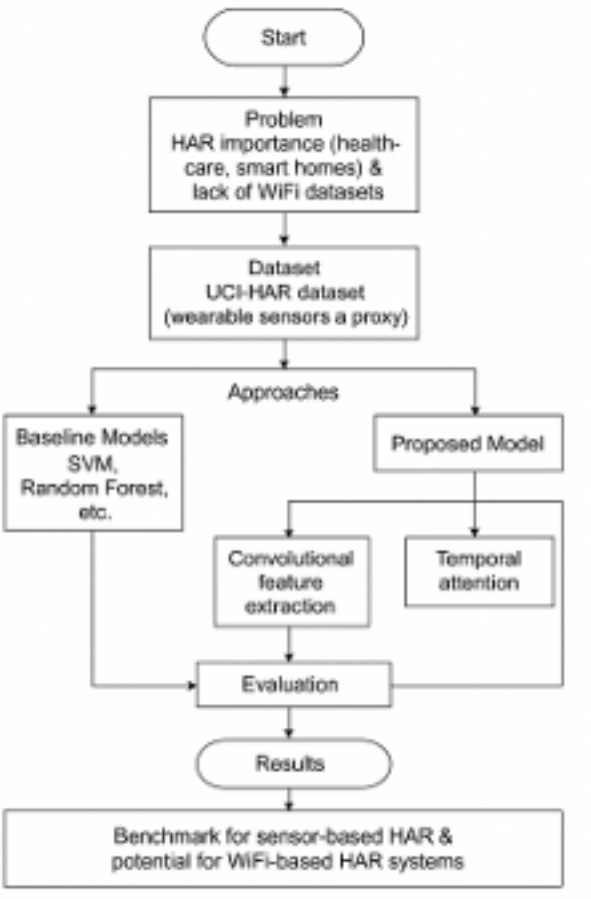


Fig. 3: Process Flow Diagram of Channel State Information-Based Human Sensing

4.3. Classification Models

Classification models are supervised learning algorithms that categorize input data into predefined classes based on patterns learned from labeled datasets [7]. They can handle tasks like binary classification (e.g., spam vs. not spam), multi-class classification (e.g., predicting fruit type), etc. Common models that we are using in our training dataset are Support Vector Machine, Random Forest, K-Nearest Neighbors (KNN), Multilayer Perceptron (MLP) Neural Network, Bi-LSTM. **1) Support Vector Machine (SVM):** SVM is a powerful supervised learning approach that constructs an optimal separating hyperplane in a high-dimensional space, with kernel functions enabling efficient handling of non-linear class boundaries and high-dimensional feature mappings [12].

2) Random Forest: Random Forest operates as an ensemble of decision trees, employing bootstrap aggregation and random feature selection to enhance generalization, mitigate overfitting and achieve strong predictive performance on diverse datasets [13].

3) K-Nearest Neighbors (KNN): The model is simple and interpretable but sensitive to noisy features. KNN a non-parametric and instance-based learning algorithm, assigns class labels by evaluating the majority voting scheme within a specified neighborhood, thereby leveraging local proximity structures in feature space [17].

4) Multilayer Perceptron (MLP) Neural Network: It uses a MLP neural network that comprises several fully connected zones of sequentially shrinking sizes. The architecture consists of three hidden layers comprising 256, 128 and 64 neurons respectively, after which these layers are accompanied by ReLU activation functions. With its Adam optimizer and categorical cross-entropy loss, the training is done on the network. To increase generalization and avoid overfitting, Batch normalization and dropout regularization is used [4].

5) Bi-LSTM: Bidirectional Long Short-Term Memory networks, as an advanced recurrent architecture, incorporate dual directional processing of sequential data, thereby modeling long-range dependencies and contextual cues more effectively than conventional unidirectional RNNs [10]. The table below represents a comparative analysis of commonly used machine learning and deep learning models for human activity recognition using Wi-Fi CSI signals, highlighting their key characteristics, strengths, limitations etc.: -

4.4. Evaluation Metrics

Evaluation metrics are measures used to assess the performance of a model by comparing its predictions with the actual outcomes. For classification tasks, common metrics include accuracy (the proportion of correct predictions) [18], precision (the proportion of correctly predicted positive instances out of all predicted positives) [1], recall (the proportion of correctly predicted positives out of all actual positives) [19], and the F1-score (harmonic mean of precision and recall, useful for imbalanced datasets) [9].

Table 1
Structural & performance-oriented comparison of ML Models

Model	Model Type	Training Time	Accuracy Rance	CSI Suitability
SVM	Classical ML	Medium	75-85%	Moderate
Random Forest	Ensembled (Tree-Based)	Fast	80-90%	Good

Evaluation using these metrics has been widely applied in wireless sensing and HAR frameworks [20].
As shown in Table 1.

Table 2: Structural & performance-oriented comparison of ML Models

Model	Model Type	Training Time	Accuracy Range	CSI Suitability
SVM	Classical ML	Medium	75-85%	Moderate
Random Forest	Ensemble (Tree-Based)	Fast	80-90%	Good
KNN	Instance based	None (Lazy)	70-85%	Moderate
MLP	Feed forward Neural Network	Medium to High	80-90%	Very Good
Enhanced Bi-LSTM	Deep Recurrent Network	High	85-95%	Excellent

5. RESULTS AND DISCUSSION

After applying the dataset on all the described algorithms we got the results in form of accuracy, precision, f1-score and confusion matrix. Below we have the description about the working and parameters used in implementation for each algorithm:

5.1. Results

1) SVM This classifier achieved an overall accuracy of 95.22%, indicating strong performance in distinguishing between the six human activity classes. The UCI-HAR dataset was employed to evaluate the effectiveness of a SVM classifier in multi-class activity recognition [21]. The raw data was preprocessed by imputing missing values with feature-wise means and applying standard normalization to ensure all features contributed equally during training. The classifier was implemented using the Radial Basis Function (RBF)

kernel, expressed as:

$$K(x_i, x_j) = exp(-\gamma||x_i - x_j||^2) \quad (1)$$

which enables the model to map input features into a higher-dimensional space and capture non-linear decision boundaries [22]. The penalty parameter was set to C = 1.0 balancing the trade-off between maximizing the margin and minimizing misclassification errors, while the kernel coefficient was set to γ = scale adapting automatically to the feature space dimensionality. The optimization problem solved by the SVM can be formulated as:

$$min\frac{1}{2}||\omega||^2 + c\sum_{i=0}^{N}\xi_i \quad (2)$$

subject to the soft margin constraints:

$$y_i(\omega^T\phi(x_i) + b) \geq 1 - \xi_i, \xi_i \geq 0 \quad (3)$$

Where $\phi(x_i)$ is the non-linear mapping induced by the kernel and ξ_i are slack variables allowing controlled misclassification. The resulting decision function is given by:

$$f(x) = sign(\sum_{i=1}^{N}\alpha_i y_i K(x_i, x) + b) \quad (4)$$

where α_i are support vector weights and b is the bias term. Model evaluation was conducted using accuracy, precision, F1-score, and confusion matrix analysis, ensuring a comprehensive performance assessment. These results confirm that, with carefully tuned parameters, kernelized SVMs provide robust non-linear decision boundaries well-suited for human activity recognition from CSI data.

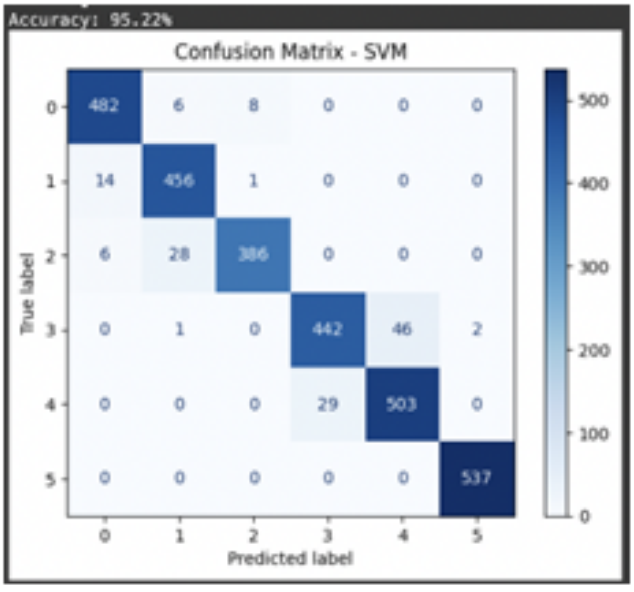


Fig. 4: Accuracy and confusion matrix for support vector machine

2) Random Forest This classifier achieved an accuracy of 92.5%, demonstrating reliable performance across all activity classes. In this approach data preprocessing was performed by imputing missing values with feature-wise means. The Random Forest was implemented with 100 decision trees (n_estimators = 100) and a fixed random state of 42 for reproducibility. A Random Forest constructs an ensemble of decision trees, each trained on a bootstrap sample of the training data with random feature selection at every split, thereby reducing correlation among trees and enhancing generalization. For an input sample x, the final prediction is determined by majority voting across all trees:

$$\hat{y} = mode\{h_t(x), t = 1, 2.....T\} \quad (5)$$

where $h_t(x)$ denotes the output of the t^{th} decision tree and T is the total number of trees. Each decision tree within the ensemble determines its splits based on an impurity measure such as the Gini index, given by:

$$G = 1 - \sum_{k=1}^{K} p_k^2, \quad (6)$$

where p_k is the proportion of samples belonging to class k at a node. Alternatively, splits can be guided by Information Gain (IG), which quantifies the reduction in entropy after a split:

$$I.G.(D, A) = H(D) - \sum_{v \in Values(A)} \frac{|D_v|}{|D|} H(D_v), \quad (7)$$

where H(D) is the entropy of the dataset D, and D_v is the subset of D when attribute A takes value v. The overall predictive power of the Random Forest can also be formalized as the expected reduction in classification error:

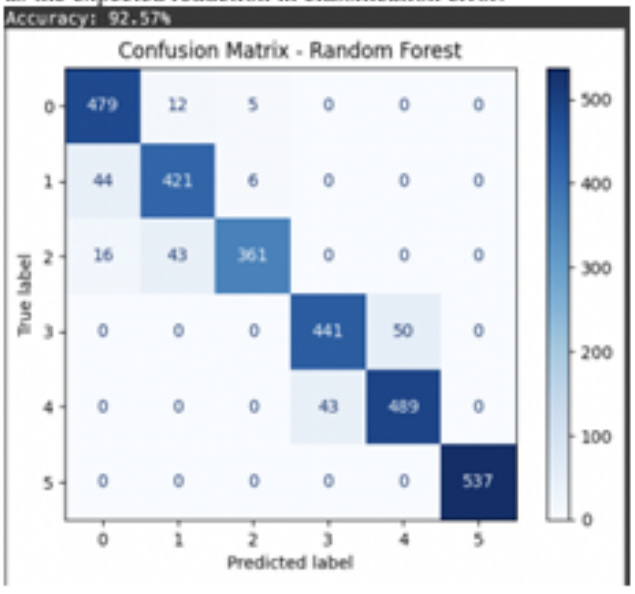


Fig. 5: Accuracy and confusion matrix for Random Forest

$$E = \frac{1}{T}\sum_{t=1}^{T} I(h_t(x) \neq y) \quad (8)$$

Where I is the indicator function. The trained Random Forest was evaluated using accuracy, precision, F1-score,

and confusion matrix analysis, providing a well-rounded assessment of predictive performance. The results highlight that ensemble-based models like Random Forest achieve high robustness by combining the strengths of multiple weak learners, making them highly effective for complex tasks such as human activity recognition.

3) K-nearest neighbours This classifier achieved an overall accuracy of 88.02%, indicating reasonable performance but slightly lower than other models. The K-Nearest Neighbors (KNN) algorithm was employed for activity recognition using the UCI HAR dataset, with preprocessing steps including missing value imputation and feature scaling. The classifier was implemented with k = 5 nearest neighbors, classifying each test instance based on the majority class among its five closest training samples. The similarity between two data points x_i and x_j is computed using the Euclidean distance:

$$d(x_i, x_j) = \sqrt{\sum_{m=1}^{n} (x_i m - x_j m)^2} \tag{9}$$

Where n denotes the number of features, x_{im} is the m^{th} feature of instance and x_{jm} is the corresponding feature of instance x_j. The classification decision is then made by majority voting over the nearest neighbors:

$$\hat{y}(x_i) = mode\{y_j | x_j \in N_k(x_i)\}, \tag{10}$$

Where $N_k(x_i)$ represents the set of nearest neighbors of x_i. In weighted variants of KNN, closer neighbors are given higher importance using weights defined as:

$$w_{ij} = \frac{1}{d(x_i, x_j) + \epsilon} \tag{11}$$

Where ϵ is a small constant to avoid division by zero. For this implementation, the unweighted version was used, ensuring all selected neighbors contribute equally. Model evaluation was carried out using accuracy, precision, F1-score, and confusion matrix, demonstrating that KNN effectively captures local neighborhood structure in data and provides competitive results for activity classification tasks.

4) Multilayer Perceptron Model This model achieved an accuracy of 95.11%, showing strong capability in capturing non-linear relationships between features. For this experiment, a Multilayer Perceptron classifier was implemented to perform human activity recognition on the UCI HAR dataset. The input features were standardized to zero mean and unit variance before training. The neural network consisted of a single hidden layer with 100 neurons, trained using the Adam optimizer with a maximum of 300 iterations and a regularization parameter of $\alpha = 10^{-4}$ .Each neuron computes a weighted sum of the inputs followed by a non-linear activation function. The forward propagation through a hidden layer can be expressed as Equation (12).

$$h^{(l)} = f(W^{(l)} x^{(l-1)} + b^{(l)}) \tag{12}$$

Where $W^{(l)}$ and $b^{(l)}$ represent the weight matrix and bias vector of layer l, $x^{(l-1)}$ is the input from the previous layer, and $f(\cdot)$ is the activation function (ReLU in this case).

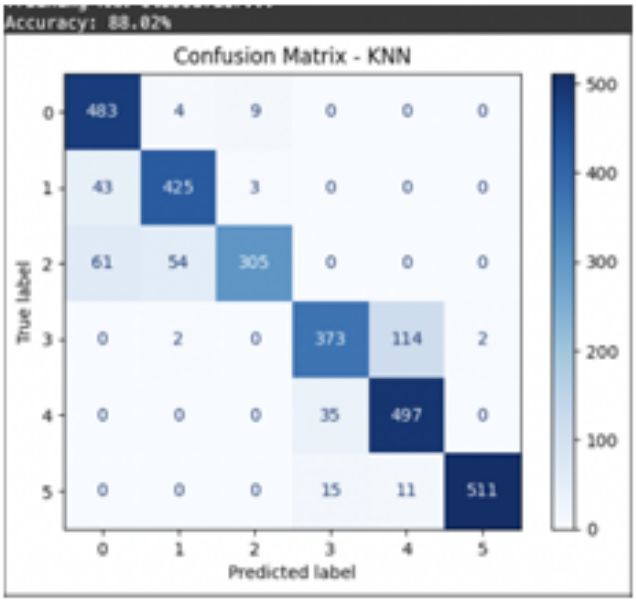


Fig. 6: Accuracy and confusion matrix for K-nearest neighbours

The final prediction is obtained using the softmax output layer:

$$\hat{y}_i = \frac{exp(z_i)}{\sum_{j=1}^{K} exp(z_j)} \tag{13}$$

Where z_i denotes the logit for class i and K is the total number of activity classes. The network parameters are optimized by minimizing the cross-entropy loss:

$$L = -\sum_{i=1}^{N} \sum_{k=1}^{K} y_{ik} \log \hat{y}_{ik} \tag{14}$$

With y_{ik} representing the true label in one-hot form. Model performance was assessed using accuracy, precision, F1-score, and confusion matrix visualization, confirming the capability of neural networks to learn complex non-linear mappings between sensor signals and human activities.

5) Enhanced Bidirectional Long Short-Term Memory: We proposed an Enhanced Bi-LSTM model for human activity recognition using WiFi CSI data. Raw CSI sequences are normalized and augmented via jittering, scaling, time warping, and mixup to improve generalization. Local temporal features are first extracted using residual CNN blocks, followed by bidirectional LSTM layers that capture long-range dependencies. A temporal attention mechanism highlights informative time steps, producing a context-aware representation, which is then classified through dense layers with dropout and a softmax output. The model is trained with categorical cross-entropy and label smoothing, employing either a cosine decay restart schedule or ReduceLROnPlateau for adaptive learning rate control, along with early stopping to prevent overfitting. This architecture efficiently models complex spatiotemporal patterns in CSI data, achieving high accuracy in human activity recognition. In this implementation, a hybrid deep learning architecture was designed

by combining convolutional layers, residual connections, bidirectional LSTMs, and temporal attention. This model aims to capture both local feature patterns from signals and long-term dependencies across time, while attention ensures that the most informative segments are emphasized during classification. Residual Learning To ensure stable gradient flow and avoid vanishing gradients, residual connections were used:

$$H(x) = F(x, W) + x \tag{15}$$

Here F(x,W) represents the output of stacked convolution and normalization layers, while the input x is directly added as a shortcut. This allows the network to preserve original information while learning transformations.

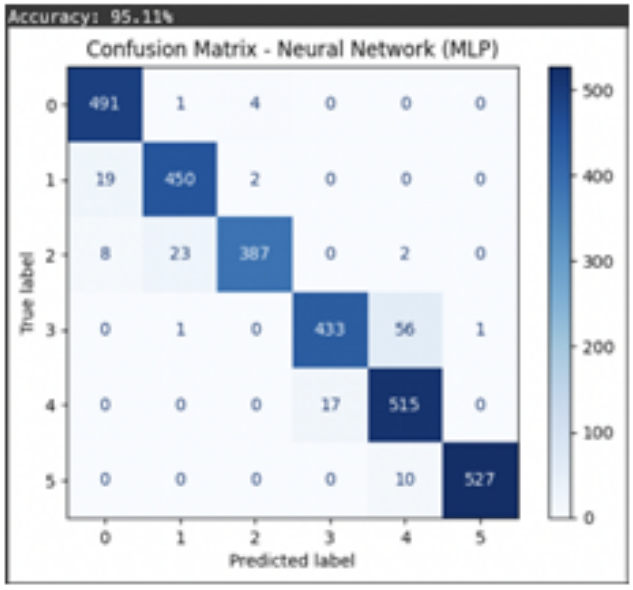


Fig. 7: Accuracy and confusion matrix for neural network (multiplayer perceptron model)

Temporal Attention Mechanism Instead of treating all timesteps equally, the model applies attention to weight important temporal features:

$$a_t = \frac{exp(e_t)}{\sum_{k=1}^{T} exp(e_k)}, c = \sum_{t=1}^{T} a_t h_t \tag{16}$$

Where h_t is the hidden state at timestep t, a_t is the learned importance score, and c is the final context vector representing the activity. This ensures that key signal segments contribute more to the decision.

Cosine Annealing Learning Rate To optimize training stability, a cosine decay with restarts strategy is used for the learning rate:

$$\eta_t = \eta_{min} + \frac{1}{2}(\eta_{max} - \eta_{min})[1 + cos(\frac{T_{cur}}{T_i}\pi)] \tag{17}$$

Where η_t is the learning rate at iteration t, T_{cur} is the current training step, and t_i is the restart period. This cyclic behavior prevents premature convergence. Evaluation Metrics Standard classification metrics-accuracy, precision, recall, and F1-score were used, as described earlier in the methodology section. These metrics evaluate the model's robustness in differentiating between human activities.

