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Generating Research Informed Evidences Examining The Science, Policy and Practice Dimensions of Sustainability

A Compendium of 21 Post-Graduate Student-Led Position Papers

(By Recipients of the Emerson CoE Major Project and Thesis Fellowship for Sustainable Research, 2025)


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From the desk of

VICE CHANCELLOR, TERI SAS

As the world stands at a critical juncture, sustainability has emerged as the foremost challenge of our era, demanding urgent attention and transformative action. Higher Education Institutions need to serve as catalysts of this change, advancing research, innovation, and experiential learning.. TERI School of Advanced Studies (TERI SAS) strives to nurture future leaders .

committed to translating knowledge into impactful, real-world solutions for a resilient future. At the TERI SAS, our academic programmes are tailored to foster student-led research which is multidisciplinary and holistic in nature. The distinguished collaboration between TERI SAS and Emerson Electric plays a pivotal role in providing impetus to the research ecosystem at the school. The Emerson Centre of Excellence (CoE) Major Project & Thesis Fellowship for Sustainable Research is an initiative that assists the academic research undertaken by master's students on diverse sustainability dimensions. The fellowship's purpose is meaningfully reflected through the compendium, which illustrates how this vision has evolved into a platform facilitating critical thinking and youth-led academic engagement with the most pressing challenges of our time. The first edition of this compendium by the Emerson CoE embodies the spirit of academic excellence and a collaborative ethos between academia, industry, and students, capturing how postgraduate students from diverse disciplines perceive contemporary sustainability challenges.

I wholeheartedly commend our postgraduate students, their faculty supervisors, and the Emerson CoE team for compiling these position papers, which reflect a diverse range of vital sustainability themes, and will continue to inspire future discourse across diverse disciplinary perspectives.

Prof. Suman Kumar Dhar



From the desk of

Emerson Electric Co.

Macro trends such as AI and sustainability are defining the unique times we are living in. Innovations of every scale need to proliferate as we align with these trends and deliver on our commitments towards national goals, societal needs, and environmental objectives. At Emerson, we believe that collaborations foster innovation.

Recognizing TERI SAS's domain expertise in sustainability, we partnered to establish the Emerson Centre of Excellence at TERI SAS to explore innovative outcomes that would yield significant benefits for a diverse set of stakeholders. The Fellowships for Major Projects and Thesis is a carefully conceptualized initiative from the Centre, intended to encourage young, sharp minds across various disciplines to cultivate curiosity, conduct research, and develop their potential as future leaders in the domain. We at Emerson are delighted to see the papers published in this compendium. We congratulate all the students for their hard work and commitment to submitting their papers. We wish the students who are planning to participate in the next cycle good luck and encouragement. We extend our gratitude to all the faculty who have guided the students. We appreciate the staff at the Emerson Centre of Excellence for making this initiative a success.

Anil Bhatia

Vice President and Managing Director, Emerson Electric Co. (India)



From the desk of

DIRECTOR, Emerson CoE

A promising industry-academia partnership led to the establishment of the Emerson Centre of Excellence for Sustainability Studies in 2022 that acts as a catalyst enriching the research ecosystem at TERI SAS. The Centre facilitates co-production of knowledge in decoding sustainability pathways with emphasis on the perspectives of next generation sustainability leaders. It gives us immense pride to celebrate the release of inaugural compendium of twenty one position papers authored by postgraduate students who were recipients of the Emerson Centre's Major Project and Thesis Fellowship for Sustainability Research, 2025. This compendium is an attempt towards generating evidences of in-depth examination of diverse science, policy and practice dimensions of sustainability. This valuable work of lead student authors and associated faculty mentors shall be instrumental in enhancing interest of young scholars and practitioners towards research led critical enquiry of complex sustainability challenges.

Prof. Shaleen Singhal



Preface

In an era marked by environmental urgency, social complexity, and rapid technological transformation, Higher Education Institutions (HEIs) hold a pivotal responsibility in shaping sustainability discourse and practice. They prepare future leaders to become informed, ethical, and innovative agents of change. As UNESCO emphasizes, education remains one of the most powerful instruments for advancing sustainability—particularly when integrated across disciplines and pedagogical frameworks.

This compendium represents the first curated collection of position papers drawn from selected master's theses of postgraduate students at TERI School of Advanced Studies during the Academic Year 2024–25. These students were recipients of the Emerson Centre of Excellence Fellowship for Major Project/Thesis Research, instituted by the Emerson Centre of Excellence for Sustainability and supported by Emerson Electric India Pvt. Ltd.

The papers herein reflect empirically grounded perspectives developed through diverse methodologies—ranging from life cycle assessment and spatial analysis to stakeholder interviews and econometric modeling. Each contribution demonstrates academic rigor and practical relevance, advancing knowledge that is contextually meaningful and locally resonant. The fellowship has catalyzed a vibrant research culture, encouraging students to engage with sustainability challenges through interdisciplinary lenses and policy-relevant frameworks.

The compendium spans a wide spectrum of themes, including circular economy and resource efficiency, climate change mitigation and adaptation, energy transitions, nature-based solutions, urban governance, water and food security, biotechnology, and environmental justice. These papers are organized into four thematic categories:

- **Agriculture, Water and Food Security in a Changing Climate** (5 studies)
- **Nature-Based Solutions for Ecosystem Restoration and Climate Resilience** (5 studies)
- **Urban Sustainability through Climate Governance** (5 studies)
- **Energy Transitions and Decarbonisation Pathways** (6 studies)

Each paper articulates a clear position supported by empirical evidence, theoretical grounding, and policy implications. This compendium is intended to serve academics seeking fresh perspectives, practitioners looking for actionable insights, and policymakers interested in evidence-based recommendations. It stands as a testament to the collaborative ethos at TERI SAS, where faculty mentorship, institutional support, and student initiative converge to produce research that matters.

We extend our sincere gratitude to Emerson Electric India Pvt. Ltd. for their generous support, to faculty mentors for their invaluable guidance, and most importantly, to the postgraduate students for their dedication and intellectual commitment. We hope this compendium inspires dialogue, research, and action toward a more sustainable and equitable future.

Dr. Sagarmoy Phukan and Ms. Bhavya Kharbanda

1. INTERLINKAGES BETWEEN AGRICULTURE, WATER AND FOOD SECURITY IN A CHANGING CLIMATE

Exploring sustainable farming, water productivity, and climate-linked food systems.

POSITION PAPERS

Bridging the Nutrition Gap through Agriculture: Aligning Crop Production with Dietary Needs in Bihar
Kalpna Kumari

Rethinking Agricultural Water Efficiency: A Regional Approach to Water Productivity of India's Dominant Crop
Nishtha Jain

Analyzing the Impact of Urbanization and Labor Market Dynamics on Water Scarcity in Bengaluru, India
Kushi Naidu

Locust Outbreaks and Climate Variability: Addressing Food Insecurity in Rewari District, Haryana, India
Bhoomika Thakur

Beyond Antibiotics: *In Silico* Discovery and Enzymatic Insights for *H. pylori* Eradication
Samruddhi Mane

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Bridging the Nutrition Gap through Nutrition Sensitive Agriculture: Aligning Crop Production with Dietary Needs in Bihar

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Executive Summary

India faces a dual burden of undernutrition and diet-related non-communicable diseases, despite being a food-surplus nation. Bihar, a state with considerable agricultural potential, exhibits some of the worst nutritional indicators in the country. This position paper draws upon original research to investigate how agricultural production in Bihar aligns with the nutritional requirements of its population. Using data from five representative districts (Araria, Arwal, Banka, Kaimur, and West Champaran), the study maps nutrient availability from 26 crops over ten years and compares it to age- and gender-specific dietary needs. The analysis revealed widespread nutrient shortfalls, especially in protein, fat, iron, calcium, and B-complex vitamins. Only carbohydrates and Vitamin C showed adequate or surplus levels in a few districts.