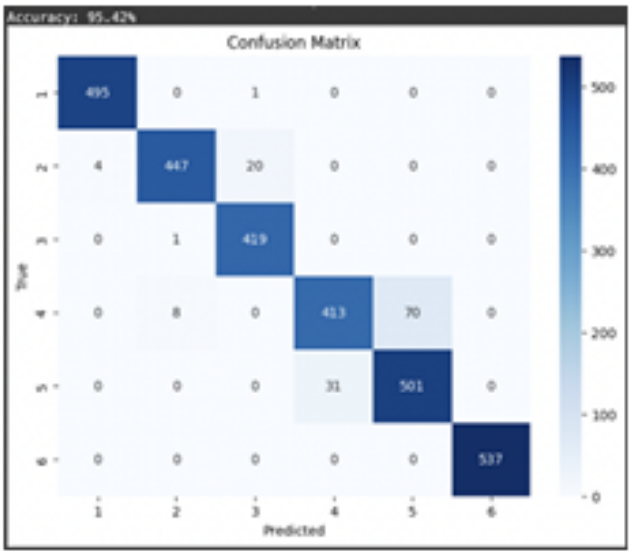


Fig. 8: Accuracy and confusion matrix Bidirectional LSTM

5.2. Performance Comparison

This section represents the evaluation results computed over different machine learning models. The results are summarized as Table 3.

Table 3: Evaluation results for selected ML models

Model	Accuracy	Precision	Recall	F1-Score
SVM	95.2%	92.1%	91.8%	91.9%
Random Forest	92.5%	91.5%	91.2%	91.3%
KNN	88.02%	88.4%	88.1%	88.2%
MLP	95.11%	93.3%	92.9%	93.0%
Enhanced Bi-LSTM	95.42%	95.5%	95.4%	95.4%

In the proposed framework, the sequence modeling stage is performed using Bi-LSTM layers, which effectively capture temporal dependencies in CSI signals by processing information from both past and future contexts. This bidirectional modeling proves crucial for human activity recognition, as activity patterns often depend on signal variations across entire time windows. By integrating dropout mechanisms to reduce overfitting and coupling the Bi-LSTM outputs with a temporal attention mechanism, the model selectively emphasizes the most informative segments of the sequence. This combination enables robust feature representation, leading to improved classification performance, with the proposed

architecture achieving an accuracy of approximately 95-96% on CSI-based human activity recognition tasks.

5.3. Confusion Matrix Analysis

The confusion matrix for the Enhanced Bi-LSTM model reveals that while the model performs reasonably well on dynamic activities such as Walking, Walking Upstairs, and Walking Downstairs, it struggles to distinguish between static activities like Sitting and Standing. These two activities generate very similar signal patterns in the CSI data due to minimal body movement, leading to overlapping feature representations. As a result, the model is often misclassified between them. This indicates that the Bi-LSTM model, in its current configuration, lacks sufficient discriminative power for static postures and requires further optimization in terms of sequence modeling, feature enhancement, or training parameters to improve its class-wise accuracy.

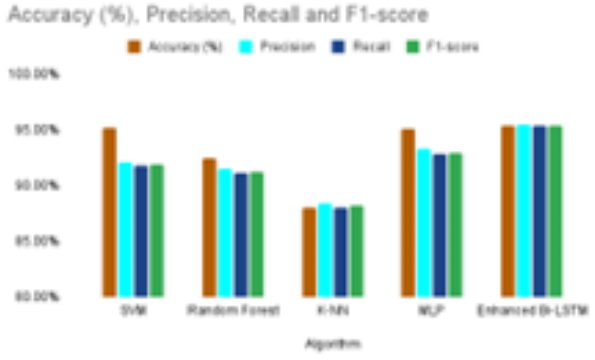


Fig. 9: Performance metrics of Algorithms on the UCI-HAR dataset

5.4. Practical Considerations

The Multilayer Perceptron neural network presents a practical balance between classification accuracy and computational efficiency. While it does not achieve the highest accuracy among all tested models (compared to Enhanced Bi-LSTM), it still performs significantly better than traditional classifiers in modeling non-linear relationships within the feature space. Due to its relatively simple architecture and feedforward nature-without the recurrent overhead of sequence modeling-MLP requires fewer computational resources, less memory, and shorter inference time. These attributes ensure that it fits the platform well where its resource requirements are low, i.e., either mobile devices, embedded systems, or edge computing units where real-time computing is required. In contrast, the classical machine learning models-particularly the Random Forest classifier-are not only computationally efficient but also highly interpretable. Random Forests are ensembles of decision trees which stratify features recursively, and the significance of the features may be measured straightforwardly. It facilitates an explanation that helps the practitioners to know what predetermines the decision of classification, what features are contributing the most to the predictions, and correcting/debugging of the prospective misclassification. Moreover, Random Forests are generally easy to tune in terms of hyperparameters, and they are resistant to overfitting, which means that they are a safe default algorithm to apply to HAR tasks, where little training data is available or the data is noisy. All in all, these models offer versatile solutions based on the application limitations: MLP offers moderately difficult, deployable at the edges, but could use better accuracy, while Random Forest offers fast and interpretable applications, either in the prototyping phase or low-latency systems.

6. CONCLUSION AND FUTURE WORK

We applied different algorithms on the UCI-HAR dataset to find it out that how these algorithms are responding for classification of different activities represented in the dataset. The classic machine learning algorithms like support vector machine is giving significantly good result. In the same way standard deep learning model like multilayer perceptron model also giving better performance. But the deep learning model Enhanced Bi-LSTM has given the best results till now. Data normalization and augmentation, local temporal feature extraction with CNN blocks and then applying this data on dense layered architecture of Bi-LSTM has improved the efficiency and performance of Bi-LSTM algorithm. So basically, it's observed, if we add some more layers for preprocessing of data on a layered deep learning architecture like Bi-LSTM so it may enhance the performance of the algorithm which would outperform the performance of other models. In the future work the focus would be on preparing the dataset by capturing it from WiFi signals and creating a sensor-less and contact-less system to detect the human activities by Wi-Fi.

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A META-ANALYSIS OF AGRI-COMMODITY PRICE MANAGEMENT APPROACHES: TRENDS AND FUTURE PROSPECTS TOWARDS DIGITAL AGRI-MARKETING

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ABSTRACT
The study offers a comprehensive meta-review of price management models on agri- derivatives, which includes commonly studied attributes such as Price Discovery (PD), Price Volatility (PV), and Price Forecasting (PF). We investigated the best-fit model for each parameter mentioned above. The meta-analysis shows that 45% of the literature focused on PV and PD for commodities like chana, maize, and wheat. Whereas studies mostly on PF were performed on soybeans. We found that the Vector Error Correction Model and Bi-Variate Exponential General Autoregressive Conditional Heteroskedastic best fit the econometric model to determine PD and PV, respectively. Nevertheless, 43% of the studies followed other econometric models for price management modelling. The present investigation finds minimal intervention in PF. The present study addresses the research gap by providing a systematic review and suggesting trajectories for efficient agri-commodity derivatives price management using advanced econometric models and advocating active digital marketing participation by stakeholders.

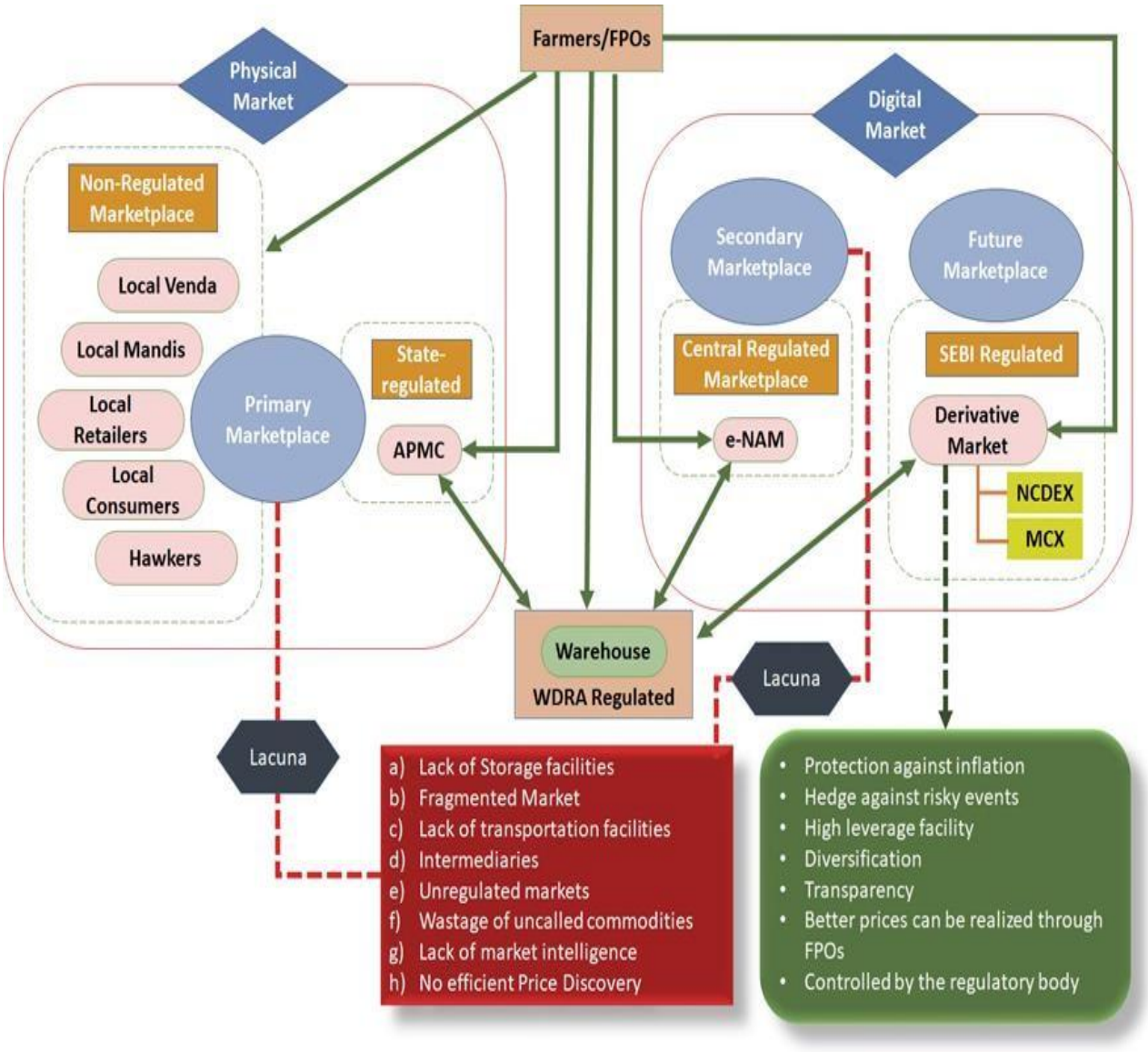
Keywords: Price management; meta-analysis; PRISMA; bibliographic analysis; agri-derivatives.

INTRODUCTION
The agricultural commodities derivatives market aims to stabilize the prices of agri- commodities. Future trading in agriculture makes it possible to ensure fair pricing to the farmers, prevent instability, provide appropriate price discovery, and manage price variations. However, the pricing of agricultural commodities is vulnerable to many factors, such as weather conditions, natural calamities, demand and supplies, production, availability of storage facilities, market information, governmental policies on procurement, and geopolitical activities. Hence, price management has become a significant concern for farmers, traders, and consumers (Broll et al. 2013). Price management incorporates all viewpoints and information to make the best pricing decisions. Agri-commodity prices are used to control by identifying the ideal price for each commodity, reducing its volatility, and making price projections for the future. Price management comprises three domains, namely price discovery (PD), price volatility (PV), and price forecasting (PF). PD mechanisms can help to achieve the best reasonable price. It allows sellers and buyers to set the market price of a tradable asset. Therefore, PD is related to finding the equilibrium price,

facilitating the maximum liquidity for that asset (Raju and Karande 2003; Yang et al. 2021). PV shows the price fluctuations in any commodity due to several market inflations. Sellers and buyers try to balance prices by minimizing PV. PF projects commodity future prices so producers can realize their best price accordingly.

These three financial tools, PD, PV, and PF, are essential for efficient price management of agricultural commodities, especially in digital agri-marketplaces like commodity derivative exchanges shown in Figure 1. In the digital agri-market, transactions are done quickly, efficiently, and safely (Lee et al. 2021). Buyers or traders from different parts of the country can participate in commodity trading. Farmers also get more options for their commodities to sell with profit. Two kinds of regulated agri-digital marketing in India are the Electronic National Agriculture Market (e-NAM) and derivative markets. e-NAM is an electronic trading platform for agri-commodities that integrate the existing APMC mandis. Yet, some lacuna exists in terms of better profitability for the farmers. The lack of transport facilities, influential intermediaries, unregulated markets, standard quality inspections, and market intelligence prevent farmers from making a profit and bound them to sell their commodities at a lower price.

Figure 1. Agricultural Marketing Framework in India.



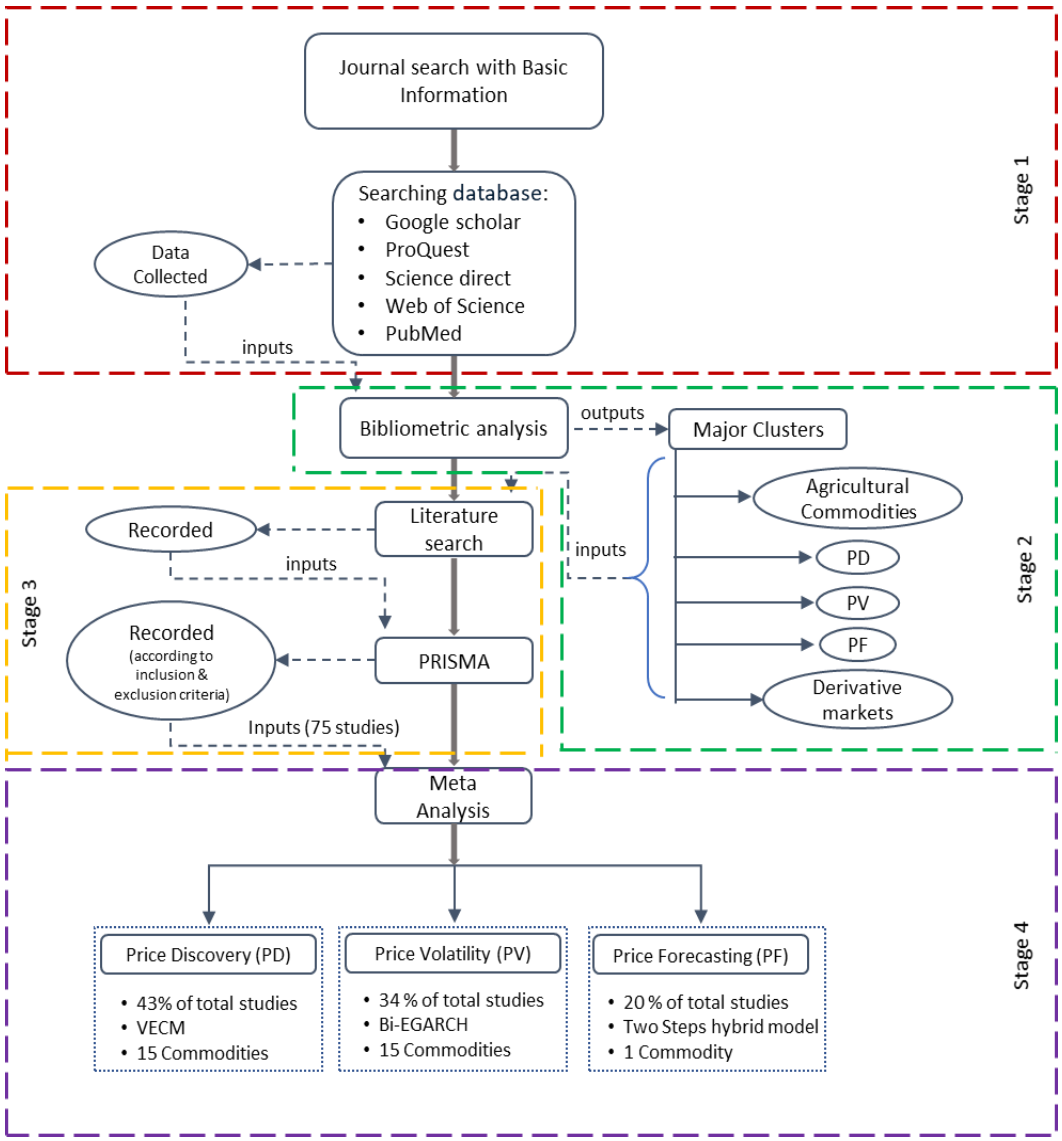
Source(s): Compiled by the authors.

However, future marketplaces such as derivative markets can be a better alternative for digital agri-marketing, where farmers make their pre-contract to sell their commodities for a future prefixed amount on a pre-determined quantity. In the derivative market Farmer Producer Organisations (FPOs), i.e., a group of farmers who participate in the trade. The FPO work as an aggregator, and farmers are its shareholders. It helps them to get government benefits, farm inputs, marketing intelligence, and experts' advice for improvement. Based on their profit, the derivative market also answers several questions to the farmers, such as what to sow, when to sell, where to sell, to whom to sell. Digitization helps all the trade processes to be clear and transparent. In India, agricultural commodities are traded in derivative exchanges through the National Commodity & Derivatives Exchange Limited (NCDEX) platform and under the regulation of the Security Exchange Board of India (SEBI) (Raju and Karande 2003), which ensures the safety of fraudulent activities. Twenty-three agricultural commodities are traded through NCDEX by traders, individual farmers, and FPOs (NCDEX 2022).

Although numerous studies have explored aspects of PD, PV, and PF in the context of agricultural commodities within Indian derivative markets (Charlebois 2008; Gordon et al. 1999; Manogna and Mishra 2021; R L and Mishra 2020; Xu and Zhang 2022), there remains a lack of comprehensive synthesis of these works. This study addresses that gap by identifying the least-studied agri-commodities and the most suitable econometric models for price management.

To achieve this, the study begins with a bibliometric analysis to identify key terms used in existing literature related to price management in agri-derivative markets (Bhattacharyya 2023). Following this, a systematic review of the most relevant peer-reviewed research articles is conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Haque et al. 2021; Nikbin et al. 2022; Sahoo et al. 2022). The findings, illustrated in Figure 2, reveal that 43% of studies focused on PD, 34% on PV, and only 20% on PF. Additionally, while 23 agri-commodities are traded by FPOs in Indian derivatives markets, only 15 have been studied in the context of PD and PV. Notably, soybean is the only commodity that has been extensively studied across all three dimensions, including PF.

Figure 2. Flowchart of the presented study



Source(s): Compiled by the authors.

The study further evaluates the effectiveness of previous works by calculating the effect size for soybean-related research, which showed a significantly large effect—highlighting the robustness of existing studies for this commodity. These insights underscore the need for future research to address the underexplored areas of PF and to apply integrated models that simultaneously consider PD, PV, and PF across a wider range of commodities. The remainder of this paper is structured as follows: Section 2 presents a literature review; Section 3 details the data sources, methodology, and data collection procedures; Section 4 discusses the results and insights; and Section 5 concludes the study with key takeaways and suggestions for future research.

LITERATURE REVIEW

History of The Derivative Market in India

The origin of future trading can be traced to the seventeenth century. In 1710, Dojima Rice Exchange started the first structured futures exchange in Osaka, Japan. The Chicago Board of Trade (CBOT) was founded on April 3, 1848, by 83 merchants to promote the trading of spot produce and forward contracts. Standardized futures contracts were first implemented in 1865. The Chicago Produce Exchange (CPEX) and Chicago Butter and Egg Board were both founded in 1874 and 1898, respectively; and in 1919, it was changed the name to Chicago Mercantile Exchange (CMEX) to enable future trading. The Exchange's main goals are to bring a lot of buyers and sellers together on one stage for spot PD and

to assure that commodities purchased and sold on the Exchange are delivered on time without exposing traders to counterparty risks (Kar 2021). Trading in commodity futures has a long history in India. Commodity futures trading has existed since prehistory; forward trading in commodities is mentioned in Kautilya's Artha Shastra (Mahajan and Singh 2015). The Bombay Cotton Trade Association (BCTA) is the first modern futures market for cotton contracts, established in 1875. With many ups and downs, forward trading doesn't fully realize its potential until 1952, thanks to the Forward Trading Regulation Act and the Forward Market Commission. However, the restriction on forward commodity trading was maintained until 2002 due to several legal and policy difficulties (Masood and Chary 2016; Shahwan and Odening 2007). After 2002, the derivative market became fully functional under the umbrella of SEBI.

Studies on Price Management of Derivative Market

The digital marketplace in India also gets a boost after the derivative market is implemented. Along with the derivative marketing systems' positive side, it also challenges farmers, traders, and customers. Price management is one of the major challenges to them. For example, Sendhil et al. (2013) has found that because of India's small-scale production system, farmers cannot participate in the futures market, and restrain themselves from the profit, However, farmers participations in futures market reduce their financial stress and improves their livelihood (Assa 2016). Dey et al. (2019) also emphasis on the factors which impressed the farmers to participation in derivative markets such as the efficiency of futures market price discovery, the spot and futures price relationship, price dissemination, understanding the socio-economic and exchange-related issues affecting farmer participation in futures markets, factors affecting demand and supply of participation, and the access to futures trading services. Ali and Gupta (2011) found Indian agricultural derivative markets are efficient and there is a long-term relationship between futures and spot prices for most of the studied commodities such as maize, chickpea, black lentil, pepper, castor, soyabean, and sugar. Several researchers have conducted on the topic research previously. Some relevant studies are discussed in the supplementary Table T1.

Methodology and Data Collections

Bibliographic Analysis for Identifying and Interlinking the Keywords

To review the previous studies published by the researchers, identifying co-occurrence keywords helps to get a path for searching the articles. Bibliographic analysis can check the concentration of co-occurrence keywords in graphical visualization based on the total link strength using the VOSviewer tool (Bhattacharyya 2023; Khan and Khan 2022). The Larger circles of the same color convey one cluster, and the size correlates to the subject's significance. Based on the bibliometric analysis, the output helped to grasp the familiarity and significance of the keywords and identified the potential gap. The size of the circles shows the frequency with which terms are presented. The distance between the circles represents the strength of their relationship. The keywords are selected after examining the clusters, circle size, and link strength created from the bibliographic analysis (Cortés-Pérez et al. 2023).

PRISMA

A systematic review is a crucial method to summarize evidence accurately and reliably and is considered a guide for researchers (Yildiz Çankaya et al. 2022). There are different methodologies for conducting a systematic review of past literature, including integrative review (Elsbach and van Knippenberg 2020; Whittemore and Knafl 2005), steps and process organizing existing literature review (Palmatier et al. 2018). However, to evaluate the previous work, PRISMA was done as a preliminary study to review the existing studies that the earlier researchers did. This will help to identify the research gaps present to map the proposed

research and the study's novelty (Acevedo et al. 2020). PRISMA is a minimal set of criteria based on evidence intended to assist scientific researchers in reporting various systematic reviews and meta-analyses from randomized trials. It enhances the systematic review reporting quality and significantly increases transparency in selecting papers for the study (Henriksson et al. 2021; Page et al. 2021). The typical processes involved in PRISMA start by identifying the research questions, followed by the critical keywords and variables related to the proposed objectives. Then, the existing publications are searched from the available peer database and other grey literature, and all the data must be recorded. The duplicate articles are excluded by screening with the titles. The screening will start from the abstract, and the non-required articles will be removed. Further screenings need to be done through the introduction, followed by the literature reviews and methodologies. In all the steps, the validations of research questions and variables must be satisfied, disconnected articles are excluded, and others are recorded. After that, the screening is done by checking the results and discussing the selected articles, and the data is recorded. This analysis may narrow future research scopes on the proposed topics and direct further research with some valuable novelties. The keywords were first finalized from bibliographic analysis for the systematic review, such as agricultural commodity, price discovery, price volatility, and price forecasting. Then, the studies will search from the database with peer-reviewed journals such as Scopus, Web of Science, and other literature found in grey journals such as Press Bureau of India, NCDEX report, NABARD, and Agmarknet. All the articles written in English are included, and duplicate studies are checked and removed after the first search with screening with the title and abstracts. Then, finally, after going through the complete text, the studies that do not fulfill the research objectives are eliminated. The established inclusion measures for the presented study are:

- The studies rely on price management of agricultural commodities in the Indian derivative market.
- All the published theoretical studies explain any PD, PV, and PF in agri-commodities for the Indian derivative market.
- The studies explain the different empirical methods for finding PD, PV, and PF.
- The published studies consider the price data of agri-commodities after 2002 from the Indian derivative market.

The article uses exclusion measures to discard the studies that are unfitting with research aims are:

- The studies focus on the market efficiency of the Indian derivative market.
- The studies that are not considering the agri-commodities of the Indian derivative market.
- The studies that are considering the post-2021 price data of agri-commodity.

The steps through which the review was conducted is shown in supplementary Figure F1. Then the selected studies were analyzed and sorted using PRISMA. Crop and market data are also required for further assessment using effect size.

All the studies are sorted and categorized according to different methods, such as data taken, period, and commodity selection, and they are grouped into PD, PV, and PF. Further divisions were made according to the methodology used in the above subdomain (PD/PV/PF). In PD, the division was made by synthesizing the commodity selection, period of data taken, and steps followed for finding the PD, such as stationarity check, cointegration check, causality check, log run check, and lead-lag approach in each study. For PV, synthesis is done based on the spillover movement of spots and futures, information biases, and the number of studies. For PF, the previous studies are synthesized according to the methodology used,

the period considered, and the commodity taken for forecasting. All the required data were synthesized and recorded.

Effect Size

Effect size is one of the important findings for empirical studies. It is the magnitude of association of the previous studies (Al Wali et al. 2022; Tehseen et al. 2019). Researchers are frequently encouraged to disclose them because it allows researchers to convey the size of the documented effects in a standardized way regardless of the scale employed to measure the dependent variable. Rather than simply presenting the statistical significance, these normalized effect sizes enable researchers to explain the actual relevance of their findings (Lakens 2013; Mohammad et al. 2021). The effect sizes also allow researchers to compare standardized effect sizes across investigations and derive meta-analytic conclusions. The effect size also helps design a new study based on earlier studies (Lakens 2013; Tam and Trang 2023).

Researchers frequently use the null hypothesis significance tests to draw inferences about observed differences between observational groups. The power of a statistical test is the likelihood of successfully rejecting the null hypothesis (Cohen 1988). The study's sample size, the magnitude of the effect, and the significance level affect statistical power. The sample size required to observe an effect of a particular size, along with the necessary statistical power, is calculated in a standard power analysis (Ng 2016).

Although there are various kinds of effect sizes, the ones covered here provide details on the amount and direction of the difference between two groups or the connection between two variables. An effect size might be a correlation, a percentage difference between means, or both (Vacha-Haase and Thompson 2004). Typically, researchers attempt to demonstrate that the groups they are investigating differ or that the factors they are examining are associated. Effect sizes analyses this information by measuring the degree of difference between groups or the strength of the association between variables. In other words, effect sizes evaluate the size or significance of the results that appear in research investigations. It cannot be attained by concentrating on a specific p-value (Vacha-Haase and Thompson 2004). A p-value with an effect's size cannot be determined directly. There is no direct correlation between an effect's size and its usefulness. A modest p-value can indicate a moderate, medium, or high impact. Depending on the situation, an effect with a minor impact on one outcome may be more significant than one with a considerable impact on another.

Effect sizes can be divided into two families: the r family, which assesses the degree of connection, and the d family, which consists of standardized mean differences. The difference between data, divided by the standard deviation of these observations, serves as the conceptual foundation for the d family effect sizes. The r family effect sizes express the percentage of variance that can be explained by group membership (Lakens 2013).

Cohen’s d describes the standardized mean difference of an effect. Even when the dependent variables are measured differently between studies, this value can be used to compare effects. It ranges from 0 to infinity. Cohen’s d refers to the standardized mean difference between two groups of the independent outcome, and it is given by:

$$d = \frac{(X_1 - X_2)}{Pooled\ SD} \quad \ldots (1)$$

$$Pooled\ SD = \sqrt{\left(\frac{(n_1 - 1)SD^2 + (n_1 - 1)SD^2}{n_1 + n_2 - 2}\right)} \quad \ldots (2)$$

There is also some correction α required to be multiplied with d if the sample size is very small.

$$\alpha = \sqrt{\frac{n_1 + n_2}{n_1 \times n_2} + \frac{d^2}{2(n_1 + n_2)}} \quad \ldots (3)$$

$$95\%\ CI = d \pm 1.96\alpha(d) \quad \ldots (4)$$

In Equation 1, the difference in mean between the two observational given groups in the numerator, and the pooled standard deviation is in the denominator. The difference between each observation and the group mean is employed to compute the standard deviation. Bessel's correction for bias in estimating the population variance is applied to this value by dividing it by the number of observations less than one. The square root is then calculated. Based on the least square estimator, this adjustment for bias in the sample estimate of the population variance (McGrath and Meyer 2006). Note that Cohen's d is also sometimes referred to as Cohen's g.

In particular, for small samples (n=20), the formula for Cohen's d, which is based on sample averages, provides a distorted estimate of the population effect size. So, the uncorrected effect size is another name for Cohen's d (Borenstein et al. 2009). Formula 3 shows the corrected effect size or Hedges's g.

$$g = d \times \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) \quad \ldots (5)$$

$$g = \frac{(X_1 - X_2)}{\text{Pooled SD}} \times \left(\frac{N-3}{N-2.25}\right) \times \sqrt{\frac{N-2}{N}} \quad \ldots (6)$$

$$\text{Pooled SD} = \sqrt{\frac{[(SD_1)^2(n_1-1)] + [(SD_2)^2(n_2-1)]}{(n_1+n_2)-2}} \quad \ldots (7)$$

When the given data are nf researchers provide the number of participants in each condition for a between-subjects comparison.

For group design, if there are mean, standard deviations, and populations involved, then the hedges's g will be Where,

$X_1 \,\&\, X_2 = Sample\ mean\ of\ sample\ 1\ and\ 2$

$SD_1 \,\&\, SD_2 = Standered\ deviation\ of\ sample\ 1\ and\ 2$

$n_1 \,\&\, n_2 = Sample\ size\ of\ 1\ and\ 2$

Interpreting Cohen's d

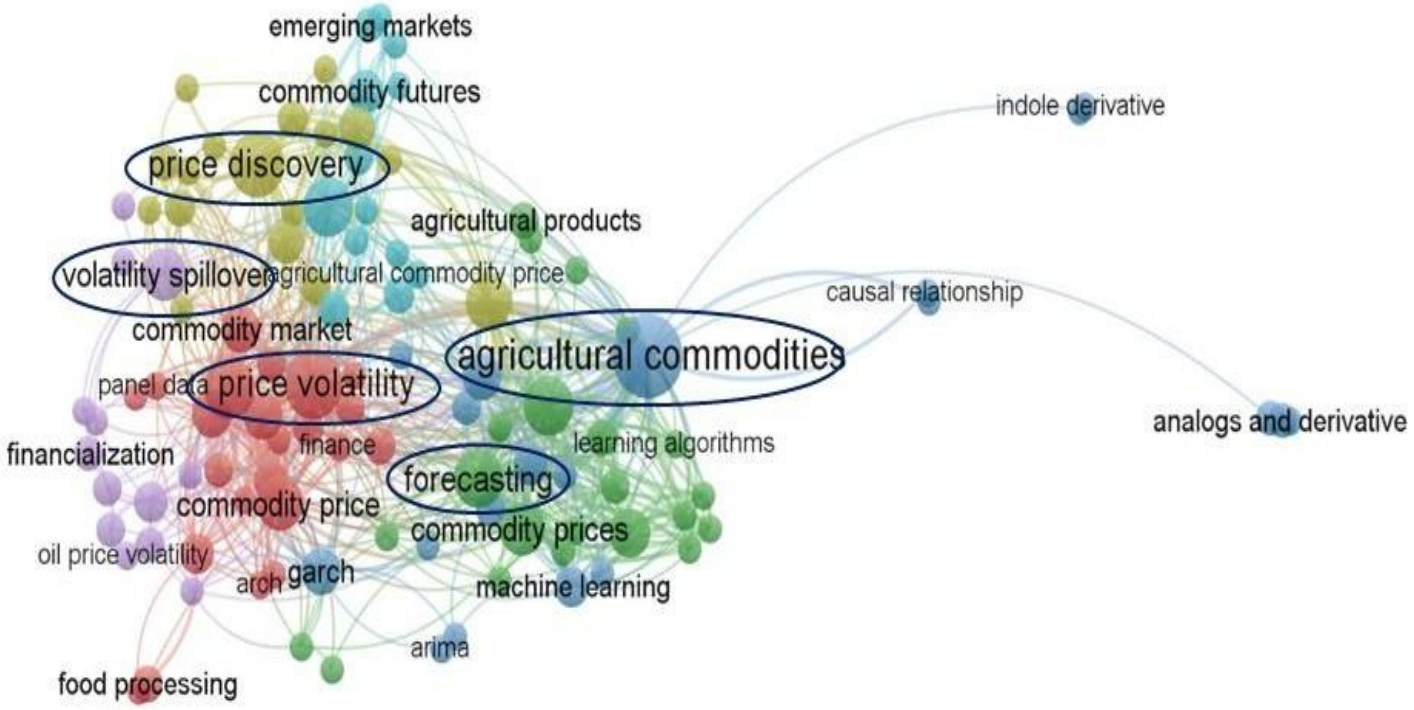
Effect sizes are frequently described as modest (d=0.2), medium (d=0.5), and large (d=0.8) based on benchmarks recommended by (Cohen 1988). However, as these values are arbitrary, they shouldn't be rigidly interpreted. Small effect sizes can have significant effects, as in the case of an intervention that reliably lowers suicide rates with a d=0.1 effect size. These criteria are only used since the findings are so new that they cannot be compared to similar conclusions from the literature. A Cohen's d of 0.5 indicates that the difference equals half a standard deviation, which is an easy way to understand Cohen's d between subject designs. The best way to analyze Cohen's d is to compare it to other effects from the literature and, if possible, explain the effect's real-world implications. Unfortunately, there are no specific instructions on how to achieve this (Fidler 2002). The values through which the study's effect size is interpreted are shown in supplementary Table T2, along with their magnitude.

The effect size calculation will be done using the STATA software, and the meta-analysis will be performed. Equations are used to calculate effect size (d) using the Cohen's d measure and the corresponding Confidence Interval (CI), and the overall effect was determined. All the sample sizes and standard deviations were tabulated before to find the effect size of the studies. Soybean is considered to find the effect size from the studies, as it is the most traded agricultural commodity in the Indian derivative market. Only nine studies were considered out of the total study because they provided the complete data information for finding the effect size of the studies. The effect size of the studies was plotted into a forest plot, and the overall effect of the study is determined.

RESULTS AND DISCUSSIONS

Six clusters are identified as having 681 links and a total link strength of 925 out of 108 items. It shows that 'agricultural commodities' is the most used term with 34 occurrences, followed by 'price volatility' (with 21 occurrences), 'price discovery' (with 18 occurrences), 'volatility' (with 13 occurrences), 'forecasting' (with 13 occurrences), and 'volatility spill over' (with ten occurrences). The top five items are selected from the graphical visualization (see Figure 3) of bibliographic analysis for article search keywords and PRISMA review, i.e., agricultural commodity, price discovery, price volatility, and price forecasting.

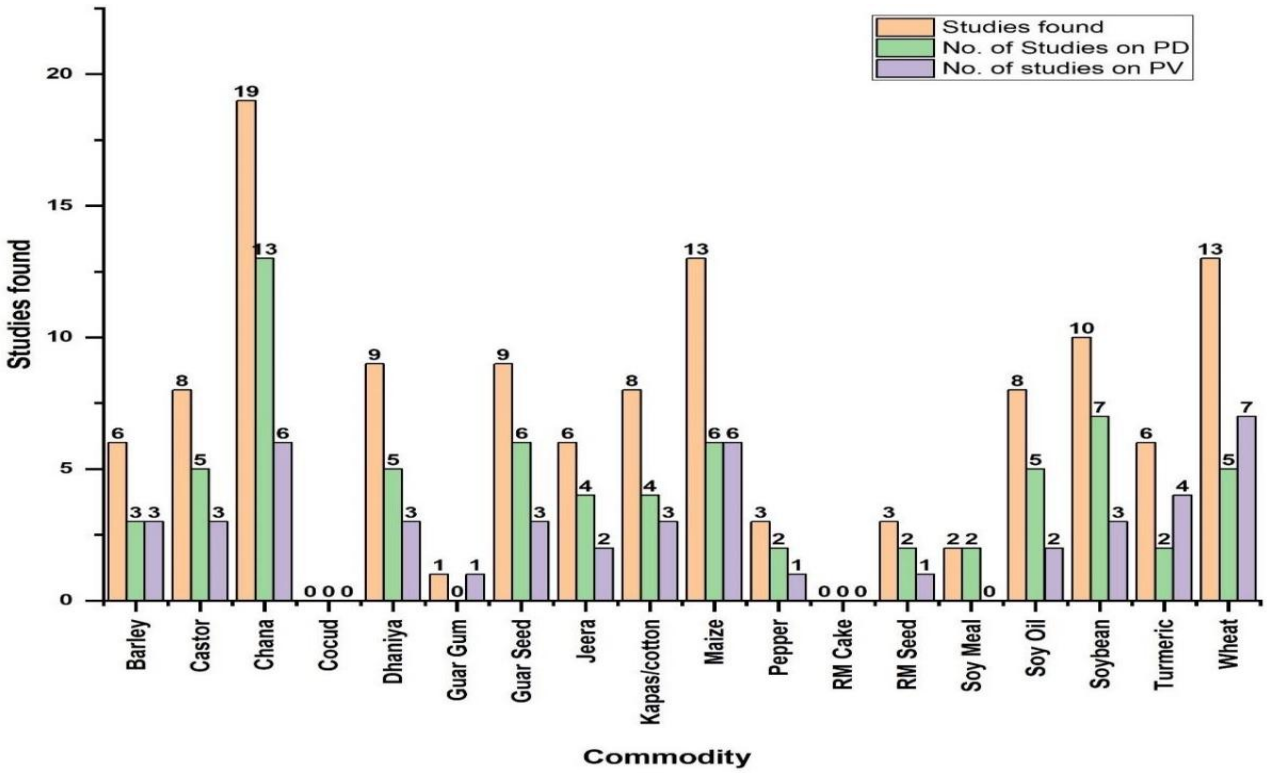
Figure 3. Graphical visualization of keyword co-occurrence



Source(s): Compiled by the authors.