The findings demonstrate a systemic misalignment between what is grown and what is needed for adequate nutrition. The paper advocates for a shift from calorie-centric to nutrition-sensitive agriculture in Bihar. Recommended strategies include crop diversification, adoption of biofortified varieties, integrated farming systems, improved soil nutrient management, and restructured food policies. Implementing these interventions can help bridge the nutritional gap and contribute to national goals under POSHAN Abhiyaan and SDG 2 (Zero Hunger). This position paper argues that current governance mechanisms are inadequate to address the specific wastewater challenges faced by India's small towns. It recommends urgent investment in decentralised wastewater treatment units (DWWTs), the establishment of town-level river health governance bodies, and the institutionalisation of water quality modelling in local planning frameworks.

Context & Problem Statement

India's agricultural system, shaped by the Green Revolution, prioritizes caloric sufficiency over nutritional adequacy. This imbalance has contributed to persistent malnutrition, particularly in states like Bihar. Bihar, despite being agriculturally rich, exhibits alarming nutritional statistics: 42.9% of children under five are stunted, and over 64% of women of reproductive age are anaemic (NFHS-5, 2019-21).

The state's agricultural policy and practice continue to favor cereal-dominant production, especially rice and wheat. These crops provide calories but lack essential micronutrients such as iron, calcium, and Vitamin A. Moreover, the limited cultivation of pulses, fruits, vegetables, and oilseeds, along with poor utilization of livestock, aggravates the nutritional crisis.

Climate vulnerabilities, small and fragmented landholdings, and poor market access further constrain agricultural diversification. Public distribution policies, focusing on cereals, reinforce unhealthy dietary patterns.

This position paper responds to a critical gap: the lack of district-level assessment of the nutritional contribution of agriculture

agriculture in Bihar. It presents empirical evidence on nutrient gaps and recommends actionable pathways to align crop production with population dietary needs.

Literature Review

The dominant focus of Indian agriculture on staple crops has come at the cost of dietary diversity. Studies highlight the unintended nutritional consequences of the Green Revolution (NIAS, 2013). Biofortification and crop diversification are increasingly recognized as essential tools to improve food system outcomes.

Swaminathan and Bhavani (2013) emphasized the three pillars of food security: availability, access, and absorption. Despite food availability, nutrient absorption remains low in Bihar due to poor dietary quality and health infrastructure. Shirsath et al. (2021) demonstrate that optimized crop planning can ensure caloric sufficiency but not necessarily micronutrient adequacy.

The role of livestock in improving protein and micronutrient intake is well established (Singh et al., 2020). Yet, policy frameworks rarely integrate animal-source foods into nutrition planning. Climate-resilient agricultural practices and biofortified crops offer promise in addressing hidden hunger, but adoption remains low.

Das (2021) proposed redesigning the Public Distribution System (PDS) to include nutrient-rich foods, and Kapoor et al. (2022) highlighted the nutritional value of underutilized crops and wild edibles. Despite growing recognition of nutrition-sensitive agriculture, there is little localized evidence from Bihar, which this paper aims to address.

Research Focus and Methodology

The study aimed to evaluate how well the nutritional output of Bihar's agriculture meets the dietary needs of its population. The specific objectives were:

- To map the nutritional values of 26 major crops grown in five districts of Bihar.
- To identify gaps between nutrient availability and population dietary requirements.
- To recommend strategies to realign agricultural practices with nutritional goals.

The study selected five districts (Araria, Arwal, Banka, Kaimur, West Champaran) based on agro-ecological and socio-economic diversity. Crop production data (2013–2023) were sourced from the Ministry of Agriculture. Nutrient content was derived from USDA and ICMR databases.

Nutrient availability was calculated by multiplying crop yields by nutrient composition. Population-based dietary demand was estimated using Recommended Dietary Allowances (RDAs) from ICMR, disaggregated by age and gender. The nutrient gap was calculated by comparing supply and demand annually.

The results were analyzed using Excel-based models and visualized through comparative graphs. This approach allowed for a spatial and temporal analysis of nutrient deficits and surpluses.

Key Findings and Observations

The study revealed that while some districts meet caloric needs, critical gaps exist across all macro- and micronutrients.

Carbohydrates: Arwal and West Champaran showed surpluses due to cereal-centric farming, while Banka faced deficits.

Proteins and Fats: All districts showed protein and fat deficits. Pulse and oilseed production remains insufficient.

Micronutrients: Severe shortfalls were found in iron, zinc, calcium, and magnesium. Even districts with better crop yields lacked micronutrient diversity.

Vitamins: Vitamin A and B-complex deficiencies were pervasive. Only Vitamin C showed adequacy in some districts due to horticultural crops.

District-level insights:

Araria and Banka: Faced the most critical nutrient deficits due to poor diversification and agroecological limitations.

Kaimur and West Champaran: Performed better but still fell short in micronutrients.

Interpretation: The dominance of rice-wheat systems, limited adoption of biofortified crops, poor soil health, and weak market incentives contribute to Bihar's nutritional deficits. Nutrient gaps are not just a production issue but a systemic outcome of policy, practice, and socio-economic constraints.

Policy and Practice Implications

To bridge Bihar's nutritional gap, the following strategies are recommended:

Crop Diversification: Integrate millets, pulses, vegetables, and oilseeds into the cropping system. These are rich in essential nutrients and climate-resilient.

Biofortified Varieties: Promote iron-rich millets, zinc -rich rice, and Vitamin A-enriched sweet potatoes. Extension services should support farmer adoption.

Integrated Farming Systems: Combine crop, livestock, and horticulture to enhance nutrient diversity and farm income.

Soil Health Management: Implement site-specific nutrient management and organic inputs to restore micronutrient-rich soils.

Nutrition-Sensitive Extension: Train farmers on the link between agriculture and health. Women's groups can lead kitchen gardens and household nutrition programs.

Reform Public Procurement: Redesign PDS to include pulses, millets, and fortified cereals. Support institutional demand in schools and hospitals.

District-Level Planning: Use GIS and nutritional mapping tools for agro-nutritional zoning. Create district dashboards to guide crop planning.

Conclusion

This paper presents evidence of a fundamental mismatch between food production and nutritional needs in Bihar. The overemphasis on cereals, ecological vulnerabilities, limited crop diversity, and policy biases contribute to systemic nutrient gaps.

A transition to Nutrition-Sensitive Agriculture (NSA) is both necessary and feasible. By integrating diversified cropping, soil health practices, biofortified seeds, and data-driven planning, Bihar can move toward nutritional security. The recommended interventions align with national goals under PM POSHAN Scheme and SDGs.

The research underscores the importance of localized data and participatory planning. Future research should expand to include livestock, fishery contributions, and food loss metrics to build a comprehensive agro-nutritional or NSA strategy for Bihar State.