Figure 4. Commodities studied by the previous researchers in terms of PD and PV

Source(s): Compiled by the authors.



Around 5187 studies are found after the first search from 1998 to 2022. For PD (1255), PV (2520), and PF (1412). Around 4487 papers were excluded due to delicacy, and 635 studies did not fulfil the inclusion measures. Furthermore, 75 studies were included per the inclusion criteria.

All 75 studies were synthesized, with 34 studies based on PD and 26 studies on PV. For PF, only 15 studies were found. It shows that forecasting and volatility measurement of price for agricultural commodities were not covered extensively, as only 35% and 20% of studies are based on PV and PF, respectively. Also, 23 commodities are traded in various markets all over the country. Barley, chana, castor, dhaniya, guar seed, jeera, cotton, maize, pepper, turmeric, soybean, and wheat; these 16 commodities were considered in studies, but based on FPO traded were not specified, as well other two commodities were not considered at all. Chana, maize, soybean, and wheat were found in more than 10 number papers, and no study was found for RM cake and cocud (see Figure 4). Hence, there is a scope for study on that aspect to better realize prices with these three price management tools.

Price Discovery (PD)

In PD, the commodities traded by the FPOs, only chana, maize, and soybean were studied more than five times. No studies were found for gaur gum, cocud, and RM cake; the remaining 12 commodities have less than five studies (see Figure 4). So, there is a scope for further research regarding the PD of the FPO-traded agricultural commodities in derivative markets.

The Augmented Dickey-Fuller (ADF) Test can be employed to determine stationarity between price time series data to detect PD of the commodity between spot and future data (Madziwa et al. 2022). For long-run associations between the spots and future price data, Johansen's Cointegration test may employ (Bohmann et al. 2019; Kumar and Pandey 2013; Singh and Singh 2017). The Granger causality (GC) test investigates the causal relationship between proposed commodity futures and spot prices. The lead-lag approaches between spot and futures price data were checked using the Vector Error Correction Model (VECM), which was then utilized to understand the existence of both long- and short-run causation among the identified determinants of market efficiency (Gupta et al. 2018; Kumar Mahalik et al. 2014). A systematic review of the previous study shows the gaps and scopes of future studies on the price management of agri-commodities using PD methods. It was found that none of the studies followed all the PD processes, and none of the studies analyzed the PD of the FPO-traded agricultural commodities. Hence, there is ample scope for study in that gap so that FPOs also can trade in the derivative market effectively (see supplementary Table T3). In Table 1, we discussed all the steps that are followed during PD and the models which follow them.

Price Volatility (PV)

The volatility hypothesis examines the lead-lag relationship between spot and future price movements. The Bivariate Exponential Generalized Autoregressive Conditional Heteroskedastic (Bi-EGARCH) will determine these price trends. It can detect positive and error terms that have asymmetric effects on volatility and informational bias. Market up (Positive News) and market downfalls (Negative News) are equal impacts on the PV of a commodity. EGARCH can check whether traders react more to negative or positive information (Kumar Mahalik et al. 2014; Rout et al. 2021).

The study synthesized 26 studies on PV. Wheat, maize, and chana are studied for PV checking (see Figure 4). None of the commodities were reviewed more than ten times in PV, and in PF, only 13 crops were covered by each study individually; two studies were found using machine learning techniques to predict the prices. Wheat, chana, and maize were considered in more than five studies out of 18 commodities that

the authors considered for PV. Five commodities were covered in three studies, eight commodities in two studies, and 12 commodities were studied at single times (see Figure 4). Hence, the previous researchers obviously did not cover all the remaining three objectives. Studying that area requires better and more efficient price management of FPO-traded agricultural commodities traded in the Indian derivative market.

To find the PV of any commodity, it's vital to check inter-linkage between markets, lead-lag between spot and future, spillover or movement detection, and information biases in the price of a commodity at a time. Some models are used by the previous researcher, such as the Generalized Supremum Augmented Dickey-Fuller (GSADF) test, Extrema Value Theory, and Generalized Autoregressive Conditional Heteroscedasticity (GARCH) (Siddiqui and Roy 2020). These models do not fulfil all the required procedures of the PV shown in Table 1 except Bivariate Exponential Generalized Autoregressive Conditional Heteroscedasticity (Bi-EGARCH). It is found that none of the studies found on analyzing the PV in commodities that the FPOs trade, and none of the models covers the external factors which affect the PV such as new market information, speculation, hazardous, etc.

Table 1. Methods for finding PD and PV, and steps involved.

	Models	Stationarity Check	Long & short run	Direction of inflation	Market Information's	Lead-lag Approach
Price Discovery	CC	✓	-	✓	-	-
	TVAR	-	-	✓	✓	-
	GISM and CSM	-	-	✓	✓	✓
	Co and GC test	✓	-	✓	-	-
	UC Test	✓	-	✓	-	-
	VECM	✓	✓	✓	✓	✓
	Models		**Inter-linkage between Markets**	**Lead-lag approach**	**Spill over**	**Information biases**
Price Volatility	GSADF test		✓	✓	-	-
	Extreme Value Theory		-	✓	-	✓
	GARCH		✓	✓	✓	-
	Bi-EGARCH		✓	✓	✓	✓

Note: (✓) Steps considered; (-) Steps not considered.

Source(s): Compiled by the authors.

Table 2. Methods used by the previous researchers for PF of agricultural product

Authors	Study area	Sample interval	Crops	Model used	FPO Consideration
Bayona-Oré et al. (2021)	Global	2011-2020	Aggregate commodities	Statistical and Graphical	✗
D. Zhang et al. (2020)	Global	2004-2016	Piglet, Pork, wheat bran, layer chick, corn, pig grain, mutton, broiler feed, broiler, wool, hog, beef, pig feed, egg, bean, fish, live chicken, plain chicken, layer feed	ANN, SVM, RF, MRMR	✗
Ouyang et al. (2019)	Global	2005-2019	Lagged Raisin	LSTNet	✗
Akın and Dizbay (2018)	World	2015	Raisins	ANN, SVM	✗
Wu et al. (2017)	China	January 2014-March 2015	cowpea	Mixed model with PLS regression	✗
Mahto et al. (2021)	India	January 2011-December 2016	sunflower seed and soybean seed	ANN, LSTM	✗
Y. Zhang and Na (2018)	FAO	July 2017-December 2017	Aggregate Food, Meat, Dairy, Cereal, Oils, Sugars	SVM	✗

Note: (✗) Not included or not considered.

Source(s): Compiled by the authors.

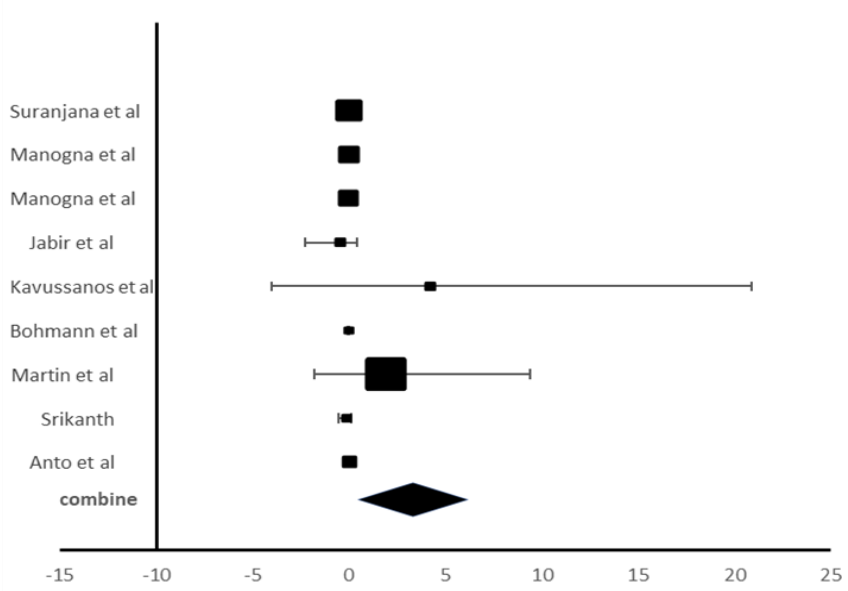
Piece Forecasting (PF)

From the overall studies, only 13 found forecasting agricultural commodities' prices in the derivative market using various models to achieve better prediction. Some of the prominent and minimum error models with their studies are shown in Table 2. Artificial Neural Network (ANN), Long short-term memory (LSTM) method, Support vector machine (SVM), and Maximum Relevance Minimum Redundancy (MRMR) are the common algorithms used by previous researchers for forecasting the prices of the agri-commodities traded in the derivative markets. Only a single study found, where researchers are trying to predict the prices of the agri-commodities traded in the Indian derivative markets using ANN and Long short-term memory (LSTM). No study has been found that considers the external factor to be an influencer of commodity prices. The discussed models cannot take external factors such as new market information, global stocks, pandemics, recession, hazards, etc., into consideration for forecasting the prices of the commodity. There is a requirement for such a model which can automatically train and employ the modal according to the price requirement and predict the prices. Forecasting of prices of agricultural commodities is important for producers and tradersin the price management of their commodities. Through the PF, the future discovery of the prices and the volatility can be predicted, and they can also develop strategies for better price management and profit.

Effectiveness of the Studies

To find effect sizes of the previous studies, soybean price data of future and spot markets were considered because soybean is the most traded commodity in the agricultural derivative market in India. But, only nine studies have been found from the previous studies where all the required data for effect size calculation on soybeans. The overall effect size was calculated using a forest plot in Figure 5. The interpretation of the effect size of the results can be traced from supplementary Table T2. It concludes that the individual studies have small and small to medium effect sizes on their studies. However, the combined results show that the overall effect size of the previous study on soybeans is large. So, there is a possibility that if the numbers of studies increase, the magnitude of the effect of studies will increase. This allows for revaluating the other commodities included in previous studies to check their effectiveness. It may also give more robust results if all other studies on every commodity are checked simultaneously.

Figure 5. Effect size of soybean from the previous study.



Source(s): Compiled by the authors.

CONCLUSION

Price management of the agricultural commodity stands on three main pillars: price discovery, price volatility, and price forecasting in the digital derivative trading space. This study systematically identified the keywords using bibliographic analysis and reviewed the most relevant past literature in the above-sited pillars using PRISMA. The research shows that most of the studies were published on PD (around 43%), while relatively fewer studies are available on the other two sub-domains, i.e., PV and PF. Moreover, there were very limited studies deriving price management using all three above sub-domains. So, further research is required to integrate PD, PV, and PF for better price management and regulation.

In India, 23 commodities are currently being traded in the derivative market, out of which chana, maize, and soybean are mostly studied for PD, wheat, chana, and maize for PV, and only soybean was studied for PF. However, other commodities are also essential to consider as they occupy 34.5% of the total traded volume in the National Commodity Derivative Exchange (NCDEX) by FPO. FPO is a group of farmers working as aggregators with scale economics and negotiation power in trade to achieve better price realization. In India, 82% of farmers are small and marginal and cannot bargain with large traders and buyers. They hardly participate in the derivative market due to limited production and capital strength. GoI is promoting FPOs in a big way, and NCDEX is facilitating the FPO-based trade in the agri-derivative segment to harness the potential of digital marketing and provide better prices to the farmers through advanced price management techniques. Till now, they have connected around 439 FPOs.

Furthermore, the government emphasizes creating and promoting 10000 new FPOs, and till now, 6000 FPOs have been successfully created across the country. However, only a small fraction (439/6000) of FPOs is connected with NCDEX for agri-derivative trading till now. Hence, there is a big opportunity to connect the significant number of FPOs to the digital trade in

the derivative market and help the farming community nationwide. We have not come across any research exploring the lacuna of FPO-based trading using advanced price management techniques. The outcome of this review work supports the active digital market participation of farmers/FPOs and other producer-centric organizations through well-regulated derivative platforms, i.e., NCDEX, for better price realization. Further, under the methodological evolution analysis, the present study concluded that the VEC model is one of the latest and most popular PD models. This model uses most PD steps, such as stationarity in the price data, long-run between the spot and future prices, positive and negative inflations, the effect of new information, and a lead-lag approach between the prices. The model can be used for the PD of other commodities traded by the FPOs. We found that the Bi-EGARCH model is robust and allows market information biases for decoding volatility. Very few researchers have used these models for volatility. Hence, Bi-EGARCH can be used for other agri-commodities and for encountering PV for future volatility estimations of prices.

Moreover, only a single study was found on PF in the Indian agricultural commodity derivative markets. However, the model used in that study did not consider how external factors such as weather data, oil and gas price data, and geopolitical activities would impact the PF of an agri- commodity. Two-Step Hybrid Models are a few examples of advanced computational econometric techniques that allow external factors during PF. This model is a machine-learning technique that will enhance the prediction's robustness; as it has a self-learning mechanism, it can quickly adapt and develop itself to show a better prognosis. The perspective has significant potential, especially in these three dimensions of price management. The conclusion of this review will help institutions and other shareholders access the scope of advanced methods in the price forecasting of agricultural commodities.

The study performed the effect size analysis to check the mutual association of the past studies in different price management domains, i.e., PD, PV, and PF, for various agri-commodities. The amount of available past literature in the specific area is essential for effect size analysis. We found that only PD studies for soybean are moderately associated with each other. We could not perform the effect size analysis for the other agri-commodities because of the availability of the required number of studies for the effect size analysis. There is a scope that if more studies are performed capturing all the domains of price management for major traded agricultural commodities, the effectiveness of conducting substantial review work in exploring the mutual association of the studies can be increased. This work empirically established (effect size) that there is a need to conduct price management work for the other agri-commodities to get more associated literature support for future PD, PV, and PF. The present work would have given more robust results if we could have performed an effect size analysis in every price management domain for all digitally traded agricultural commodities.

This study supports that digital agri-marketing participation by the farmers/FPOs, producer collectives, traders, and consumers need to increase using derivative platforms. This is one of the most effective ways to achieve better price management and income realization at the farmer level. There is plenty of scope for enabling high-end price management approaches for effective price realization and better profitability.

Author Contributions:

Kripamay Baishnab: Writing – original draft, review & editing, Methodology, Software, Formal analysis, Visualization, Formal analysis, Conceptualization. **Piyush Kumar Singh:** Review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Alok Kumar Singh:** Review & editing, Validation, Supervision, Conceptualization

Disclosure statement: No potential conflict of interest was reported by the author(s).

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APPENDIX - 1

Table T1. Findings of the related studies related Indian agri-commodity derivative market

Authors	Sample size	Methods used	Name of methodology	Commodity Selected	Major Finding
Iyer and Pillai (2010)	Up to 2008		Two-regime, TVAR	Cu, Au, Ag, Ni, Ru, CkP	Five of six commodities have evidence that the PD process occurs in the futures market. The pace of convergence during the futures contract expiry week was instantaneous for copper, gold, and silver, confirming the usefulness of futures contracts as an efficient hedging tool. However, this wasn't the case for chickpeas, nickel, and rubber.
Pavabutr and Chaihetphon (2010)	2003 - 2007		VECM	Au	Even though they only make up 2 percent of the trading value on the MCX, mini contracts are responsible for nearly 30 per cent of PD in the gold futures market.
Joarder and Mukherjee (2021)	2005 - 2014	LL	GC, F-statistic	S_1, ReSO, Sm, CaSe, CoSeOC, MuSe	The assessment of spot market volatility and improved PD is greatly aided by information about futures market volatility. Government interference and speculative activity could harm the derivative market's risk control.
R L and Mishra (2020b)	2010 - 2019	SC, CC, SR, LL	ADF, PP, GC, VECM, EGARCH	CoSe, CaSe, S_1Se, RMuSe, Tu, J, Cor, GuSe and Ch	Nine commodities show the futures market leading the spot in the case of six commodities, including turmeric, soybean seed, coriander, guar seed, castor seed, and chana, while the spot market uses VECM to determine the price of three commodities, including rapeseed, mustard seed, and jeera. The futures markets have robust ability to predict spot prices, indicated by the Granger causality test.
Inani (2018)	2009 - 2015	CSM, ISM, MISM, SC, Co	VECM, ADF, PP, JTME, EGC	CaSe, Cor, CoSeOC, SO, Su-M, Tu, Ch, GuSe, J, MuSe	Given that the results reveal that the futures market outperforms the spot market in the case of six commodities, it was concluded that it is more effective in determining the price of agricultural commodities. At the same time, PD occurs in the spot market for four commodities: chana (chickpea), guar seed, jeera, and mustard seed.
Pani et al. (2022)	2005 - 2019	CC	GC, JJC, VECM	Ag, Al, Cu, Pb, Ni, Zn, CudO	The spot market is ahead of the futures market regarding copper and zinc PD. However, in terms of PD for silver, aluminium, and lead, the futures market outperforms the spot market. The study concludes that market players should employ hedging and arbitrage tactics.
Minakshi (2018)	2009 - 2013		VECM	Ch, Co	Investigate the connection between spot and futures prices. The cointegration results do not support a long-term link between spot and futures prices. The implication is that futures prices are unlikely to act as market expectations of upcoming spot prices of certain agricultural commodities in India and do not aid in PD.
Vijayakumar (2022)	2017 - 2020	SC, LL, Ca test	JC, VECM, GC, RDV	Crd	According to the statistical findings, PD in the e-auction market results in spot and futures pricing. Cardamom futures and spot prices negatively correlate with cardamom e-auction prices. Additionally, it discovers that India's high-value cardamom e-auction system does not have a day-of-the-week effect.

Kumar Mahalik et al. (2014)	2005 - 2008	SA	VECM, Bi-EGARCH	S_1Se, Cor, Tu, CaSe, GuSe and Ch	A flow of data from future to spot commodity markets is implied by the effectiveness with which the agriculture future price index, energy future price index, and aggregate commodity index serve the PD function in the spot market, but the reverse causality is not present. The metal future price index and the metal spot price index do not cointegrate.
Sendhil et al. (2013)	Up to 2009	MIPT	JMVrA, GS	Ckp, Wh, Mz, Bar	According to the study, wheat and maise futures are more effective at determining price. The study has found that because of India's small-scale production system, farmers cannot participate in the futures market.
Mallikarjunappa and Afsal (2010)	2006 - 2006	URT, Co, DE	VECM EGARCH	CT, IC, Inf, IVR Infra, RC, SBI, Sterlite, Tata Steel, Wp, Hdl, PLyd, and RIL	There is a short-lived feedback loop between the two markets. Both marketplaces experience PD simultaneously. Short-term disequilibrium exists, but it can be fixed in the following time frame. The spot and futures markets have a simultaneous and bidirectional lead-lag relationship.
Ali and Bardhan Gupta (2011)	2003 - 2007	EM	JC, GC, ADF, PP	Wh, R, Mz, Ckp, BkL, RdL, GuSe, Pep, Csw, CaSe, S_1, Su	Cointegration is present in futures and spot prices for all the agricultural commodities chosen except for wheat and rice. This suggests that there is a long-term association between futures and spot prices for most agricultural commodities, including maise, chickpeas, black lentils, pepper, castor seed, soybeans, and sugar. For chickpea, castor seed, soybean, and sugar, the analysis of short-term correlations by causality test show that futures markets have higher ability to anticipate subsequent spot prices than for maise, black lentil, and pepper, where short-term bi-directional links exist.
Salvadi Easwaran and Ramasundaram (2008)	2007	EM	B Test, ET	Ca, Co, Pep, S	PD does not occur in the agricultural commodity futures market, according to a statistical examination of data from a sample of four agricultural commodities traded on futures markets. The econometric assessment of the relationship between price return, volume, market depth, and volatility has demonstrated that the return and volatility of futures and spot markets do not significantly affect the market volume and depth.
Garg et al. (2023)	2004 - 2015		Stat	Bar, CaSe, Ch, Cl, Cor, CoSeOC, Co, CudPol, Gu Gum, GuSe, Gu, Je, Kp, Mz, MentaO, MuO, P, Pep, Pot, Ru, S_1, SO, Su, Tu and Wh	In most agricultural commodities, the PD between futures and spot prices indicates substantial information transmission from futures markets to spot markets. Additionally, there is one-way causal connectivity between spot and futures market prices and a feedback relationship between futures and spot market prices. According to the study, the agri-futures market's volatility spillover effects are relatively significant.
Irfan and Hooda (2017)	2005 - 2015		DStat, ADF, PP, JC, GC	Wh, Su, Ch, MuSe, Ch, Pep, Tu, S_1, Bar, and Mz	Ten commodities have a long-term equilibrium relationship established. When there were two cointegrations and causality, the Granger causality test revealed unidirectional Granger lead-lag correlations between spot and futures markets for all agricultural commodities.