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Rethinking agricultural water efficiency: a regional approach to water productivity of India's dominant crops

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Executive Summary

India's agriculture, which supports nearly half of the country's population, is increasingly burdened by unsustainable water use, particularly in the cultivation of water-intensive crops such as rice, wheat, and sugarcane. These three crops, while central to national food security and export earnings, account for a disproportionate share of the country's irrigation water, contributing to ecological stress in groundwater-dependent regions. Despite long-standing policy incentives such as minimum support prices (MSP) and free electricity, the environmental trade-offs of these cropping patterns are becoming more severe in the face of climate change, declining water tables, and regional water imbalances. This position paper builds on a multi-scalar assessment of water productivity (WP) in Indian agriculture, with a focus on the temporal and spatial efficiency of water use across major crop-producing states. Using a combination of empirical trends from secondary datasets and simulation modeling through FAO's CROPWAT tool, the study examines physical and economic water productivity (PWP and EWP) across key states and blue and green water productivity (BWP and GWP) across selected districts, identifying stark variations and misalignments between water use and crop returns. Key findings reveal that states like Punjab and Maharashtra maintain high productivity levels through intensive irrigation, yet face growing groundwater depletion. Meanwhile, eastern and central Indian states often demonstrate lower productivity not due to lack of water, but because of policy neglect and infrastructural gaps. The study emphasizes the importance of regional realignment of crop production, targeted irrigation reform, and export policy recalibration to reduce India's virtual water losses.

This paper argues for a paradigm shift from yield-maximizing to water-efficient cropping systems, integrated with sustainable irrigation technologies and region-specific policy interventions. Addressing the spatial and economic inefficiencies of current practices is essential to building climate-resilient and water-secure agricultural futures in India.

Context & Problem Statement

India's agricultural sector is at a critical juncture, facing a dual burden: meeting the food demands of a growing population while conserving its increasingly scarce water resources. Agriculture consumes approximately 90% of India's total freshwater withdrawals (World Bank, 2021), a figure driven largely by the cultivation of a few dominant crops i.e., rice, wheat, and sugarcane. These crops are not only central to the country's food security and export economy but are also responsible for some of the most unsustainable patterns of water use in the country.

This imbalance is most pronounced in ecologically vulnerable regions. In Punjab, for instance, groundwater levels are rapidly declining due to entrenched rice-wheat cultivation, incentivized by MSPs and free electricity for irrigation.

Similarly, in Maharashtra, sugarcane cultivated over just 4% of the state's farmland uses more than 60% of the available irrigation water, often through inefficient flood irrigation methods. These trends reflect a systemic misalignment between cropping patterns and regional water availability, exacerbated by outdated subsidy structures and policy inertia.

At the same time, policy frameworks continue to favor high-input, high-output systems with little consideration for ecological cost. The substantial export of water-intensive crops, particularly rice, has led to a surge in virtual water trade, India is effectively exporting its limited freshwater resources embedded within agricultural goods. As groundwater stress intensifies, this silent loss threatens long-term national water security. Despite the mounting risks, much of the existing water productivity analysis in India remains confined to national or state-level aggregates. Such analyses obscure micro-level variations in water use efficiency and fail to capture the nuanced interplays between climate, irrigation practices, and crop choice. There is also insufficient understanding of how physical and economic water productivity varies across regions and how it intersects with environmental degradation.

Crucially, climate variability and changing rainfall patterns are increasing irrigation demands and shifting agro-climatic zones. This calls for urgent evidence-based strategies that go beyond general water-use metrics to include crop-specific, regionally grounded assessments of water productivity and sustainability.

The core problem this research addresses, therefore, is the lack of integrated, granular insights into how and where India's water is being used to grow its major crops and how effectively. Without such knowledge, efforts to improve irrigation efficiency, promote sustainable cropping, or redesign export policy remain incomplete. By bridging this gap, the study aims to support informed, regionally differentiated strategies that align agricultural production with ecological realities and long-term water resilience.

Literature Review

The sustainability of water use in agriculture has been a subject of growing academic and policy interest, particularly in countries like India where irrigation demands are exceptionally high. Two key analytical frameworks have emerged in this context: water productivity (WP), which measures crop yield per unit of water used (kg/m³), and water footprint (WF), which quantifies the total volume of water consumed, including blue (irrigation), green (rain-fed), and grey (pollution-assimilating) components through the crop's life cycle (Hoekstra et al., 2011). Molden et al. (2007) and Zwart & Bastiaanssen (2004) emphasized WP as a critical indicator of agricultural water use efficiency, arguing that improvements in WP can help reduce pressure on water resources without compromising yields. In India, Sharma et al. (2018) demonstrated considerable variability in WP across crops and regions, with rice showing particularly low physical water productivity, especially in groundwater-dependent zones. Jain et al. (2021) further highlighted that while wheat displays relatively better WP, it often relies on unsustainable extraction practices in the Indo-Gangetic Plians.

WF studies have added important dimensions to this conversation. Studies by Mekonnen & Hoekstra (2016) and Aldaya et al. (2010) documented how virtual water trade i.e., the export of water-intensive crops contribute to "invisible" freshwater losses from water-stressed regions. In the Indian context, Punjab and Haryana, despite being water-deficient, remain key exporters of rice and wheat, leading to the paradox of food security gains at the cost of long-term water insecurity (Gulati & Mohan, 2018). Technological interventions such as micro-irrigation (e.g., drip, sprinkler systems), alternate wetting and drying (AWD) in rice, and resource-conserving practices like zero tillage have been proposed to enhance WP (Bhatt et al., 2023; Vatta et al., 2018). However, as Perry et al. (2009) and Lankford (2025) caution, such interventions may not translate into real water savings at the basin scale due to rebound effects and increased cropping intensity.

Recent literature has also stressed the importance of integrating economic dimensions into water analysis. Cai et al. (2017) and Lee et al. (2024) propose economic water productivity (EWP) as a more policy-relevant indicator, accounting for monetary returns per unit of water. Yet, few studies have rigorously

compared EWP across crops and regions or evaluated trade-offs between physical efficiency and economic gain.

This study builds on these strands by offering a multi-scalar WP analysis that combines temporal trends, spatial disparities, and simulated irrigation requirements for selected crops in key regions of India. It also responds to a research gap by focusing on district-level disparities and the underexplored role of virtual water trade in agricultural planning.

Research Focus and Methodology

This research aims to analyse the spatial and temporal dynamics of water productivity in India's agriculture, with a focus on wheat, rice, and sugarcane i.e., the most water-intensive and policy-influential crops. By understanding how water is used across diverse agro-ecological and administrative scales, the study provides evidence for sustainable planning, irrigation policy, and crop diversification strategies. The study was guided by **four primary objectives:**

1. To analyze long-term trends (2000–2020) in physical and economic water productivity of rice, wheat, and sugarcane across major producing states.
2. To assess spatial disparities in water productivity for these crops across diverse agro-climatic regions.
3. To compare water productivity of wheat, rice, and sugarcane with other high-water-demand crops such as maize and cotton.
4. To simulate crop water requirements and estimate WP indicators at the district level using CROPWAT 8.0 for select regions.

Study crops and regions- Three major crops: wheat, rice, and sugarcane were selected due to their significant contribution to India's irrigated area, food grain production, and virtual water exports. Maize and cotton were included as comparative crops to assess the potential of crop substitution.
Nine states: Uttar Pradesh, Punjab, Madhya Pradesh, Bihar, Maharashtra, Andhra Pradesh, Karnataka, West Bengal, and Gujarat were chosen for state-level analysis based on their contribution to crop production. For micro-level analysis, four districts were selected: Ludhiana and Amritsar in Punjab (for wheat), and Pune and Ahmednagar in Maharashtra (for sugarcane).

The analysis used a combination of secondary and modeled data:

- Water productivity data: Sourced from the India Water Productivity Atlas (IWMI-ICAR), which integrates remote sensing and field datasets.
- Climate and soil data: Extracted from FAO's CLIMWAT 2.0 for CROPWAT simulations.
- Yield and production data: Obtained from the Directorate of Economics and Statistics (DES), FAO, and APEDA.

A two-tiered methodology was used:

1. **Temporal-spatial analysis:** State-level physical (kg/m³) and economic (USD/m³) water productivity were evaluated over two decades (2000-2020) using WP Atlas data to identify spatial disparities and temporal trends.
2. **Simulation modeling:** The FAO CROPWAT 8.0 tool was used to estimate district-specific crop water requirements (CWR), evapotranspiration (ETc), and irrigation needs. These outputs were combined with crop yield data to compute:

$$PWP = Yield/Etc$$

$$GWP = Work/Effective\ Rainfall$$

$$BWP = Yield/Irrigation\ Requirement$$

This mixed-method approach offers both empirical breadth and micro level precison, making it possible to triangulate results and formulate actionable recommendations tailored to regional conditions.

Key Findings & Argument

The findings from this multi-scalar study highlight stark temporal and spatial variability in water productivity across India's key agricultural crops and regions. These patterns are shaped not just by agro-climatic conditions but also by historical policy choices, irrigation infrastructure, and market incentives.

1. Temporal trends: Unequal gains in water productivity

Over the two-decade analysis period (2000-2020), the physical water productivity (PWP) of wheat, rice, and sugarcane exhibited moderate to high fluctuations across states. Punjab consistently recorded the highest PWP for wheat, often exceeding 1.5 kg/m³ driven by assured procurement and advanced irrigation infrastructure. However, this came at the cost of unsustainable groundwater extraction, highlighting a classic case of high productivity with low ecological sustainability.

Uttar Pradesh, though India's largest wheat producer, showed only moderate PWP (0.7-1.1 kg/m³), reflecting continued reliance on outdated irrigation practices. Bihar and Madhya Pradesh, despite improvements, lagged due to fragmented landholdings, climatic risks, and poor irrigation infrastructure. These disparities reinforce the need for targeted irrigation support and precision water management in the eastern Indo-Gangetic plains.

Sugarcane followed a similarly uneven trajectory. Andhra Pradesh and Karnataka achieved relatively higher PWP (0.5-0.6 kg/m³), attributed to partial adoption of micro-irrigation systems and policy support through programs like PMKSY and APMIP. Maharashtra's productivity data was inconsistent due to reporting gaps, though field evidence suggests excessive water use through flood irrigation. Uttar Pradesh's sugarcane belt maintained moderate WP levels, but rising cultivation in less irrigated eastern districts threatens to drag efficiency down further.

For rice, Punjab again stood out with high PWP (up to 0.8 kg/m³), but its agro-climatic unsuitability and heavy groundwater dependence make this an unsustainable model. West Bengal and Andhra Pradesh showed stable performance, with room to improve through better irrigation scheduling and water-saving technologies like direct seeded rice (DSR).

2. Spatial disparities and misalignments

Spatial analysis across nine major crop-producing states revealed a deeper structural misalignment between crop selection and regional water availability. High water-consuming crops are concentrated in states facing critical groundwater stress like Punjab, Maharashtra, and parts of Uttar Pradesh. Meanwhile, ecologically suitable eastern and northeastern states remain underutilized for irrigated agriculture despite better rainfall and aquifer recharge potential.

This spatial disconnect stems largely from distorted policy incentives especially MSPs, subsidized electricity, and procurement assurances that have led to persistent monocultures of water-intensive crops in fragile zones. Such patterns are not only economically inefficient but also ecologically dangerous, given the declining water tables and deteriorating soil health in these areas.

3. Comparative water productivity with alternative crops

When benchmarked against maize and cotton, wheat and sugarcane demonstrated relatively high physical productivity but poor economic returns per unit water. Cotton, although water-intensive, showed better economic water productivity (EWP) due to its high market value. Maize emerged as a promising alternative in regions with moderate irrigation capacity, offering better WP without heavy groundwater dependence.

These comparisons reveal the potential of crop diversification, not necessarily abandoning current staples, however gradually transitioning toward a more balanced cropping mix that includes maize, oilseeds, millets, and pulses in suitable regions.

4. District-level simulation insights

Using CROPWAT 8.0, district-level simulations were conducted for wheat in Ludhiana and Amritsar (Punjab) and for sugarcane in Pune and Ahmednagar (Maharashtra). These case studies revealed important micro-level insights:

Wheat in Punjab: High PWP values (~1.8 kg/m³) were achieved but were reliant on intensive irrigation and minimal rainfall contribution. Blue water productivity (BWP) was comparatively lower, indicating dependence on pumped groundwater.

Sugarcane in Maharashtra: Despite relatively high yields, irrigation demand was extremely high (~1400 mm), and sugarcane is a perennial crop, requiring water throughout the year. Effective rainfall makes minimal contribution, especially in Ahmednagar, due to erratic monsoon patterns.

These findings suggest that improving WP is not just about increasing yield but optimizing the mix of rainfall use and irrigation. The high share of blue water use also highlights the urgent need to promote techniques such as drip irrigation and mulching to enhance green water utilization and reduce groundwater extraction.

5. Economic trade-offs and virtual water losses

Economic water productivity remained consistently lower than physical productivity across all crops and states, highlighting a critical gap between input efficiency and monetary return. This divergence often stems from stagnant market prices, high input costs, and post-harvest losses.

Moreover, the analysis pointed to significant virtual water losses through agricultural exports. For instance, rice exports from Punjab equate to the externalization of over 3,000 m^3 of water per tonne of grain. Without region-specific trade regulations or virtual water audits, such practices pose long-term risks to national water security.

Policy and Practice Implications

A recurring theme was the neglect of regional equity in resource allocation. States like Bihar and Madhya Pradesh, which have potential for sustainable intensification, remain underfunded in irrigation support and policy incentives. Meanwhile, ecologically overburdened regions continue to receive disproportionate benefits under centrally driven procurement and subsidy regimes.

This imbalance calls for policy decentralization, empowering states to promote cropping patterns aligned with their resource endowments. Equity in water allocation especially in terms of financial and technological access is essential for achieving national food security without compromising environmental resilience.

Conclusion

This position paper has argued for a fundamental rethinking of how water is managed in India's agriculture, particularly in relation to the production and trade of water-intensive crops like rice, wheat, and sugarcane. By assessing water productivity (both physical and economic) across temporal and spatial scales, and by simulating crop water requirements at the district level, the research highlights critical inefficiencies in current cropping patterns, irrigation practices, and policy frameworks.

A key insight is that high productivity in itself does not guarantee sustainability. In states like Punjab and Maharashtra, productivity gains are being achieved at the cost of depleting groundwater, while many eastern and central states with relatively better water endowments remain underutilized. Furthermore, India's significant export of high water-footprint crops contributes to the hidden loss of freshwater resources through virtual water trade. The central position of this paper is clear: India's agricultural water governance must become both ecologically sensitive and economically rational. Only then can the country move toward a future where food systems are not just productive but also resilient, equitable, and water-secure.

Future research could extend this work by incorporating grey water components, analysing carbon-water trade-offs, or integrating basin-level hydrological modelling. Such efforts would further enrich policy dialogue and help build adaptive capacity in a climate-stressed, water-scarce world.