Narsimhulu and Satyanarayana (2016)	2004 - 2013	JC, VECM, WchS, GC	Ch, Cl, and Tu	The findings of the Granger causality test showed that there is only a unidirectional connection between the spot returns of the commodities, chili and turmeric, and futures returns. However, there is a two-way causal relationship between spot returns and futures in the case of chana.

Source(s): Compiled by the authors.

Commodities**:** CkP-Chickpea, Wh-Wheat; S1-Soybean; ReSO-Refined_Soyoil; Sm-Soymeal; CaSe-Castor_Seed, CoSeOC-Cotton_Seed_Oilcake; MuSe-Muster Seed; CoSe-Cotton Seed; CaSe-Castor Seed; S1Se-Soybean Seed; RpMuSe-Rape_Muster_Seed; Tu-Turmeric; J-Jeera; Cor-Coriander; GuSe-Guar Seed; Ch-Chana; SO-Soy Oil; SuM-SugarM; Co-Cotton; Crd-Cardomom; Mz-Maize; Bar-Barley; BkL-Black Lentil; RdL-Red lentil; Pep-Pepper; Csw-Cashew; Su-Sugar; S-Soya; Cl-Chilli; CudPol-Crude Plam Olein; Cn-Corn; SSe-Soy Seed; Kp-Kapas; O-Oil; P-Peas; Pot-Potato; Pol-Palm Olein; G-Gram; Cu-Copper; Au-Gold; Ag-Silver; Ni-Nickel; Ru-Rubber; Al-Aluminium; Pb-Lead; Zn-Zinc; CudO-Crude Oil; NG- Natural Gas.

Company: CT - Century Textiles; IC - India Cements; Inf - Infosys; RC - Reliance Capital; SBI – State Bank of India; Wp – Wipro; Hdl - Hindalco; PlyD - Pun Lloyd; RIL - Reliance Industries Limited.

Methodology: JTME-Johansen Trace and Maximum Eigenvalue; EGC-Engle-Granger Cointegration; JGHC-Johansen and Gregory-Hansen Cointegration; TYC-Toda-Yamamoto Causality; JJCA-Johansen and Juselius Cointegration Analysis; JT-Johansen's Trace; LR-Likelihood-ratio Test ; JMVrA-Johansen's Multivariate Approach; GS-Garbade and Silber's Approch; Bi-RW-Bivariate Random Walk; WchS-Wald chi-square test; Stat-Statistical; SC-Stationarity Check; LR-Long Run between spot and Future; DI-Direction of inflation; MI-Market Information's ; LL-Lead-lag Approach; DStat-Descriptive statistics; LLR-Linear long-run relationship; IsSMI-Inter-state Spatial Market Integration; CC-Cointegration Causality test; SR-Short-run Check; CSM-Component share method; ISM-Information share method; MISM-Modified information share method; Ca-Causality test; SA-Spillover analysis; Pa-Parametric; UR-Unit root tests; Co-Cointegration tests; UPH-Unbiasedness and prediction hypotheses; CFP-Comparison with futures prices; MIPT-Market Integration and Price Transmission; DE-Dynamic Effect; EM-Econometric methods; RDV-regression with dummy variables; ET-Expectations Theory; GISM-Generalised Information Share Measure; CSM-Component Share Measure.

Table T2. Interpretations for reporting effect size in quantitative research

Reference	Effect size statistic	Values	Interpretation of effect size
		0.10	Small effect size
Cohen (1988)		0.30	Medium effect size
		0.50	Large effect size
	Cramer's Phi or Cramer's V for nominal data	0.00 and under 0.10	Negligible association
		0.10 and under 0.20	Weak association
Rea and Parker (1992)		0.20 and under 0.40	Moderate association
		0.40 and under 0.60	Relatively strong association
		0.60 and under 0.80	Strong association
		0.80 and under 1.00	Very strong association
	Cohen's d for independent t-tests	0.20	Small effect size
		0.50	Medium effect size
		0.80	Large effect size
Cohen (1988)			
	Cohen's f for ANOVA and ANCOVA	0.10	Small effect size
		0.25	Medium effect size
		0.40	Large effect size
		0.196	Small effect size
Cohen (1988)	R2 for multiple regression	0.1300	Medium effect size
		0.2600	Large effect size

Source(s): Statistical Power Analysis for the Behavioral Sciences Second Edition (2nd ed.). LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS.
https://www.utstat.toronto.edu/~brunner/oldclass/378f16/readings/CohenPower.pdf

Table T3. Relevant studies on PD in Indian agri-derivative with their methods

Authors	Sample Size	Commodity selected	Methods						FPO
			SC	LR	DI	MI	LL	O	
Iyer and Pillai (2010)		Cu, Au, Ag, Ckp, Ni, Ru						TVAR	✗
Joarder and Mukherjee (2021)	2005-2014	S_1, ReSO, Sm, MuSe, CaSe, CoSeO Cake	✓						✗
R L and Mishra (2020)	2010-2020	S_1Se, Cor, Tu, CaSe, GuSe, Ch		✓	✓		✓		✗
Inani (2018)	2009-2015	CaSe, Cor, CoSeO Cake, SO, Su-M, Tu, Ch, GuSe, Je, MuSe			✓	✓	✓	CS, IS, MS	✗
Irfan and Hooda (2017)	2005-2015	Wh, Su, Cl, MuSe, Ch, Pep, Tu, S_1, Bar, Mz	✓	✓	✓			St, PP test	✗
Brahmaiah and Palamalai (2016)	2004-2015	Bar, CaSe, Ch, Cl, Cor, CoSeO Cake, Co, Crude PO, Gu Gum, GuSe, Gu, J, Kp, Mz, Menta O, MuO, P, Pepper, Pot, Ru, S_1, SO, Su, Tu, Wh						S	✗
Anupama and Malik (2010)	2004 - 2009	GuSe and Ch	✓					GS, BRW	✗
Narsimhulu and Satyanarayana (2016)	2004 - 2013	Ch, Cl, and Tu		✓			✓	S	✗
Vijayakumar (2022)	2017-2020	Crd		✓	✓		✓	RDV	✗
Kumar Mahalik et al. (2014)	2005-2008	S_1Se, Cor, Tu, CaSe, GuSe, Ch					✓		✗
Sendhil et al. (2013)	2009-2010	Ckp, Wh, Mz, Bar	✓		✓		✓		✗
R L and Mishra (2020)	2010-2019	CoSe, CaSe, S_1Se, RpMuSe, Tu, J, Cor, GuSe, Ch			✓		✓		✗
Salvadi Easwaran and Ramasundaram (2008)	2007	Ca, Co, Pep, S						B Test, S	

Source(s): Compiled by the authors.

Notations: '✓'=Methods included in the study; '✗'=FPO not considered;

Methods: SC-Stationarity Check; LR-Long Run between spot and Future; DI-Direction of inflation; MI-Market Information's; LL-Lead-lag Approach.

Commodities: CkP-Chickpea, Wh-Wheat; S1-Soybean; ReSO-Refined Soy Oil; Sm-Soymeal; CaSe-Castor Seed, CoSe-Cotton Seed; MuSe-Muster Seed; RpMuSe-Rape_Muster_Seed; Tu-Turmeric; J-Jeera; Cor-Coriander; GuSe-Guar Seed; Ch-Chana; Su-Sugar; Cn-Corn; Cl-Chilli; Crd-Cardomom; SSe-Soy Seed; BkL-Black Lentil; RdL-Red lentil; Pep-Pepper; Csw-Cashew; Kp-Kapas; Mz-Maise; Bar-Barley; Mz-Maise; R-Rice; O-Oil; P-Peas; Pot-Potato; S-Soya; Pol-Palm Olein; G-Gram; Cu-Copper; Au-Gold; Ag-Silver; Ni-Nickel; Ru-Rubber.

APPENDIX – 2

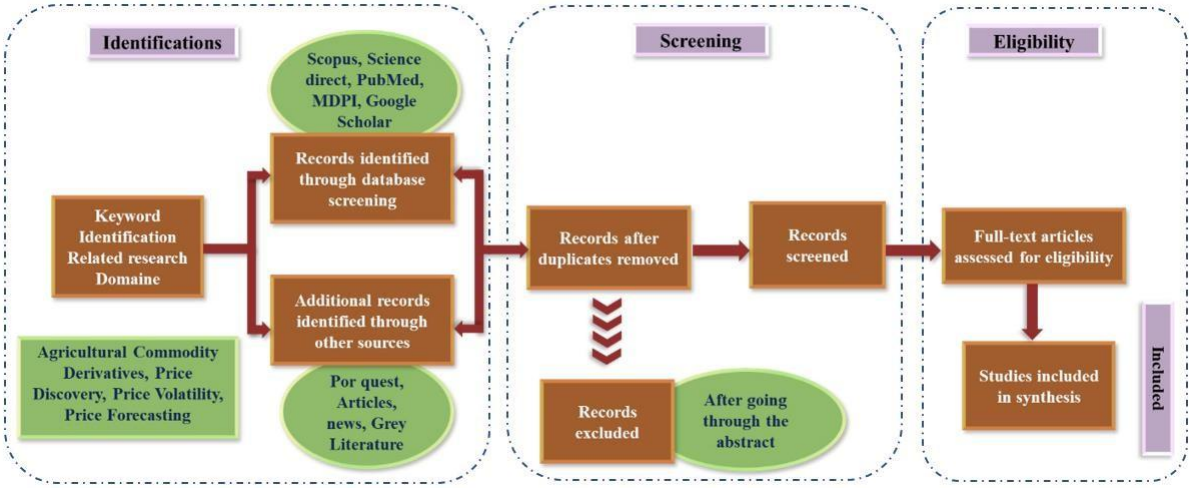


Figure F1. Steps of PRISMA review were made for the study

Source(s): Compiled by the author.

COMPARATIVE REVIEW OF BRAIN TUMOR DETECTION TECHNIQUES: TRADITIONAL APPROACHES TO DEEP LEARNING INNOVATIONS

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ABSTRACT

Accurate and early detection of brain tumours is essential for effective treatment planning and improved patient outcomes. Over the past two decades, a wide range of computational techniques has been developed to support tumour diagnosis using medical imaging, particularly magnetic resonance imaging (MRI). This review presents a comparative analysis of various brain tumour detection methods, including traditional image processing, machine learning, deep learning, and hybrid approaches.

Conventional techniques such as thresholding and morphological operations offer simplicity but lack robustness in handling complex tumour structures. Machine learning methods, using algorithms like SVM and Random Forests along with feature extraction techniques such as GLCM and PCA, provide improved accuracy but depend heavily on feature quality. Deep learning, particularly CNN-based models like U- Net and ResNet, has shown superior performance in both classification and segmentation tasks due to its ability to learn features directly from raw images.

Hybrid and ensemble models, combining deep features with classical classifiers or handcrafted features, further enhance detection accuracy. Performance comparisons on benchmark datasets like BRATS demonstrate that deep and hybrid methods consistently outperform traditional techniques. Finally, this review discusses ongoing challenges and future directions, including explainable AI, real-time detection, and clinical system integration, highlighting paths toward more reliable and deployable diagnostic tools.

Keywords*:* SVM, GLCM, PCA

INTRODUCTION

Brain tumours are among the most complex and aggressive forms of neurological disorders, often characterized by high mortality and recurrence rates. The irregular morphology, variable size, and infiltrative nature of tumours such as gliomas and glioblastomas present significant challenges in clinical diagnosis and treatment planning [1]. Early and accurate detection of these tumours plays a pivotal role in improving patient outcomes, as delayed diagnosis can lead to rapid disease progression.

Medical imaging techniques, particularly magnetic resonance imaging (MRI), have become indispensable tools for non-invasive tumour detection and characterization. MRI provides excellent soft-tissue contrast and spatial resolution, making it the imaging modality of choice in neuro-oncology [2]. However, manual interpretation of brain scans by radiologists is time-consuming and prone to inter-observer variability, which can lead to inconsistent diagnoses [3]. This has driven significant interest in automated,computer-aided etection systems that aim to enhance diagnostic accuracy and support clinical decision-making.

The earliest approaches to automated detection relied on conventional image processing techniques, including thresholding, edge

detection, and morphological operations. These methods are computationally efficient and easy to implement, but their performance often suffers in cases with poor contrast or noise, limiting their clinical reliability [1].

To overcome these limitations, machine learning (ML) techniques such as Support Vector Machines (SVM), Random Forests, and k-Nearest Neighbors (k-NN) were introduced. These algorithms require well-defined features extracted from the images using methods like the Gray-Level Co-occurrence Matrix (GLCM), Local Binary Patterns (LBP), and Principal Component Analysis (PCA). ML models have shown improved accuracy and adaptability, but their performance is sensitive to feature selection and dataset variability [4][5].

The introduction of deep learning (DL), especially Convolutional Neural Networks (CNNs), marked a major breakthrough in medical image analysis. CNNs can automatically learn hierarchical features from raw data, eliminating the need for handcrafted feature engineering [6][7]. Architectures such as U-Net, ResNet, and VGGNet have demonstrated state-of-the-art performance in both tumour segmentation and classification tasks, particularly on benchmark datasets like BRATS [8][6]. These models are capable of handling the variability in tumour appearance, improving detection accuracy across different imaging scenarios.

Despite the progress, several limitations remain, including high computational demands, overfitting on small datasets, and a lack of interpretability—making the integration of these systems into clinical workflows a complex task [9]. Explainable AI (XAI) and hybrid models that combine traditional ML with DL features are emerging to address these concerns [10].

This review provides a comprehensive comparison of conventional, machine learning, deep learning, and hybrid approaches for brain tumour detection. We evaluate their performance, clinical applicability, and limitations, offering insights into future research directions aimed at improving automated diagnostic systems.

Conventional image processing techniques

Before the rise of machine learning and deep learning, conventional image processing techniques served as the primary computational tools for brain tumour detection and segmentation. These methods typically rely on pixel intensity

values, structural patterns, and mathematical rules to extract regions of interest from medical images, especially MRI scans [1].

Thresholding is one of the earliest and most straightforward approaches, segmenting images by classifying pixels based on intensity levels. It is computationally efficient but highly sensitive to image contrast and noise, making it less reliable in heterogeneous tumour environments [1][2].

Edge detection methods, including the Sobel, Canny, and Laplacian operators, aim to identify discontinuities in pixel intensities, often corresponding to tumour boundaries. While effective in some cases, these methods can struggle with fuzzy or irregular edges, commonly seen in gliomas [3].

Region-based methods, such as region growing and watershed segmentation, attempt to group similar pixels starting from seed points. They offer improved spatial coherence but are prone to over-segmentation, especially when intensity variation within the tumour is significant [1]. **Morphological operations**—like dilation, erosion, opening, and closing—are typically used to refine segmentation outputs, eliminate small artifacts, and enhance structural continuity [4].

Although these techniques are intuitive and fast, they lack the adaptability required to handle

complex tumour shapes, varying contrast levels, and inter-patient variability. As such, they are often used today as preprocessing steps or in combination with more advanced algorithms in hybrid systems [5].

Machine learning-based methods

The application of machine learning (ML) has substantially improved brain tumour detection by enabling systems to learn complex relationships from labelled imaging data. Unlike conventional rule-based methods, ML algorithms depend on a set of discriminative features extracted from medical images and use statistical models to classify tumour presence, type, or location [4][5].

Popular ML algorithms in this domain include Support Vector Machines (SVMs), k-Nearest Neighbors (k-NN), Random Forests, and Decision Trees. SVMs are particularly effective for binary classification tasks and are known for their robustness in high-dimensional feature spaces, making them well-suited for medical image analysis [4]. Random Forests and Decision Trees offer the advantage of interpretability and resistance to overfitting when trained on moderately sized datasets [5].

These classifiers depend heavily on feature extraction techniques that convert raw image data into quantifiable descriptors. Commonly used methods include the Gray-Level Co-occurrence Matrix (GLCM) for texture analysis, Local Binary Patterns (LBP) for spatial texture encoding, and Principal Component Analysis (PCA) for dimensionality reduction [5][6]. The performance of ML models is strongly influenced by the choice and quality of these features, making feature engineering a critical step.

To ensure fair evaluation and reproducibility, researchers frequently use benchmark datasets such as BRATS (Brain Tumor Segmentation Challenge) and REMBRANDT. These datasets provide annotated MRI scans that facilitate model training, testing, and cross-study comparison [8].

Although ML-based methods offer improved accuracy over conventional techniques, they remain limited by their reliance on handcrafted features and may underperform on highly variable or noisy clinical data [7].

Deep learning methods

In recent years, deep learning (DL) has emerged as the most transformative approach in brain tumour detection, significantly outperforming conventional and classical machine learning techniques in both segmentation and classification tasks. At the core of this progress are Convolutional Neural Networks (CNNs), which can automatically learn hierarchical features from raw image data without the need for manual feature extraction [6][7].

Among the various CNN architectures, U-Net has become particularly popular in the medical imaging domain due to its symmetric encoder–decoder structure and skip connections that preserve spatial information across layers. It has demonstrated high accuracy in tumour segmentation tasks, especially when applied to MRI data [7]. Other widely used architectures include VGGNet and ResNet, which offer deeper network configurations capable of capturing more complex patterns in imaging datasets [6][9].

A key advancement in this field has been the use of pre- trained models and transfer learning strategies. Given the limited availability of annotated medical datasets, models trained on large-scale datasets like ImageNet are fine-tuned on domain-specific MRI data to improve generalization and reduce training time [11]. This approach has been shown to significantly boost performance, especially in smaller datasets like BRATS and REMBRANDT [8].

Deep learning models are typically applied to two types of tasks: classification, which

involves categorizing the entire scan or tumour region (e.g., benign vs. malignant), and segmentation, which requires pixel-level delineation of tumour boundaries. While classification models are less computationally intensive, segmentation models such as U- Net provide detailed spatial information critical for diagnosis and treatment planning [7].

Despite their superior performance, deep learning models face challenges such as high computational cost, data dependency, and lack of interpretability—issues that current research seeks to address through methods like explainable AI and hybrid modelling [10][12].