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Analysing the Impact of Urbanization and Labour Market Dynamics on Water Scarcity in Bengaluru, India

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Executive Summary

The study aims to explore the intricate relationship between urbanization, changes in labour market dynamics, and water scarcity, with focus on the depletion of groundwater that often goes unnoticed in urban settlements. Today, more than half of world's population resides in urban clusters, facing serious socio-economic and environmental implications. Unplanned and unregulated urbanization has led to range of urban issues including to traffic congestion, surge of informal settlements, poor resource quality, overcrowding, insufficient infrastructure among others.

In this context, the study assesses the impact of urbanization on the water scarcity situation in Bengaluru in the past decade, i.e., 2013 - 2023. The study disaggregates urbanization into landscape urbanization (land use change indicators), demographic urbanization changes in labour market (captured through change in employment in key sectors), and economic urbanization. To assess this relationship, the study undertakes a multivariate regression analysis to regress the urbanization indicators on groundwater levels of Bengaluru; the results indicate towards a negative relationship, i.e., changes in land use and land cover, high population density and economic growth without adequate water infrastructure exerts strain on not only groundwater levels but also impacts the aquifer recharge capacity. Furthermore, the study also evaluates the role of Bangalore Water Supply & Sewerage Board (BWSSB) under indicators of environmental (unaccounted water) and financial sustainability (non-revenue water) respectively. The analysis highlights the governance gaps through mismatch between roles/functions and the scale of water regulation in the city. Finally, as one of India's leading economic hubs, this study on Bengaluru acts as the guiding pillar in proposing sustainable urban planning practices for several metropolitan cities on a similar growth trajectory.

Context & Problem Statement

Bengaluru mainly consists of two major water sources – the Cauvery River and groundwater. Before large-scale urbanization, the city mainly relied on the Cauvery River to meet its water needs. The efficient use and transportation of this water was attributed to the massive system of interconnected lakes the city adorned. A study on Bengaluru's lakes revealed that rejuvenation of lakes alone has the potential to meet close to 50% of drinking water demand (Ahmed & Ramamoorthy, 2024). With Britishers settling in Bengaluru post 1800s, the demand for water significantly increased that caused unprecedented pressure upon the existing water system. As the alterations made by Britishers on the water system increased, the dependence and usage of these lakes drastically reduced. As a result, the lakes began to shrink. To add to this misery, urbanization paved path to build concrete constructions on these lake beds. Bengaluru mainly consists of two major water sources – the Cauvery River and groundwater. Before large-scale urbanization, the city mainly relied on the Cauvery River to meet its water needs. The efficient use and transportation of this water was attributed to the massive system of interconnected lakes the city adorned. A study on Bengaluru's lakes revealed that rejuvenation of lakes alone has the potential to meet close to 50% of drinking water demand (Ahmed & Ramamoorthy, 2024).

With Britishers settling in Bengaluru post 1800s, the demand for water significantly increased that caused unprecedented pressure upon the existing water system. As the alterations made by Britishers on the water system increased, the dependence and usage of these lakes drastically reduced. As a result, the lakes began to shrink. To add to this misery, urbanization paved path to build concrete constructions on these lake beds. Around 43 lakes have been concretized into infrastructure such as, hospitals, commercial parks, stadium to name a few (Bengaluru's 43 Lost Lakes and What Stands on Them Today, 2024). Furthermore, discharge of harmful chemical effluents into lakes have caused deterioration in the quality, rendering large volumes of water unusable. Thus, with decreasing number of water bodies due to infrastructure expansion, the city reflects a strong misalignment between urban growth and environmental sustainability a major concern this thesis aims to address.

At the core of this study, the research problem is to understand how unregulated urbanization and shifts in labour market dynamics has escalated the water crisis in Bengaluru. Given the growth in urban population in the city, resulting in human encroachment into the green tapestry and causing ecological imbalance, it becomes imperative to understand how such changes in land use and land cover alter the city's hydrological system contributing to chronic water stress. Additionally, despite mandatory policy interventions stated by the water utility in Bengaluru, effective on-ground implementations have not been observed, calling for an assessment of the efficiency of water governance in Bengaluru.

Literature Review

This chapter presents a thematic review of the literature, with a focus on Bengaluru, India. The chapter is broadly sub-divided into urbanization trends (global and Bengaluru's urbanization trends), insights on water scarcity (emphasizing on its environmental impacts), the importance of economics in urban water supply and the role of economic instruments in encouraging efficient water governance.

Urbanization is defined as "The transformation of unoccupied or sparsely occupied land into densely populated cities" (Urbanization, n.d.). In 2019, The United Nations forecasted that more than half of the world's population, i.e. around 6 billion people will live in urban areas by 2041 (Kuddus et al., 2020). With such rapid rates of urbanization resulting in high population density settled in confined 'urban' boundaries, the allocation and use of resources ranging from housing, healthcare, education, employment opportunities should all be meticulously planned (Ritchie et al., 2024). Among the metropolitan cities in India, Bengaluru has stood out as a prime example of rapid urbanization. The surge in urbanization has led to large environmental degradation, one of the most prominent impacts in Bengaluru was seen on its water resources.

The literature on establishing a relationship between urbanization and water scarcity is well documented. According to IPCC's report, urbanization combined with climate change impacts 7 is likely to have a negative impact on urban development, and lead to several societal concerns ranging from water security, degradation of water quality, rising pollution level to food shortages (Tayebi et al., 2022). Forecasted estimates also reveal that the world will face a 40 percent gap between water supply and demand (Tayebi et al., 2022), calling for an imperative need to articulate sustainable water management policies.

In situations of water scarcity, it becomes imperative to not just find sources of freshwater supply, but also use and value water adequately to ensure sustainable urban progress. As Adam Smith asserts, valuing water appropriately reflects the true utility, also referred to as 'value-in-use' of a commodity in economic literature (Batten, 2007). In the entire gamut of water governance discussions, where the decisions are mainly influenced by geography, population rise, and often political considerations, ironically, the economic factor that directly depicts scarcity (Convery, 2013) price, is frequently ignored. Despite this, several developing countries' will/capacity to develop pricing instruments grounded in economic theories remains limited, leading to institutional failure or governance collapse. Lack of identification of water as an economic good, remains one of the critical reasons behind poor urban water management. Instruments such as tiered water pricing helps cost recovery because of efficient

commodity pricing. In this context, tiered water pricing encourages behavioural shifts in water consumption by rewarding a lower water tax with every decrease in water consumption, thus inculcating social welfare along with cost recovery. Another economic theory "Marginal cost pricing" equates the price to the marginal cost incurred with additional production of output; this also includes the increase in price necessary to cut excessive consumption (Turvey, 1964). In their study, Hanke & Davis (1973), assessed the role of marginal cost pricing in efficient resource allocation. They further state that, with expansion in commodity demand, extraction from supply resource increase; however, prices often fail to account for the cost to future consumers of forgone resource or service. This results in failure of the primary function of price, i.e., to balance price and cost at the margin, further encouraging excessive consumption as a result of under-pricing the commodity.

Research Methodology

This chapter presents an overview of the data and methodology employed in this study to assess the impact of urbanization on water scarcity in Bengaluru between 2013-2023. In this period, the built-up area of Bengaluru is increase by a massive 1055% (Kaggere, 2024); thus, the time frame serves an appropriate period to capture the impact of sudden rise in urbanization on the city's water resources.

Furthermore, the study employs a mixed method approach to address both the research questions:

1. How does the rise in urbanization rate and change in labour market dynamics impact the water availability and usage in the city?

2. To what extent do water management and urban planning policies play a role in mitigating or exacerbating water scarcity problems?