Hybrid and ensemble techniques

To leverage the strengths of both machine learning and deep learning, researchers have developed hybrid and ensemble models for brain tumour detection. These approaches aim to combine the feature learning capabilities of deep networks with the decision-making strengths of classical machine learning algorithms, or to aggregate multiple models for more robust performance [5][10].

One common hybrid framework involves using a Convolutional Neural Network (CNN) to automatically extract deep features from MRI images, followed by a machine learning classifier such as Support Vector Machine (SVM) or Random Forest for final classification. This CNN + SVM approach benefits from the rich, hierarchical features learned by the CNN while utilizing the SVM's robustness in small or imbalanced datasets [4][5]. Such combinations have been reported to outperform both standalone CNNs and classical ML classifiers in tumour classification tasks. Another popular direction is feature fusion, where handcrafted features (e.g., GLCM, LBP) are combined with deep features learned by CNNs to enrich the input representation. This fusion allows models to incorporate both domain-specific characteristics and high-level abstract patterns, leading to improved classification and segmentation accuracy [6].

In addition, ensemble techniques such as bagging, boosting, and stacking are widely used to integrate predictions from multiple models. These techniques reduce variance, enhance generalization, and improve performance on noisy or heterogeneous datasets [10][12].

Hybrid and ensemble models represent a promising direction for brain tumour detection, offering improved performance, robustness, and adaptability—especially in real- world clinical applications where data quality and diversity can vary significantly.

PERFORMANCE COMPARISON

Evaluating the effectiveness of brain tumour detection methods requires a consistent framework based on standard performance metrics and benchmark datasets. Commonly used metrics include accuracy, sensitivity (recall), specificity, precision, F1-score, and the Dice Similarity Coefficient (DSC)—each providing unique insights into model performance, especially in the context of medical image classification and segmentation [4][5].

Accuracy offers a general measure of correct predictions but may be misleading in class-imbalanced datasets, where tumour regions occupy a small portion of the image. In such cases, sensitivity (the ability to detect true tumour regions) becomes more important, as missing a tumour can have severe clinical implications. Specificity measures the model's ability to correctly identify healthy tissue and avoid false positives [6]. For segmentation tasks, the Dice Similarity Coefficient is widely used to quantify the overlap between the predicted tumour region and the ground truth annotation, with values closer to 1 indicating higher spatial accuracy [8][9].

Benchmark datasets such as BRATS (Brain Tumor Segmentation Challenge) and REMBRANDT are commonly used for

performance evaluation. These datasets provide high- quality, annotated MRI scans and standardized evaluation protocols, making them ideal for cross-study comparison [8].

Reported results across different methods show that deep learning models, particularly segmentation architectures like U-Net and CNN–SVM hybrids, consistently outperform conventional and classical machine learning techniques in terms of accuracy and Dice score [6][7]. For example, CNN- based models trained on BRATS data have achieved Dice scores above 0.85, while traditional ML approaches (e.g., SVM with handcrafted features) typically range between 0.70 and 0.80 [7][8].

A conceptual performance summary is provided below:

Table 1

Method	Accuracy (%)	Sensitivity	Specificity	Dice Score
SVM with GLCM Features	86.7	0.82	0.89	0.74
CNN (Custom)	91.4	0.90	0.92	0.84
U-Net (Segmentation)	93.2	0.91	0.93	0.87
CNN + SVM Hybrid	94.1	0.93	0.94	0.89

While performance depends on model architecture, training protocols, and dataset quality, current evidence suggests that deep and hybrid models provide the highest accuracy and spatial reliability, making them most suitable for clinical deployment [6][8][10].

CHALLENGES AND LIMITATIONS

Despite significant progress in automated brain tumour detection, several key challenges and limitations must be addressed to enable widespread clinical adoption. These issues include the scarcity and variability of medical imaging data, the risk of model overfitting, and the gap between research-grade models and real-world clinical application.

One of the most pressing limitations is the limited availability and quality of annotated medical datasets. High- performing models—particularly deep learning architectures—require large, diverse, and accurately labelled datasets to generalize well. However, acquiring such datasets is constrained by privacy regulations, institutional differences, and the high cost of manual expert annotation [4][5]. Even benchmark datasets like BRATS and REMBRANDT, though valuable, may not fully capture the heterogeneity seen in real clinical environments [8].

Another major issue is overfitting, especially in deep neural networks with millions of parameters. When trained on small or homogeneous datasets, these models may achieve high training accuracy but fail to generalize to new, unseen data. Techniques such as dropout, data augmentation, and transfer learning have been introduced to mitigate this issue, but the risk persists, particularly in small-sample settings common in medical applications [6][11].

A further limitation is the difficulty in translating AI models into clinical settings. Models that perform well in controlled research environments often struggle when deployed on clinical data due to differences in imaging protocols, scanner types, and patient populations [5][10]. In addition, many deep learning models are considered "black boxes," offering little interpretability or insight into their decision-making process—posing a barrier to clinician trust and regulatory approval [9][12].

Overcoming these limitations will require a multi- disciplinary effort involving not only AI researchers but also clinicians, regulatory experts, and system designers to ensure models are robust, transparent, and clinically useful.

FUTURE DIRECTIONS

As brain tumour detection systems continue to evolve, several promising directions are emerging to address existing limitations and enhance clinical applicability. Among these, the development of explainable AI (XAI), implementation of real-time detection systems, and integration with clinical decision support systems (CDSS) stand out as key areas of future research and innovation.

A persistent concern with deep learning models is their lack of interpretability. Despite high accuracy, many models operate as "black boxes," providing little insight into how decisions are made. This opacity poses a challenge in clinical environments, where transparency and accountability are essential [10][12]. Explainable AI aims to bridge this gap by making model outputs more understandable to human users. Techniques such as Grad-CAM, saliency maps, and attention mechanisms can highlight the specific regions in MRI scans that influenced the model's decision, thereby improving clinician trust and facilitating model validation [9][10].

Another important direction is the push towards real-time detection. Advances in computing hardware, including GPUs and edge devices, are enabling faster model inference, opening up possibilities for real-time or near-real-time processing of brain MRI scans [6]. Such capabilities are particularly useful in time-

sensitive settings like surgical planning, intraoperative imaging, or emergency diagnostics, where rapid feedback can support immediate clinical decisions [5].

Equally important is the integration of AI models with existing clinical workflows via clinical decision support systems (CDSS). Embedding tumour detection algorithms into systems such as PACS (Picture Archiving and Communication Systems) or EHRs (Electronic Health Records) can assist radiologists by flagging abnormal regions, suggesting diagnoses, or prioritizing critical cases [10]. For effective adoption, these systems must be user-friendly, interoperable with hospital infrastructure, and compliant with data privacy and medical device regulations [4][5].

Additionally, federated learning and multi-institutional collaborations are emerging to overcome the data scarcity challenge without compromising patient privacy, allowing models to be trained on distributed datasets across hospitals [11].

In summary, the future of brain tumour detection lies not only in improving model performance but also in developing systems that are interpretable, fast, reliable, and seamlessly integrated into clinical practice. These advancements will be essential for moving AI from the lab to the bedside.

CONCLUSION

The detection and classification of brain tumours using medical imaging has seen significant advancements, moving from traditional image processing to complex machine learning and deep learning frameworks. Each category of methods—conventional techniques, classical machine learning, deep learning, and hybrid approaches—offers distinct advantages and limitations.

Conventional image processing techniques, such as thresholding and edge detection, are computationally simple and interpretable. However, they often fail to handle the complexity and variability inherent in tumour morphology, especially in noisy or low-contrast MRI scans [1][2].

Machine learning methods, including SVMs, k-NNs, and Random Forests, demonstrated better adaptability by leveraging handcrafted features like GLCM, LBP, and PCA

[4][5]. These methods offer higher accuracy than rule-based approaches but depend heavily on the quality and relevance of feature selection, and may struggle with generalization in diverse datasets.

The most promising breakthroughs have emerged from deep learning techniques, particularly Convolutional Neural Networks (CNNs) and architectures like U-Net, VGGNet, and ResNet [6][7]. These models learn deep, abstract features directly from image data, resulting in superior performance for both classification and segmentation tasks, especially when trained on benchmark datasets like BRATS [8]. Moreover, transfer learning has allowed models pre-trained on large datasets to be fine-tuned for brain tumour detection, mitigating data scarcity challenges [11].

Among all reviewed approaches, deep learning and hybrid models—especially those combining CNNs with machine learning classifiers like SVM—have shown the most promise, delivering high accuracy, sensitivity, and Dice scores on public datasets [6][7][10]. Feature fusion and ensemble strategies further enhance robustness and generalization, making these models more suitable for real-world scenarios.

Despite these advances, challenges such as limited data availability, overfitting, and lack of interpretability remain. These limitations must be addressed through explainable AI, federated learning, and integration with clinical decision support systems (CDSS) to ensure practical usability and clinician trust [9][10][12].

In conclusion, while no single method is universally optimal, deep learning and hybrid frameworks currently represent the state-of-the-

art in automated brain tumour detection. Continued interdisciplinary research focusing on transparency, scalability, and clinical integration will be essential to bridge the gap between research models and real- world diagnostic tools.

The author declares no conflict of interest..

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UTILIZING ARTIFICIAL INTELLIGENCE TO DRIVE SUPERIOR EFFICIENCY IN SUPPLY CHAIN OPTIMIZATION

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ABSTRACT

This study critically investigates the transformative role of Artificial Intelligence (AI) in enhancing operational efficiency, innovation, and sustainability within Supply Chain Management (SCM). Employing a systematic literature review and content analysis of peer reviewed journal articles and conference papers published between 2015 and 2024, the research synthesizes emerging trends, challenges, and strategic implications of AI adoption across global supply chains.

The analysis encompasses a diverse range of AI technologies machine learning, deep learning, natural language processing, robotics, blockchain, and AIoT (Artificial Intelligence of Things) and examines their practical applications in demand forecasting, inventory optimization, supplier evaluation, logistics automation, and sustainability management.

Findings reveal that AI-driven systems significantly enhance decision making accuracy, cost efficiency, and risk mitigation, while fostering intelligent, adaptive, and resilient supply chains. Innovations such as Generative AI, Digital Twins, and autonomous SCM systems further demonstrate the potential for real time responsiveness and sustainability driven logistics. However, challenges including data privacy concerns, algorithmic bias**,** skill shortages, and regulatory uncertainties hinder widespread AI adoption.

The study concludes that realizing AI's full potential in SCM demands collaborative efforts across technological, organizational, and policy dimensions. Strengthening digital infrastructure, investing in workforce upskilling, and developing robust governance frameworks are imperative for responsible AI integration.

This research contributes to the ongoing discourse on digital transformation and sustainable supply chain strategies, emphasizing AI's enduring impact on efficiency, resilience, and global competitiveness.

Keywords: AI, SCM, Operational Efficiency, Sustainability, Digital Transformation, IoT

INTRODUCTION

The Implementation of Artificial Intelligence in Modern Supply Chain Systems

The integration of Artificial Intelligence (AI) into Supply Chain Management (SCM) has profoundly reshaped conventional processes, driving enhanced efficiency, automation, and data-informed decision- making. In the last decade, AI has evolved from simple automation technologies into intelligent, self-learning systems that enable predictive analytics, real time optimization, and autonomous operations (Pattnaik et al., 2022; Torres-Franco, 2023). This digital transformation is redefining how organizations design and manage their supply chains, fostering greater agility, data-centric responsiveness, and operational resilience (Kumari et al., 2023).

AI enables supply chains to process vast amounts of data, predict demand fluctuations, and optimize logistics in ways that were previously unattainable. According to Torres-Franco (2023), AI contributes to bridging the gap between large firms and SMEs by delivering affordable and innovative technological solutions, allowing smaller businesses to participate competitively in global markets.

Beyond improving efficiency, AI is essential for enhancing strategic business planning. Pattnaik et al. (2022) highlight how AI-enabled systems support strategic decision-making by providing businesses with the capability to foresee market shifts and adjust operations accordingly. AI does not replace human intelligence but augments it, enabling companies to develop more adaptive and intelligent supply chain strategies.

Additionally, AI strengthens core SCM functions such as demand forecasting, inventory management, and logistics. Kumari et al. (2023) emphasize that AI's predictive capabilities allow businesses to anticipate market changes, reduce inventory waste, and improve supply chain agility. As AI continues to evolve, its ability to automate and optimize complex supply chain tasks will further drive operational excellence.

The evolution of Artificial Intelligence (AI) within Supply Chain Management (SCM) demonstrates a consistent advancement toward increasingly intelligent and self-governing systems. Early implementations focused on basic automation, but recent advancements in machine learning and data analytics have enabled

AI to make real-time, data-driven decisions with minimal human intervention. This trend is expected to continue, leading to even greater efficiency and flexibility in global supply chain networks.

This study aims to explore the impact of AI on supply chain operations from 2015 to 2024, identifying key advancements, challenges, and future trends. Through an examination of existing research, this study aims to offer understanding of the ways in which Artificial Intelligence (AI) technologies improve supply chain efficiency and strengthen organizational competitiveness.

In conclusion, Artificial Intelligence represents a pivotal development in supply chain management, offering tools for large-scale data analysis, trend prediction, and process automation. AI provides businesses with powerful capabilities to optimize operations and enhance decision-making. As AI continues to advance, it will play an increasingly important role in shaping the future of global supply chains, making them more efficient, resilient, and

adaptive to market demands.

AI's Contribution to Efficient Supply Chain Management

Artificial Intelligence (AI) has become a transformative force in Supply Chain Management (SCM), enabling businesses to streamline operations, enhance efficiency, and improve decision-making. The integration of machine learning, deep learning, natural language processing (NLP), and robotic process automation (RPA) has redefined traditional supply chain functions, making them more predictive, autonomous, and data-driven (Wamba et al., 2018; Ivanov & Dolgui, 2021). AI-driven supply chains are not only faster and more resilient but also more adaptable to disruptions, market fluctuations, and global uncertainties (Min, 2019).

AI's Impact on Core Supply Chain Functions

- **Enhanced Demand Prediction and Inventory Control**

AI has revolutionized demand forecasting by leveraging real-time data analytics, historical patterns, and external factors such as weather conditions, economic indicators, and consumer sentiment. Deep learning models and AI-driven predictive analytics enhance forecast accuracy, reducing the risks of stockouts and overstocking (Min, 2019). Reinforcement learning algorithms further optimize inventory management by dynamically adjusting stock levels in response to demand fluctuations (Ivanov & Dolgui, 2021).

- **AI-Powered Supplier Selection and Risk Management**

AI automates supplier evaluation by analyzing large datasets on pricing, quality, delivery performance, and sustainability. Machine learning algorithms can rank suppliers based on historical performance, helping businesses select the most reliable partners (Choi et al., 2018). Furthermore, AI plays a vital role in risk mitigation, identifying geopolitical risks, financial instability, and potential supplier failures through predictive modeling (Dubey et al., 2019).

- **Intelligent Logistics and Transportation Optimization**

AI enhances logistics by improving route optimization, predictive maintenance, and autonomous delivery systems. Computer vision-powered autonomous warehouses and AI-driven fleet management systems increase delivery accuracy and efficiency (Wamba et al., 2018). Emerging technologies such as AI-enabled digital twins allow supply chain managers to simulate and optimize operations in real time (Pattnaik et al., 2022).

- **Sustainability and Green Supply Chain Management**

AI is instrumental in promoting sustainable supply chain practices. AI-powered analytics optimize carbon footprint reduction, energy-efficient logistics, and waste management strategies. For instance, AI-based route optimization tools help logistics firms reduce fuel consumption and emissions (Kumari et al., 2023). AI also supports circular economy models by tracking product lifecycles and improving recycling processes (Dubey et al., 2019).

The future of AI-driven supply chains is expected to bring further advancements in the following areas:

- **AI and Blockchain Integration:** Enhancing data security and traceability across global supply

chains (Casino et al., 2019).

- **Edge AI and IoT Sensors:** Improving real-time decision-making by analyzing data at the source, thereby reducing latency (Xu et al., 2021).

- **Autonomous Supply Chains:** The rise of fully automated warehouses, robotic process automation (RPA), and self-learning AI systems will minimize human intervention and improve operational efficiency (Ivanov & Dolgui, 2021).
- **AI-Driven Decision Intelligence:** Merging AI with strategic planning tools will allow businesses to anticipate market trends and create resilient supply chains (Pattnaik et al., 2022).

AI has established itself as a cornerstone of modern supply chain innovation, significantly improving forecasting accuracy, logistics efficiency, risk management, and sustainability efforts. The continued development of AI-powered tools will further enhance automation, adaptability, and strategic decision- making in SCM. As businesses increasingly embrace AI, supply chains will become smarter, more agile, and better equipped to navigate complex global challenges. The next phase of AI evolution in SCM will focus on greater autonomy, real-time intelligence, and sustainability-driven solutions.

Technological Trajectory: From Traditional Supply Chain Practices to AI-Enabled Solutions

The progress of Artificial Intelligence (AI) within Supply Chain Management (SCM) marks a significant shift in the operational and strategic dynamics of global supply networks. This shift from conventional manual practices to intelligent, data-driven systems reflects not only the progress of technology but also the increasing complexity and competitiveness of global markets. Since 2015, the integration of AI has moved beyond basic automation toward intelligent systems capable of forecasting, autonomous decision-making, and real-time operational optimization, fundamentally altering the landscape of SCM (Ivanov & Dolgui, 2021). In its early stages, the application of digital tools in SCM primarily involved basic computerization, automating tasks such as order processing and inventory tracking. However, the digital revolution, particularly post-2015, introduced new frontiers, including the proliferation of cloud computing, the Internet of Things (IoT), and advanced analytics. These developments laid the groundwork for AI's deeper integration into SCM systems. According to Rickardo and Wites (2023), The extensive implementation of AI since 2015 has been propelled by the growing demand for agile, adaptive, and resilient supply chains that can effectively manage the uncertainties of contemporary markets.

The role of AI has since expanded significantly, moving from rule-based automation to adaptive systems utilizing machine learning, natural language processing, and intelligent algorithms. These technologies enable real-time data analysis, improve demand forecasting accuracy, optimize inventory levels, and facilitate dynamic supply chain network configurations. Sharma et al. (2022) emphasize that AI's influence now extends to critical SCM functions such as supplier selection, risk management, sustainability tracking, and green logistics.

One of the most impactful milestones in this evolution has been the deployment of machine learning models that can extract insights from vast datasets, enabling organizations to predict customer demand, mitigate risks, and enhance delivery performance. As Helo and Hao (2021) observe, AI has transformed traditional demand forecasting and logistics planning into dynamic, responsive systems capable of proactive adjustments to market signals.

Beyond analytics, AI has enabled the creation of integrated digital ecosystems within supply chains. When Artificial Intelligence (AI) combines with Internet of Things (IoT) and blockchain technologies, it creates better visibility, tracking, and trust across all supply chain partners (Casino et al., 2019; Xu et al., 2021). This integration enables continuous monitoring, timely maintenance, and smoother coordination between different parts of the supply chain, resulting in a system that is more efficient and transparent.

Between 2015 and 2024, AI-driven innovation in SCM has not only improved operational efficiency but also strengthened resilience amid disruptions ranging from geopolitical instabilities to global health crises. AI tools have proven instrumental in enabling rapid scenario analysis, adaptive planning, and autonomous execution of logistics operations (Queiroz et al., 2020).

In conclusion, the evolution of AI in supply chain management—from traditional methodologies to intelligent systems—marks a paradigm shift toward automation, adaptability, and sustainability. What began as basic digitalization has matured into a transformative force that enables organizations to streamline operations, reduce environmental impact, and foster long-term competitiveness. As digital technologies continue to advance, the strategic role of AI in SCM will only grow, paving the way for autonomous, self- regulating, and ethically governed supply networks (Wamba et al., 2018).

Purpose and Research Objectives

This review endeavours to conduct a critical analysis of the integration of Artificial Intelligence (AI) technologies within Supply Chain Management (SCM), highlighting their implications for enhancing operational efficiency, advancing sustainability practices, and shaping strategic decision-making across the global supply chain ecosystem.

The specific objectives of the review are as follows:

- To explore the developmental trajectory and historical progression of AI adoption within supply chain management.
- To assess the effects of AI integration on enhancing supply chain efficiency and responsiveness.
- To investigate contemporary applications, tools, and innovations in AI-driven supply chain practices.

METHODOLOGY

The methodology of this study, focused on AI in SCM, involves conducting a systematic literature review alongside content analysis to thoroughly assess existing research, identify trends, and uncover gaps for future exploration.

Sources of Data

The primary data for this research were obtained from scholarly journals,

conference papers, and industry reports available in reputable databases, including IEEE Xplore, Scopus, Web of Science, and Google

Scholar. These sources offer extensive and reliable coverage of studies related to the application of Artificial Intelligence (AI) in Supply Chain Management (SCM).

Search Strategy

The research employed a systematic search strategy utilizing specific keywords and phrases, including "Artificial Intelligence," "Supply Chain Management," "AI in Logistics," and "AI-driven Supply Chain Innovations." Boolean operators (AND, OR) were incorporated to enhance precision and ensure the retrieval of only pertinent studies. The review concentrated on publications from 2015 to 2024, capturing recent developments and real-world implementations of AI within supply chain management.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were defined to preserve the study's focus and uphold academic rigor in assessing the influence of Artificial Intelligence (AI) on Supply Chain Management (SCM).

Inclusion Criteria:

- Peer-reviewed studies focusing on AI applications in SCM.
- Empirical studies demonstrating AI's role in enhancing efficiency, promoting sustainability, and supporting strategic decision-making in supply chains.
- Literature published between 2015 and 2024, ensuring coverage of current advancements.
- English-language studies for consistency.

Exclusion Criteria:

- Sources that are not peer-reviewed, including blogs, reports, or other non-academic publications lacking scholarly reliability.
- Studies not directly related to AI's role in SCM.
- Pre-2015 or non-English studies excluded for relevance and consistency.

Applying these criteria ensured a focused, high-quality literature base that supports a clear understanding of AI's evolving role in SCM.

Selection Criteria

A two-stage screening approach was adopted for literature selection. In the first stage, titles and abstracts were reviewed to assess their relevance to the study's objectives. In the second stage, full-text articles were examined to verify compliance with the inclusion criteria. To maintain reliability, two researchers

independently conducted the screening, resolving any disagreements through discussion or, if needed, by consulting a third reviewer.

Data Analysis

A content analysis method was employed to organize and interpret findings from the selected studies. The reviewed data were coded into major themes, namely:

- AI-driven innovations in Supply Chain Management (SCM)
- Challenges in AI implementation
- Strategic implications for SCM stakeholders

To deepen the analysis, qualitative insights, expert opinions, and case study evidence were integrated, emphasizing both the theoretical and practical dimensions of AI in SCM. Following this methodological framework, the study provides a systematic and comprehensive assessment of AI's influence on supply chain management, offering meaningful insights for researchers, industry professionals, and policymakers.

LITERATURE REVIEW

Key Principles Underpinning AI Integration in Supply Chains

Integrating Artificial Intelligence (AI) into Supply Chain Management (SCM) has fundamentally transformed operational frameworks, driving improvements in accuracy, productivity, and innovation. Leveraging data-driven insights, predictive analytics, and real-time monitoring, AI enables organizations to streamline workflows, manage risks effectively, and foster sustainable growth (Chaudhari, 2022).

At the core of AI's transformative influence in SCM is its ability to process vast amounts of data and enhance strategic decision-making. Previous research highlights the utilization of AI methodologies such as demand forecasting, supply prediction, and text analytics in optimizing key business functions (Adewusi et al., 2024). Through these technologies, firms can anticipate market fluctuations, forecast disruptions, and determine optimal strategies, thereby minimizing operational expenses and improving supply chain flexibility.

Machine Learning (ML) and Data Science (DS) have become pivotal components of modern SCM. As noted by Pandey et al. (2023), ML algorithms strengthen supply chain visibility by identifying bottlenecks, improving inventory control, and enhancing logistics performance. These AI-based systems continuously learn from historical data, enabling them to become increasingly autonomous, adaptive, and efficient in decision-making.

The integration of Big Data and the Internet of Things (IoT) has further amplified AI's role in SCM. Zeng and Yi (2023) emphasize that IoT devices enable real-time tracking and data analysis across supply chain operations, fostering synchronization between production outputs and demand requirements. AI-driven analytics provide actionable, real-time intelligence to resolve issues such as demand-supply imbalances and inventory management, promoting proactive and evidence-based decisions throughout the supply chain.

A defining feature of AI in SCM is its inherent capacity for adaptability and self-improvement. AI-powered systems evolve continuously by utilizing both real-time and historical data to refine their analytical and decision-making capabilities (Rahman et al., 2024). Such adaptability is essential in an era marked by market volatility, geopolitical uncertainties, and global disruptions, where supply chains must remain agile and responsive.

In addition, AI enhances collaboration and integration across supply chain partners by consolidating information into unified, data-driven platforms. This connectivity fosters seamless coordination among suppliers, manufacturers, distributors, and retailers—resulting in reduced lead times, lower operational costs, and improved

customer satisfaction (Singh & Patel, 2024). AI-based solutions also reinforce transparency and resilience, ensuring that supply chains sustain competitiveness in dynamic global markets.

In conclusion, the fundamental principles of AI in SCM—encompassing data-driven decision-making, the integration of ML and DS, the utilization of Big Data and IoT, continuous learning, and collaborative networks—form the cornerstone of modern supply chain systems. As businesses navigate increasing complexity in global operations, AI-enabled supply chain solutions will continue to drive efficiency, innovation, and long-term sustainability.

Structural Frameworks for AI-Driven Supply Chain Management

The integration of Artificial Intelligence (AI) within Supply Chain Management (SCM) has facilitated the emergence of advanced architectural frameworks designed to enable seamless AI implementation. These frameworks commonly incorporate Machine Learning (ML), blockchain technology, and the Internet of Things (IoT) to enhance supply chain efficiency, improve transparency, and strengthen risk management mechanisms (Singh & Prabhu, 2023).

According to Singh and Prabhu (2023), an agile, blockchain-based risk management framework embeds AI capabilities into core supply chain processes. This model utilizes decentralized ledgers, smart contracts, and AI-driven risk evaluation tools to identify and mitigate potential risks in real time, thereby improving operational resilience. Blockchain technology ensures the security and transparency of transactions, while AI continuously detects and responds to challenges such as demand fluctuations and regulatory compliance issues (Oguejiofor et al., 2023). The inclusion of components like risk association trees and risk item ledgers enhances scalability and adaptability across supply chain networks.

AI-driven mobile application frameworks have also proven transformative in optimizing logistics, inventory control, and tracking operations. As highlighted by Ananth et al. (2023), mobile platforms powered by AI streamline supply chain activities, reduce costs, and enhance decision-making agility. By employing machine learning algorithms, these systems facilitate automated demand forecasting, predictive inventory management, and real-time shipment visibility. Such frameworks empower managers with instant access to actionable insights, enabling swift responses to market dynamics and operational disruptions.

Beyond risk management and logistics, AI integration frameworks have been instrumental in advancing organizational decision-making. Richey et al. (2023) introduce a research-oriented AI framework that provides a strategic roadmap for implementing AI technologies across supply chains. This framework delineates AI's functional capabilities, limitations, and potential barriers—including concerns about data quality, privacy, and system interoperability. By consolidating diverse AI applications, it helps organizations enhance logistics visibility, operational efficiency, and overall performance.

Furthermore, AI-enabled Decision Support Systems (DSS) have become essential to modern supply chain architectures. Zhang et al. (2024) describe DSS models that integrate neural networks, big data analytics, and cloud computing to optimize workflow planning, routing efficiency, and demand forecasting. These intelligent systems automate complex decision-making processes, fostering supply chain resilience in the face of market uncertainty and global disruptions.

In summary, AI-based architectural frameworks represent the foundation for effective AI deployment in SCM. Whether through blockchain-supported risk management, AI-powered mobile platforms, research- driven integration models, or AI-enabled decision support systems, these frameworks enhance supply chain visibility, adaptability, and strategic responsiveness. As AI technologies continue to evolve, such architectures are expected to play a pivotal role in shaping the future of Supply Chain Management, driving innovation, operational excellence, and sustainable growth.

AI Implementation Scenarios in Supply Chain Operations

The incorporation of Artificial Intelligence (AI) into Supply Chain Management (SCM) has significantly improved efficiency, flexibility, and strategic decision-making across various operational domains. AI- based applications now encompass demand forecasting, supplier evaluation, logistics optimization, quality

assurance, risk mitigation, and customer relationship management, thereby transforming conventional supply chains into intelligent, adaptive, and automated networks (Torres-Franco, 2023).

AI in Demand Forecasting and Inventory Management

One of the most impactful uses of Artificial Intelligence (AI) in Supply Chain Management (SCM) lies in demand forecasting and inventory optimization. Through the application of machine learning algorithms and big data analytics, AI produces highly accurate demand predictions, allowing organizations to maintain optimal inventory levels while avoiding shortages or excess stock. According to Torres-Franco (2023), AI utilizes historical sales records, market dynamics, and social media sentiment analysis to generate precise forecasts. These predictive insights help minimize waste, reduce inventory holding costs, and improve customer satisfaction by ensuring timely product availability

Artificial Intelligence (AI) strengthens supplier selection and relationship management

By evaluating key parameters such as cost efficiency, quality standards, delivery reliability, and associated risks. According to Pournader et al. (2021), AI-driven systems enable real-time monitoring of supplier performance, allowing firms to identify potential issues early, manage risks proactively, and negotiate more favorable contracts. Through data-informed decision-making, AI supports the development of strategic supplier partnerships, resulting in a more resilient, transparent, and responsive supply chain.

AI in Logistics and Transportation

Optimization

AI-driven technologies are transforming logistics and transportation management by enhancing routing, scheduling, and fleet optimization. As noted by Helo and Hao (2021), AI-based predictive analytics account for variables such as traffic flow, weather conditions, and vehicle capacity to identify the most efficient delivery routes, thereby minimizing transportation costs and reducing carbon emissions. Additionally, the deployment of autonomous vehicles and AI-enabled drones is revolutionizing last-mile delivery operations, enabling faster, more reliable, and cost-efficient shipment management (Okunade et al., 2023).

AI in Quality Control and Compliance Monitoring

AI plays a vital role in quality control and regulatory compliance by utilizing computer vision and machine learning models to detect defects, anomalies, and deviations in production processes. Ajala and Balogun (2024) highlight how AI-powered image recognition systems can analyze product quality in real time, ensuring that defective items are identified before reaching customers. Additionally, AI aids in compliance monitoring by analyzing supply chain data for adherence to ethical sourcing and sustainability regulations, helping businesses maintain corporate social responsibility standards.

AI in Risk Management and Mitigation

Risk management is another domain where AI excels by providing predictive insights into potential supply chain disruptions. AI-driven systems analyze data from diverse sources, including weather reports, geopolitical trends, and supplier reliability scores, to anticipate risks such as supply shortages, political instability, or cybersecurity threats (Zhang et al., 2024). These predictive capabilities allow organizations to develop contingency plans, optimize risk mitigation strategies, and ensure business continuity in uncertain environments.

AI in Customer Service and Personalization

AI-driven chatbots and virtual assistants have revolutionized customer service in SCM, offering real-time tracking updates, handling return requests, and providing instant query resolution (Mehta et al., 2023). By leveraging natural language processing (NLP) and machine learning, AI enhances customer engagement, personalization, and satisfaction. Businesses that implement AI-powered customer service solutions experience improved brand loyalty and operational efficiency.

AI applications in supply chain operations cover a wide range of functions, including demand forecasting, supplier management, logistics optimization, risk mitigation, and customer service. Artificial Intelligence has transformed SCM into a data-driven, intelligent, and efficient system, offering businesses greater visibility, resilience, and adaptability. As AI technologies continue to advance, their role in enhancing supply chain operations and driving innovation will only expand, enabling companies to remain competitive in an increasingly complex global market.

Key Developments in the Advancement of AI for Supply Chain Optimization (2015–2024)

The advancement of AI applications in SCM from 2015 to 2024 has been marked

by significant technological progress, transforming traditional supply chain operations into more efficient, resilient, and data-driven systems. AI's role has expanded from automating routine tasks to predictive analytics, IoT integration, smart warehouses, and sustainability initiatives. This evolution underscores the strategic importance of AI in enhancing decision-making and fostering innovation within supply chains.

Early AI Integration: Process Automation (2015–2017)

In the early stage of AI integration into supply chain management, the emphasis was on automating routine and repetitive activities such as inventory tracking, order processing, and production scheduling. According to Gomes Rickardo and Morais Wites (2023), this period saw a shift from manual operations to automated systems, reducing human error and improving operational efficiency. Enterprise Resource Planning (ERP)

systems powered by AI, along with robotic process automation (RPA), began enhancing efficiency in logistics, warehouse operations, and procurement activities.

AI-Driven Predictive Analytics (2018–2020)

One of the significant advancements in the evolution of supply chain management (SCM) was the integration of predictive analytics and machine learning (ML) techniques for demand forecasting. According to Singh (2023), AI-based algorithms facilitated the examination of extensive datasets, resulting in more precise demand predictions. This advancement enabled firms to optimize inventory management, minimize stockouts, and enhance overall supply chain resilience. Furthermore, AI-enabled predictive maintenance models supported manufacturers in anticipating equipment malfunctions, thereby decreasing downtime and reducing maintenance expenses (Chen et al., 2019).

IoT and AI-Enabled Real-Time Supply Chain Visibility (2020–2022)

The integration of AI with the Internet of Things (IoT) revolutionized supply chain visibility. Jagadeesan et al. (2023) emphasize how IoT sensors in transportation, warehouses, and manufacturing units provide real-time tracking and monitoring of goods. AI analyzed sensor-generated data to enhance logistics optimization, risk management, and route planning. Companies leveraged AI for automated quality control, identifying defects using computer vision and anomaly detection algorithms (Zhao et al., 2021).

The Rise of Smart Warehouses and Robotics (2022–2023)

The emergence of Industry 4.0 accelerated the adoption of AI-powered smart warehouses. AI-driven robotics and autonomous mobile robots (AMRs) improved inventory management, order fulfillment, and warehouse automation. Gomes Rickardo and Morais Wites (2023) note that AI-powered robotic systems optimized picking, packing, and sorting operations, significantly reducing costs and increasing efficiency.

AI for Sustainability and Ethical Sourcing (2023–2024)

In recent years, Artificial Intelligence has become instrumental in advancing

sustainability and fostering ethical practices within supply chain management. AI-driven carbon footprint analysis tools help businesses track emissions, optimize energy consumption, and improve waste management. Adewusi et al. (2023) discuss how AI has been instrumental in ensuring compliance with environmental regulations and fostering responsible sourcing practices. Companies now use AI-powered blockchain systems to monitor ethical sourcing and combat counterfeit goods (Li & Zhang, 2023).

Challenges and Future Outlook

Integrating AI into supply chain management (SCM) still faces notable challenges, including issues related to data privacy, cybersecurity risks, and ethical use of AI (Adewusi et al., 2023). Moreover, organizations need to overcome workforce skill shortages and inadequate infrastructure to fully capitalize on AI's capabilities. Looking ahead, emerging technologies such as generative AI, digital twins, and hyper-automation are expected to further revolutionize supply chain performance and efficiency (Huang & Patel, 2024). From 2015 to 2024, the evolution of AI in supply chain optimization has witnessed key developments—from basic task automation and predictive analytics to the integration of IoT systems, establishment of intelligent warehouses, and implementation of sustainability-driven strategies. Throughout this period, AI has continuously improved the efficiency, flexibility, and resilience of supply chains. Future innovations are projected to enhance real-time decision-making and automation even further. As global supply networks grow more complex, the strategic application of AI technologies will be essential for maintaining competitiveness and achieving long-term sustainability.

Leading-Edge Developments in AI Applications for Supply Chains

Between 2015 and 2024, the integration of Artificial Intelligence (AI) into Supply Chain Management (SCM) has led to transformative innovations that greatly improved efficiency, visibility, and sustainability. AI-enabled developments in blockchain, the Artificial Intelligence of Things (AIoT), and big data analytics have revolutionized supply chain operations by facilitating real-time monitoring, predictive analysis, and process automation. These advancements have allowed organizations to build more resilient, adaptive, and competitive supply networks.

AI and Blockchain for Secure, Transparent Supply Chains:

The combination of AI and blockchain technology has revolutionized supply chain security, transparency, and automation. Torres-Franco (2023) explains that AI-powered blockchain applications ensure secure transactions, automated compliance, and fraud prevention by maintaining an immutable digital ledger. AI enhances blockchain capabilities by enabling predictive analytics for demand forecasting, real-time tracking of shipments, and risk mitigation strategies. AI-driven smart contracts automate procurement and payments, reducing inefficiencies and enhancing trust across the supply chain. As a result, businesses leveraging AI-blockchain integration can increase operational efficiency and improve data integrity.

The Fusion of AI and IoT in Supply

Chains:

The Artificial Intelligence of Things (AIoT), which integrates artificial intelligence with the Internet of Things (IoT), facilitates intelligent and autonomous supply chain operations. As noted by Nozari, Szmelter-

Jarosz, and Ghahremani-Nahr (2022), AIoT plays a crucial role in real-time inventory monitoring, predictive maintenance, and logistics optimization. Through AI-powered IoT devices such as sensors, RFID tags, and GPS trackers, continuous data is collected on inventory status, environmental conditions, and fleet movements. This data is then processed by AI algorithms to forecast potential stock shortages, optimize transportation routes, and improve warehouse management. Despite its numerous advantages, the adoption of AIoT is hindered by challenges, including cybersecurity vulnerabilities and significant infrastructure costs, which must be addressed to unlock its full potential. In parallel, artificial intelligence and big data analytics are revolutionizing food supply chains by enhancing both sustainability and efficiency. According to Sharma et al. (2021), machine learning (ML) techniques and artificial neural networks (ANNs) have enabled advancements in precision agriculture, food safety assurance, and demand forecasting, thereby strengthening the resilience and sustainability of modern food supply systems. AI-powered traceability systems enhance product tracking, ensuring compliance with quality and regulatory standards. Additionally, AI-driven consumer behavior analysis helps optimize production planning and inventory levels, reducing food waste and supply chain disruptions. These technologies promote a sustainable and cost-effective food supply network.