To address the first research question, the study uses secondary data from government sources, further segregating the data into five divisions of Bengaluru – Yelahanka, North, East, South, Anekal. Using this data, the study builds two multivariate regression models; model 1 analyses the impact of demographic (captured through increase in employment over the years) and landscape urbanization (captured through land-use change categorised by residential and commercial establishments) on water scarcity and model 2 analyses the impact of economic urbanization (captured through increase in employment in key industrial sectors) on water scarcity. The models are as shown below:

Model 1:

$$GW\ Level_{it} = \beta 0 + \beta 1 Lag_Rainfall_{it} + \beta 2 Residential_{it} + \beta 3(Commercial_{it} \times Employment_{it}) + \beta 4 Commercial_{it} + \beta 5 Employment_{it} + \beta 6 Temperature_{it} + \epsilon_{it}$$

Model 2:

$$GW\ Level_{it} = \beta 0 + \beta 1 Textiles_{it} + \beta 2 Chemicals_{it} + \beta 3 Engineering_{it} + \beta 4 Others_{it} + \epsilon_{it}$$

The choice of GW (groundwater) level as the dependent variable is grounded in literature suggesting that any alterations in land use & land cover is likely to impact the groundwater reserves more intensely than surface water. In his study, Patra et al., (2018) finds that increase in impervious surfaces as a consequence of urbanization leads to reduced evapotranspiration in urban clusters, thus having direct impacts on 'groundwater'. Additionally, it has been observed that, core city has not been facing severe water shortages since they have piped Cauvery water supply service facilitated by the water utility; whereas, the periphery is facing severe shortage as rely mainly on groundwater sources. Hence, it is established that the water crisis in Bengaluru is fundamentally a 'groundwater crisis'. Moreover, to address the second research question, the study employs the IAD Framework to identify the key water management authority concerned with water collection and distribution in the city. Further, the role of the water utility is assessed in regulating such a water crisis under key parameters of environmental and financial sustainability.Overall, this study adopts an interdisciplinary approach to understand the combined effect of the interaction between urbanization changes and water governance on water scarcity.

Results and Discussions

This section will present the results and analysis based on the methodology outlined in the previous section. In its centrality, the study aims to empirically establish a relationship between urbanization variables and groundwater level. To support this narrative with empirical evidence, the following section presents the regression results, followed by some discussion.

Model 1: Impact of demographic & landscape urbanization on groundwater (2013-2023)

$$GW\ Level_{it} = \beta_0 + \beta_1 Lag_Rainfall_{it} + \beta_2 Residential_{it} + \beta_3 (Commercial_{it} \times Employment_{it}) + \beta_4 Commercial_{it} + \beta_5 Employment_{it} + \beta_6 Temperature_{it} + \epsilon_{it}$$

Table 1: Multiple linear regression results for the impact of urbanization on groundwater level (2013-2023)

	Estimate	Std. Error	t value	Pr(>t)
(Intercept)	1.111e+02	32.65	3.402	0.0013 ***
Lag Rainfall	-1.156e+01	4.204	-2.749	0.008 ***
Commercial	-1.024e+00	0.589	-1.738	0.08 *
Employment	-3.701e-05	0.000015	-2.457	0.01 **
Residential	-3.220e-02	0.0558	-0.577	0.566
Temperature	-2.650e+00	1.323	-2.003	0.05 *
Comm*Emp	4.988e-06	0.00000199	2.508	0.01 **

Source: Author's Compilation

Signif. codes: *** p < 0.01, ** p < 0.05, * p < 0.1

Residual standard error: 6.301 on 47 degrees of freedom

Multiple R-squared: 0.4344, p-value: 0.0001

Relationship between groundwater and the independent variables are presented below,

Commercial Sites

The estimate presents a significant negative relationship between commercial sites and groundwater level. The estimate is statistically significant at 10%. In areas where commercial growth outpaces residential settlements, piped water supply infrastructure spread at a slow pace, leaving no choice for these commercial zones but to rely on underground aquifer systems.

Labour Influx

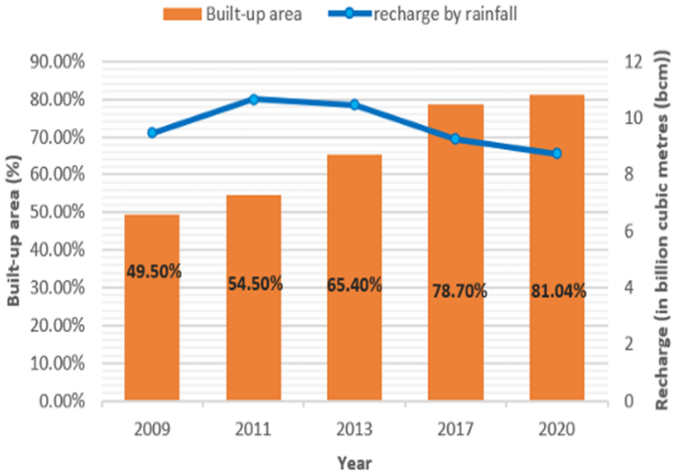
The regression estimate indicates a negative relationship between labour influx (proxied by employment data) and groundwater level. The estimate is statistically significant at 5%. As demand for labour rises in a specific city, they bring along residential, commercial and other service-related demand, leading to infrastructure expansion. This infrastructure expansion leads to various kinds of land use changes, altering the city's natural water infrastructure and recharge mechanism.

Rainfall

The estimate of rainfall indicates a negative impact on groundwater, as seen in the regression results. The estimate stands highly statistically significant at 1%. This result may seem counterintuitive, since conventional functioning of rainfall is understood to have a positive impact on groundwater recharge. The reasoning behind the negative relationship is three-fold, reduced rainfall potential to recharge groundwater could be due to – soil sealing (urbanization), changes in hydrological patterns as a result of climate change, and gaps in governance.

To validate the literature empirically, a graph indicating the increase in built-up area in Bengaluru along with the level of groundwater recharge is presented below.

Figure 8: Annual trend of recharge by rainfall and built-up area during 2009, 2011, 2013, 2017, and 2020



Source: Author's Compilation

As can be seen in the graph above, with increase in built-up area in Bengaluru, the potential of rainfall to recharge groundwater has significantly reduced (Patra et al., 2018).

Model 2: Impact of economic urbanization on groundwater level (2013-2023)

$$GW\ Level_{it} = \beta 0 + \beta 1 Textiles_{it} + \beta 2 Chemicals_{it} + \beta 3 Engineering_{it} + \beta 4 Others_{it} + \epsilon_{it}$$

Table 2: Multiple linear regression results for the impact water-intensive industries on groundwater level (2013-2023)

	Estimate	Std. Error	t value	Pr(>t)
(Intercept)	4.038e+01	1.593e+01	2.535	0.0444 **
Textiles	2.646e-04	1.342e-04	1.972	0.0961 *
Chemical	-1.327e-04	4.338e-05	-3.060	0.0222 **
Engineering	-5.157e-06	5.095e-05	-0.101	0.9227
Others	-3.315e-05	3.217e-05	-1.030	0.3427

Source: Author's Compilation

Signif. codes: ** p < 0.05, * p < 0.1

Residual standard error: 2.397 on 6 degrees of freedom

Multiple R-squared: 0.7813, p-value: 0.03497

Relationship between chemical industry and groundwater level: The estimate indicates a negative relationship between chemical industry and groundwater level. The estimate is statistically significant at 5%. This result aligns with conventional expectation of chemical industry's high exertion on groundwater, given its water-intensive nature. The production of chemical involves a series of sequential processes that require continuous water (Ellis et al., 2017). Bengaluru's intermittent piped water supply may cause hindrance in manufacturing processes (Vairavamoorthy et al., 2007). Hence, they tend to rely on tankers or private borewells, causing local aquifer stress.

As an additional exercise, the study forested the groundwater level for the time period 2024 – 2028, given the pattern of industrial water use remains the same. The graphical representation of the same is given below.

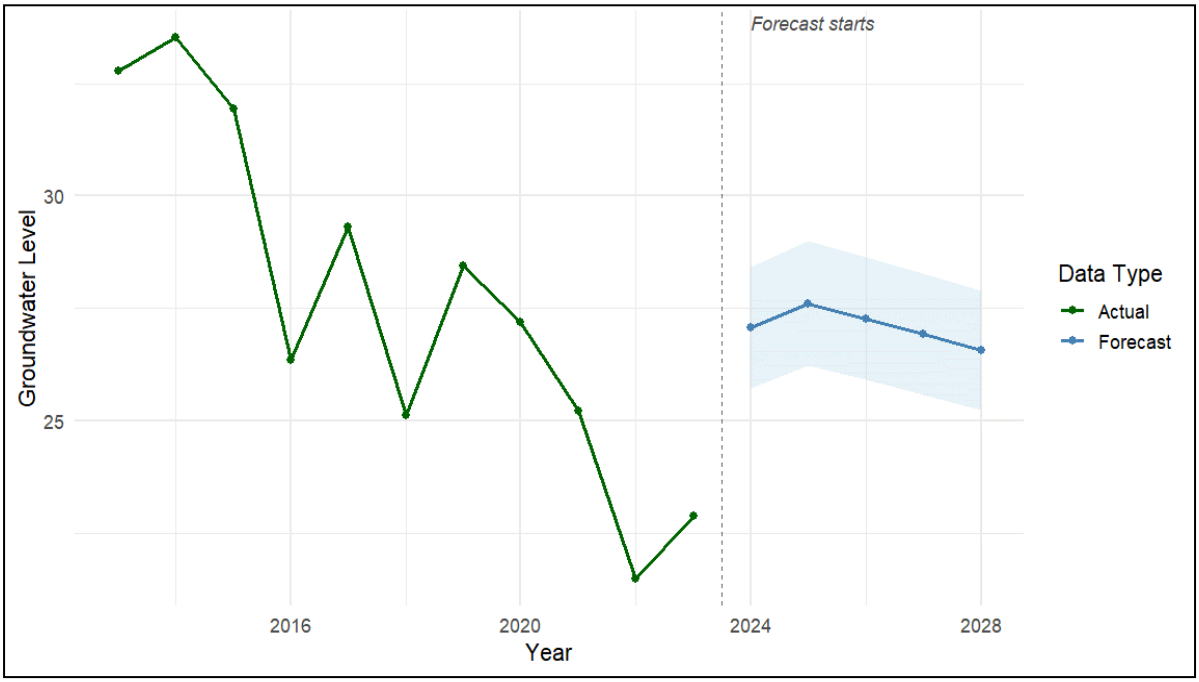


Figure 9: Groundwater Level Trend: Actual v/s Forecast (2010-2028)
Source: Author's Compilation (created using RStudio)

As seen in the graph above, groundwater level is expected to decline if both – the use of groundwater remains unaccounted of the environmental cost and management remains unregulated.

Qualitative Analysis

In the following sections, the analysis is undertaken on two critical dimensions of water management, i.e., environmental, and financial sustainability. The indicators assessed under each of these dimensions is discussed in detail below.

Environmental Sustainability: Unaccounted Water

Unaccounted water in Bengaluru, was found to be as high as 48% in 2012-23, much higher than the suggested benchmark by the American Water Works Association (AWWA), i.e., around 10%. To address this, BWSSB undertook a project to reduce UFW, funded by the Japan International Cooperation Agency (JICA) in 2013. In 2025, with these efforts, BWSSB slashed the amount of UFW by more than half of what persisted a decade ago (51%), bringing the UFW down to 24%. Moreover, with rising volumes of water being saved, large amount of BWSSB's revenue is being saved, using which the board aims to UFW further down to 15-16% in coming years and eventually to zero percent *(Bengaluru: Unaccounted for Water Project Is Finally Yielding Results, Claims BWSSB, 2017).*

Financial Sustainability: Non-Revenue Water

A subset of unaccounted water explored in the previous section is Non- Revenue Water (NRW), which comprises of water that is supplied but not billed. As per the Central Public Health and Environmental Engineering Organization (CPHEEO) standards, the allowable level of NRW should be under 15% (Sridhar, 2025). Bengaluru's NRW stood at around 52% in 2007, much higher than the permissible level.

In April 2025, BWSSB announced a 3% hike in the tariff structure as per the recommendation of the Karnataka State Administrative Reforms Commission (BWSSB Hikes Water Tariff by 1 Paise per Litre; Annual 3% Rise Planned, 2025).

This revision in tariff structure becomes significant for two reasons. First, when water is priced fairly, it helps bring behavioural shift in water usage among citizens, which is critical to a city facing chronic water stress. Second, the increase in BWWSB's revenue can be used in investment in advanced water technology, construction of sewage treatment plants to utilize wastewater potential, lake rejuvenation among others.

Policy Implications

This section builds on the key findings discussed in the previously to point out some policy recommendations.

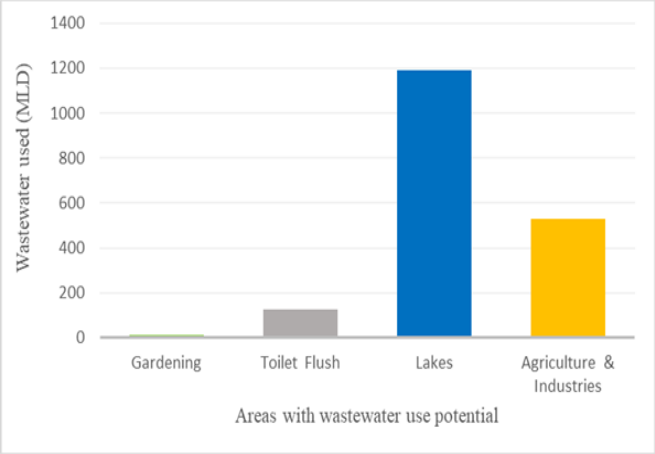


Figure 12: Distribution of wastewater use in different tertiary purposes (Source: Author's Compilation)

Wastewater Treatment: According to report by WELL Labs, Bengaluru generates approximately 2000 MLD of wastewater, of which only 30% is being reused (Ramesh, 2023). The usage of this 30% for several purposes is presented in the graph above. As it can be seen in the graph, large amount of wastewater is being released into lake. Release of treated wastewater into lakes not just renders volumes of water waste, but also pollutes these water bodies (Palur et al., 2024). While the city is making considerable attempt to encourage construction of decentralized sewage treatment plants, a lot of wastewater potential remains untapped.

Demand-Side Management: Citizens can take measures such as mandatory installation of Rainwater Harvesting in private properties, residential complexes, industrial zones, commercial establishments among others. Additionally, embracing use of grey water for gardening or flushing can reduce demand for water significantly. Installation of water-efficient technologies (water filters, low-flow taps) could slash wastage by a great amount.

Policy implementation from lessons around the globe: Singapore: The country has a robust water supply system referred to as Singapore's 'Four National Taps' (Tortajada, 2018). They consist of increasing local catchment area for rainwater collection, imported water through pipe infrastructure from Malaysia (water agreement that expires in 2061), NEWater – water recycled using high grade technology making it fit for industrial and agricultural uses. Additionally, along with wastewater treatment through centralized and decentralised sewage treatment plants, the country has set up two large-scale desalination plants that involves the process of salt segregation from saline water, making it suitable for consumption.