AI-Powered Predictive Supply Chain Analytics:

One of the most recent advancements (2024) in AI-driven SCM is the application of predictive analytics to forecast market demand, supplier risks, and logistical bottlenecks. Kumar & Zhang (2024) explain how AI models analyze historical data and external factors (e.g., weather patterns, economic trends) to generate accurate demand forecasts. Companies using AI-powered predictive analytics have reported higher efficiency in supply planning, reduced operational costs, and improved delivery reliability. Despite these advancements, AI-driven SCM faces challenges, including data privacy issues, AI model biases, integration complexities, and workforce skill gaps (Adewusi et al., 2023). Addressing these barriers requires collaborative efforts among technology developers, industry leaders, and policymakers to establish AI regulations, invest in AI research, and promote training programs for AI adoption. AI-driven innovations in blockchain, AIoT, predictive analytics, and big data are reshaping supply chains, making them more efficient, transparent, and sustainable. Businesses that strategically adopt AI technologies will gain a competitive edge in the global market. However, organizations must navigate the challenges of AI implementation to fully realize its transformative potential in SCM. Moving forward, AI's role in supply chains will continue to evolve, driving resilience, adaptability, and innovation

Table 1 Key AI Developments in Supply Chain Management (2015–2024)

Period	AI Development / Innovation	Impact on Supply Chain Management (SCM)	References
2015–2017	Early AI integration; process automation, ERP systems, RPA	Reduced human error, improved operational efficiency, automated routine tasks (inventory, order processing, production scheduling)	Gomes Rickardo & Morais Wites, 2023
2018–2020	AI-driven predictive analytics, machine learning for demand forecasting	Improved accuracy in demand prediction, optimized inventory management, reduced stockouts, predictive maintenance for equipment	Singh, 2023; Chen et al., 2019
2020–2022	IoT and AI integration for real-time visibility	Real-time tracking, enhanced logistics optimization, risk management, automated quality control	Jagadeesan et al., 2023; Zhao et al., 2021
2022–2023	Smart warehouses, AI-powered robotics, AMRs	Increased warehouse automation, improved order fulfillment, reduced costs, faster operations	Gomes Rickardo & Morais Wites, 2023
2023–2024	AI for sustainability and ethical sourcing, AI-powered blockchain	Optimized carbon footprint, compliance with environmental regulations, traceability, ethical sourcing, reduced waste	Adewusi et al., 2023; Li & Zhang, 2023
2024	AI-powered predictive analytics & AIoT in supply chains	Forecasting market demand, supplier risks, logistical bottlenecks, intelligent autonomous operations, predictive maintenance, enhanced decision-making	Kumar & Zhang, 2024; Nozari et al., 2022; Sharma et al., 2021

Future Pathways of AI-Enabled Solutions in Supply Chain Management

The landscape of Supply Chain Management (SCM) has been evolving significantly since 2015, influenced by the increasing integration of Artificial Intelligence (AI) technologies across operational and strategic domains. This transformation is redefining the structure and performance of global supply chains by enhancing efficiency, agility, and resilience. The adoption of AI has gone beyond resolving traditional inefficiencies, establishing a foundation for advanced and future-ready supply

chain models. In the early phase, Wamba et al. (2015) highlighted the transformative role of big data analytics and AI in operations and supply chain management, suggesting that AI could generate strategic advantages through predictive analytics, real-time visibility, and enhanced decision-making. This early insight effectively foreshadowed the evolution toward data-driven approaches in SCM.

Building on this, Min (2017) explored how AI technologies, particularly in forecasting, inventory control, and logistics, could transition supply chains from reactive mechanisms to proactive systems. He highlighted the importance of machine learning in identifying demand patterns and mitigating supply disruptions, marking a turning point in AI's application to supply chain resilience and performance.

By 2019, Dubey et al. (2019) offered a more systematic analysis of AI's role in SCM, emphasizing its impact on enhancing transparency, optimizing complex networks, and improving end-to-end visibility. Their work provided a comprehensive framework for understanding how AI applications, such as robotic process automation, predictive analytics, and intelligent decision-support systems, could contribute to competitive advantage and strategic agility.

As AI capabilities matured, new forms of digital transformation began shaping supply chains. Singh (2024) observed how AI and Machine Learning (ML) technologies are now central to real-time inventory management, demand forecasting, and logistics optimization. These technologies reduce operational costs and improve supply chain responsiveness, though their successful implementation still depends on overcoming challenges related to data privacy, ethical governance, and digital workforce transformation.

In recent years, generative AI has become a transformative innovation in supply chain planning and operations. According to Shekhar et al. (2024), generative AI plays a crucial role in enhancing procurement efficiency, improving forecasting precision, and strengthening risk management strategies. This form of AI enables dynamic scenario simulations, allowing firms to proactively adjust to shifting market demands. However, Shekhar and colleagues caution that effective adoption requires addressing skill shortages, ethical concerns, and integration complexities.

Another noteworthy advancement is the development of autonomous supply chains, where AI systems operate with minimal human intervention. Zhang et al. (2024) describe how reinforcement learning and deep neural networks enable end-to-end automation, from warehouse robotics to adaptive routing and delivery systems. These innovations reduce lead times, improve accuracy, and enhance resilience, though concerns such as cybersecurity risks and human-machine collaboration remain critical.

Sector-specific applications also highlight AI's expanding relevance. For instance, Painuly, Sharma, and Matta (2024) investigate AI's integration in e-healthcare supply chains, emphasizing its role in improving real-time tracking, optimizing medical inventory, and safeguarding data. However, successful implementation in such high-stakes environments demands robust infrastructure and security protocols.

In conclusion, the evolution of AI in supply chain management from 2015 to 2024 illustrates a clear trajectory from foundational data analytics to intelligent, autonomous, and context-specific applications. Early studies underscored AI's potential, while recent advancements demonstrate its realized impact and emerging complexity. Moving forward, the future of AI-enabled supply chain solutions will depend on addressing technical, ethical, and workforce-related challenges to unlock innovation, sustainability, and competitive advantage in global supply networks.

ANALYSIS AND INTERPRETATION OF RESULTS

Assessing the Influence of Artificial Intelligence on Supply Chain Performance:

The integration of Artificial Intelligence (AI) into Supply Chain Management (SCM) has become a powerful driver of operational transformation, delivering substantial gains in efficiency, flexibility, and sustainability. Xue (2023) investigates the strategic use of AI across large-scale enterprise supply chains, illustrating how technologies like machine learning, natural language processing, and computer vision enhance reliability and optimize workflow processes. AI's ability to analyze vast volumes of supply chain data supports predictive maintenance, dynamic scheduling, and enhanced automation through robotics, ultimately reinforcing operational transparency and supply chain robustness.

In a comprehensive assessment of AI in SCM, Atwani, Hlyal, and ElAlami (2022) highlight AI's efficacy in addressing challenges like demand uncertainty, variability, and the bullwhip effect. Their findings underscore AI's capacity to revolutionize core functions—including planning, forecasting, procurement, and distribution—thereby improving responsiveness, resilience, and overall supply chain performance. These developments are situated within the broader framework of Industry 4.0, wherein digital transformation is viewed as a foundational driver of competitive advantage.

Likewise, Gupta, Kumar, and Khurana (2023) examine how the adoption of AI enhances operational efficiency while simultaneously promoting environmental sustainability within supply chain systems. AI enhances resource allocation, facilitates precise demand forecasts, and supports the implementation of energy-efficient logistics, all of which reduce environmental impact. Despite these advancements, the transition to AI-integrated SCM presents challenges, such as data privacy concerns, talent shortages, and compatibility with legacy systems. Effective integration will require coordinated action among supply chain stakeholders, including investment in infrastructure, regulatory frameworks, and workforce development.

In summary, AI's influence on supply chain performance is substantial, delivering tools that advance automation, sustainability, and innovation. As AI technologies evolve, managing ethical, technical, and human capital dimensions will be essential for maximizing their strategic potential within SCM.

Cost, Climate, and Performance Dimensions

The adoption of Artificial Intelligence (AI) within Supply Chain Management (SCM) significantly influences economic viability, environmental sustainability, and overall operational performance. Its economic impact is particularly evident among small and medium-sized enterprises (SMEs) in developing nations. For instance, Tan (2022) investigated the factors influencing AI adoption among SMEs in Da Nang, Vietnam, revealing that technological advantages, organizational preparedness, and institutional support are critical enablers of successful implementation. These findings indicate that AI adoption enhances cost- effectiveness, agility, and innovation; however, persistent challenges such as technological complexity, system incompatibility, and high implementation costs continue to restrict its widespread adoption.

From an environmental perspective, Gupta, Kumar, and Khurana (2023) highlight AI's pivotal role in promoting sustainable supply chains. Through intelligent forecasting and optimized routing, AI improves inventory and logistics efficiency, thereby minimizing material waste, reducing energy consumption, and lowering greenhouse gas emissions. Such advancements help align SCM practices with global environmental objectives and corporate sustainability commitments.

Operationally, AI plays a vital role in supporting supply chain agility and resilience. Hatamlah et al. (2023) analyze AI's performance during the COVID-19 pandemic, demonstrating how AI-enabled analytics improved alliance coordination and real-time adaptability. The study illustrates how AI enhances responsiveness and decision-making accuracy, particularly in complex and dynamic environments. Nevertheless, barriers to integration persist, particularly regarding data security, digital literacy, and organizational readiness.

Collectively, these findings underscore AI's ability to drive economic, environmental, and operational gains within SCM. Continued research and coordinated implementation strategies are needed to overcome integration challenges and fully realize the transformative benefits of AI technologies.

Assessing Constraints and Designing AI-Integrated Responses

While AI promises to enhance SCM capabilities, its successful adoption is constrained by several organizational, managerial, and technological barriers. Adobor, Awudu, and Norbis (2023) investigate these constraints, identifying the absence of clear economic justification, insufficient planning, and underdeveloped core competencies as key impediments. They propose that organizations must develop

strategic roadmaps that emphasize the augmentation of human capabilities, rather than replacement, to foster trust in AI systems and reduce resistance to change.

Wamba et al. (2021) present real-world case studies highlighting AI's dual nature—its potential to enhance supply chain performance and the complexity of its implementation. The challenges they outline include data protection, workforce skill gaps, and technological integration. Their study calls for a collaborative, cross-sectoral approach involving policymakers, scholars, and industry leaders to build a conducive

environment for AI integration.

In essence, while AI holds great promise for SCM, realizing its full potential requires addressing multifaceted barriers through strategic planning, inter-organizational collaboration, and capacity building. By investing in education, infrastructure, and governance, supply chains can leverage AI technologies to enhance agility, efficiency, and resilience in the face of evolving global challenges.

Strategic Advancements and Emerging Directions in AI-Integrated Supply Chains

The integration of Artificial Intelligence (AI) into supply chains has sparked a wave of strategic innovation, fundamentally reshaping SCM practices across multiple industries. Sharma et al. (2022) identify five major research clusters in AI-enabled SCM: supply chain network design, supplier selection, inventory and demand planning, and green supply chain management. Their findings highlight the growing influence of intelligent learning systems and the development of AI-driven sensing and interaction capabilities. Collectively, these advancements mark a broader paradigm shift where AI technologies foster strategic agility and promote environmental responsibility.

Expanding on this perspective, Richey et al. (2023) propose a roadmap for advancing research and practical applications of AI in logistics and SCM, with particular attention to the emerging role of generative AI. While generative AI offers promising avenues for scenario modeling and predictive simulations, it simultaneously raises important discussions regarding automation's societal implications especially labor displacement and ethical considerations in research. Richey and colleagues emphasize the need for a comprehensive research framework that balances innovation with accountability, ensuring that AI-driven progress remains both responsible and sustainable.

Despite rapid advancements, integrating AI into supply chain strategies still faces obstacles such as data governance, ethics, and talent shortages. Addressing these issues will require sustained stakeholder engagement, adaptive planning, and proactive policymaking to ensure that technological change results in long-term, inclusive value creation.

Future Outlook on AI Integration in Supply Chain Technologies

AI's expanding role in SCM is not only transforming current operational models but also shaping the trajectory of future technological evolution. Riahi et al. (2021) conduct a bibliometric analysis tracing AI research from 1996 to 2020, categorizing studies by analytical level, algorithmic method, application sector, and supply chain function. They identify machine learning, robotics, and natural language processing as primary enablers of AI's transformative potential. Their study recommends a structured decision-making framework to guide AI application across diverse supply chain domains.

Sharma et al. (2022) contribute to this forward-looking perspective by identifying dominant research clusters and proposing a framework to guide both scholars and practitioners. Their work supports the development of viable AI-based solutions tailored to contemporary supply chain challenges, including

sustainability, scalability, and complexity.

Richey et al. (2023) reaffirm the significance of generative AI in future logistics and supply chain systems. Their research framework aims to equip organizations with practical tools to integrate AI while balancing innovation with ethical and societal considerations. The strategic implementation of AI, they argue, will become a critical determinant of competitive success in the digital economy.

Overall, future advancements in AI are poised to further revolutionize SCM, driving intelligent automation, real-time decision-making, and enhanced adaptability. Continued investment in research, ethical frameworks, and organizational readiness will be essential to ensure that AI technologies contribute meaningfully to resilient and sustainable global supply chains.

The Influence of Regulatory Frameworks and Standardization on AI Integration in Supply Chain Management

The integration of Artificial Intelligence (AI) into supply chain management (SCM) has redefined efficiency, sustainability, and resilience across global networks. However, the effective adoption of AI is influenced by the presence of standards and regulations, which ensure ethical practices, data security, and compliance with industry norms (Richey et al., 2023). These regulatory frameworks facilitate transparency, accountability, and trust among supply chain stakeholders, providing a structured pathway for AI integration.

Richey et al. (2023) emphasize that AI has the potential to revolutionize logistics and supply chain processes, but without proper regulatory oversight, businesses may face risks such as data breaches, algorithmic biases, and operational disruptions. To mitigate these risks, standards and regulations act as guiding principles for AI adoption, ensuring compliance with ethical guidelines, data privacy laws, and industry specific protocols.

Sharma et al. (2022) highlight critical domains where artificial intelligence (AI) strengthens supply chain management (SCM), including supplier selection, inventory control, and demand forecasting. Their study emphasizes the pivotal role of regulatory frameworks in guiding AI adoption, ensuring that technological applications are aligned with sustainability objectives and efficiency standards. The adoption of standardized regulations further assists firms in mitigating ethical risks and safeguarding credibility within the supply chain ecosystem. Similarly, Dey et al. (2023) investigate AI-driven supply chain resilience in Vietnamese manufacturing SMEs, stressing that compliance with industry standards enables a smoother digital transformation. Their findings underscore that leadership commitment, organizational culture, and workforce capabilities are fundamental to effective AI adoption. Beyond legal compliance, standards and regulations foster ethical AI utilization, reinforce data security, and promote continuous organizational learning, thereby enabling SMEs to develop more resilient and adaptive supply chains.

In conclusion, standards and regulations play a pivotal role in the responsible

adoption of AI within supply chains. They ensure ethical AI usage, enhance data protection, and streamline compliance processes. As AI technologies advance, the development and enforcement of comprehensive regulatory frameworks will be essential in fostering trust, transparency, and sustainability in AI-driven supply chains (Reis et al., 2024).

Impacts and Opportunities for Stakeholders in the Supply Chain Landscape

The integration of AI in SCM has transformed traditional supply chain operations, introducing efficiency, innovation, and strategic reconfiguration. These changes present significant strategic implications for stakeholders, who must navigate AI adoption while ensuring security, compliance, and ethical considerations (Hryhorak, Harmash, & Popkowski, 2023).

Al-Alawi, Al-Busaidi, and Ali (2021) discuss the application of the National Institute of Standards and Technology (NIST) Special Publication (SP) 800-161 in AI-empowered supply chains, emphasizing the importance of security frameworks. AI tools contribute to safeguarding supply chain integrity by detecting and mitigating anomalies in business operations. The strategic implication for stakeholders is the necessity of aligning AI investments with security standards to minimize risks and enhance operational resilience.

Hryhorak, Harmash, and Popkowski (2023) examine the emergence of autonomous AI-driven decision- making systems within supply chain management, emphasizing the importance of maintaining a balance between automation and human oversight. This shift poses challenges to professional competencies,

requiring supply chain managers to develop digital literacy and AI governance expertise to mitigate risks associated with algorithmic biases and data privacy concerns.

Pawlicka and Bal (2022) propose a Sustainable Supply Chain Finance (SSCF) framework that incorporates artificial intelligence into omnichannel logistics, illustrating how AI contributes to enhancing both sustainability and operational efficiency. For stakeholders, this underscores the need to develop digital infrastructures and build strong supplier partnerships to gain competitive advantages. AI-driven supply chains must strategically balance technological innovation with regulatory compliance to achieve long-term sustainability.

The strategic implications of AI adoption in SCM are multifaceted, involving security measures, regulatory adherence, workforce development, and sustainability. Stakeholders must approach AI integration with a long-term vision, ensuring alignment with ethical standards and business objectives. By investing in AI training, regulatory compliance, and collaborative AI strategies, supply chain stakeholders can harness AI's transformative potential while mitigating associated risks (Reis et al., 2024).

CONCLUSIONS

This study presents a comprehensive overview of the transformative influence of Artificial Intelligence (AI) on supply chain management (SCM) from 2015 to 2024. The integration of advanced AI technologies such as machine learning, robotics, AIoT, and generative AI has

fundamentally restructured traditional supply chain processes, delivering exceptional improvements in demand forecasting, logistics optimization, supplier evaluation, and sustainability management. Through an extensive analysis of both academic research and industry evidence, this review highlights how AI significantly enhances operational efficiency, decision-making precision, and overall supply chain resilience amid a rapidly evolving global landscape.

The results affirm that AI functions not merely as an automation tool but as a strategic enabler of intelligent, adaptive, and data driven supply chains. Cutting-edge innovations like AI-powered digital twins, blockchain integration, and predictive analytics have fostered real-time visibility, dynamic optimization, and proactive decision making across interconnected global networks. Furthermore, AI-enabled sustainability and ethical sourcing initiatives underscore the increasing importance of responsible and transparent supply chain practices in the digital age. Nonetheless, despite these advancements, large-scale AI adoption continues to face major barriers such as data security risks, algorithmic bias, inadequate infrastructure, and gaps in workforce digital competencies.

For industry practitioners, success depends on aligning AI initiatives with long-term strategic objectives while cultivating digital literacy, innovation, and a mindset of continuous improvement. Simultaneously, policymakers must develop robust regulatory and ethical frameworks that ensure privacy, accountability,

and fairness in AI deployment. Collaborative partnerships among academia, industry, and government are essential for building shared knowledge platforms, ethical standards, and inclusive policy guidelines that promote sustainable AI adoption.

Looking ahead, AI in SCM is expected to evolve toward greater autonomy, deeper integration, and stronger sustainability orientation marking a new era of intelligent, responsible, and future-ready supply chains.

Emerging technologies, such as generative AI, reinforcement learning, and hyper-automation, are likely to further transform supply chains into self-regulating, intelligent ecosystems capable of anticipating disruptions and dynamically optimizing operations. Nonetheless, ensuring that these systems remain ethically aligned, socially inclusive, and environmentally sustainable will be central to their successful implementation.

In sum, AI is not merely optimizing the supply chain; it is reshaping its very foundation. As digital transformation accelerates, continued interdisciplinary research is essential to explore the long-term implications of AI, particularly concerning sustainable development, ethical deployment, and socio- technical integration. This study provides a foundational framework for future inquiry, offering valuable insights into the design of next-generation, AI-enabled supply chains that are resilient, competitive, and responsible.

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Thank you for attending the 19th ISDSI-Global Conference, IMI Kolkata. We look forward to welcoming you again at the **XXIX Society of Operations Management (SOM)** Conference scheduled for December 19-21, 2026.

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