Denmark: One of the best practices include the 'producer pays' approach to wastewater discharge. This incentivizes industries to cut massively on their pollutants. Additionally, discharge beyond the stated threshold is heavily penalized in the country. Also, a NRW (drinking water) greater than 10% imposes a penalty fee on drinking water management board.

Conclusion

The exploration of urbanization and its association with water resources present a dynamic view of how spatial expansion, economic growth and change in labour market dynamics intersect with the natural ecosystem. The choice of Bengaluru as the study area is both timely and interpretatively valuable in the light of the severe water crisis that occurred in the summer of 2024. Being one of India's fastest-growing metropolitan cities, Bengaluru serves as a strong analytical example of the complex interaction between urban sprawl, economic growth, and environmental vulnerability.

There were two primary objectives of the study: to quantify the impact of urbanization, disaggregated as three broad types – landscape, demographic and economic – on groundwater levels in Bengaluru; and study the role of water utility in mitigating and exacerbating water stress. Three key findings for Bengaluru hold important implications for sustainable urban development and water regulation. First, water stress is not a by-product of urbanization, but an active manifestation through choices made in the process of urbanization. The empirical findings in this respect suggest that the expansion in built-up area, mainly commercial establishments and population increase (employment driven), as well as economic growth, exert unprecedented pressure on already overexploited aquifers.

This results when the scale and speed of urbanization is much faster than the what the infrastructure mechanism can support. Second, the scale of water utility must be sufficiently large to look after both operational as well as regulatory functions related to water governance.

The qualitative analysis of BWSSB (concerned with supply and distribution) from this study indicates that, while areas in the city periphery fall in the jurisdictional boundary of governance, the scope of water supply and monitoring of extraction from aquifers mainly remains confined to Bengaluru's core areas. This caused settlements in peri-urban areas to resort to illegal drilling of borewells due to limited formal water supply facility, emphasizing the need to expand governance capacity with increase in urban footprints.

In conclusion, the study underscores the need to internalize environmental costs in urban planning and reduce water vulnerability through strengthening regulatory framework to achieve economic resilience and ensure sustainable urban development.

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Locust Outbreaks and Climate Variability: Addressing Food Insecurity in Rewari District, Haryana, India

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Executive Summary

This research investigates the growing threat of desert locust (Schistocerca gregaria) outbreaks in the Indian subcontinent, with a focused case study on the Rewari district of Haryana. The study explores the relationship between changing climatic variables particularly rainfall, temperature, and wind speed and the frequency and intensity of locust swarms. Utilizing a mixed methods approach, the study combines long-term meteorological data (19792020), regression and correlation analyses, and qualitative field surveys across three vulnerable villages in Rewari block to assess the ecological and socioeconomic consequences of locust invasions. Findings reveal a significant shift toward erratic rainfall, persistent high summer temperatures, and intermittent wind spikes all of which create conducive conditions for locust breeding, maturation, and migration. The 2020 locust outbreak, exacerbated by unseasonal rainfall and favourable wind patterns, aligns with these observed climatic anomalies. Regression analysis shows a strong negative correlation between temperature and rainfall, with rising temperatures linked to decreasing precipitation, an alarming trend in the context of increasing locust activity.

The socioeconomic survey of 90 respondents highlights that over 80% of households experienced total crop damage, with significant loan burdens and income losses during the 2020 outbreak. The dual shock of COVID19 and locust invasion amplified rural distress, revealing gaps in government relief mechanisms and pest management preparedness. The research underscores the need for integrated locust management that aligns climate data with real-time surveillance, early warning systems, and community participation. Sustainable alternatives such as botanical pesticides, remote sensing, and locust utilization for food security are explored. The study advocates for policy reforms recognizing locust invasions as natural disasters and recommends developing adaptive strategies involving all stakeholders to mitigate future risks. This work contributes to climate resilient pest control and food security planning in arid and semiarid regions of India.

Context & Problem Statement

The research addresses the issue of food insecurity resulting from locust infestations, specifically in the Rewari district of Haryana, India. It investigates how climatic factors such as temperature, rainfall, and wind speed contribute to the occurrence and intensity of locust swarms, which in turn disrupt agricultural productivity and food supply. The study focuses on understanding the link between changing weather patterns and locust outbreaks, and the cascading effects these have on local livelihoods, socioeconomic stability, and food security in rural communities through interdisciplinary tools and regional cooperation is crucial for effective, climate resilient locust management amid increasing weather extremes.

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The study focuses on understanding the link between changing weather patterns and locust outbreaks, and the cascading effects these have on local livelihoods, socioeconomic stability, and food security in rural communities . This issue is significant because locust outbreaks pose a serious threat to food systems, particularly in agrarian economies like India, where a large portion of the population depends on farming for survival. Uncontrolled swarms can destroy vast tracts of crops within hours, leaving communities without food or income. In Rewari district, such invasions have exacerbated rural poverty, disrupted livelihoods, and highlighted the inadequacy of current pest control measures. Moreover, the study underscores the urgency of developing sustainable, climate resilient strategies that can both predict and mitigate the impact of such biological threats in the future.

From a social and economic perspective, the study is rooted in the lived experiences of rural communities that have suffered crop losses due to recent locust attacks. It captures the local challenges, including loss of income, food shortages, and pressures on health and education. Environmentally, it recognizes the role of climate change in altering ecosystems and creating favourable conditions for locust breeding and migration. Politically, the research evaluates the response of government schemes and administrative interventions aimed at managing locust outbreaks, while also suggesting improvements in policy design to better protect vulnerable populations and ensure food security in the face of ecological uncertainty. Despite extensive research on locust outbreaks, key gaps persist such as the lack of integrated climate Locust models, limited socioeconomic impact analysis, untested tech interventions, and weak cross border coordination. Addressing these through interdisciplinary tools and regional cooperation is crucial for effective, climate resilient locust management amid increasing weather extremes.

Literature Review

Locusts, especially the desert locust (Schistocerca gregaria), are among the most destructive migratory pests, capable of decimating crops across large areas. Northwestern Indian states like Rajasthan, Gujarat, and Haryana are particularly vulnerable due to changing climatic conditions (Sharma, 2014). Temperature, humidity, and rainfall are key factors in triggering outbreaks. Optimal breeding conditions include 32.235°C temperatures, 3545% humidity, and moist soils aided by rainfall, which also stimulates vegetation growth (Mitra et al., 2024). Events like Cyclone Mekunu (2018) and erratic monsoons have triggered largescale breeding and swarm movement (Mitra et al., 2024b; Singh et al., 2022). The socioeconomic consequences of locust attacks are severe ranging from crop and fodder loss to food insecurity, poverty, and educational setbacks, especially among children (Friedman, 2024). In extreme cases, invasions trigger migration, social unrest, and strain on government resources through emergency pesticide campaigns and compensation (Sokame et al., 2024).

Control measures include chemical spraying (e.g., chlorpyrifos, malathion), biological agents, and cultural deterrents like waving cloths or smoke (Mehta, 2020). However, excessive pesticide use harms ecosystems, affecting pollinators, natural predators, and human health (Aggarwal, 2020; Biotic Invasions, 2000). Neem oil, a safer botanical pesticide, has shown localized effectiveness (Hartbauer, 2020). Innovative solutions, like harvesting protein rich locusts as food or feed, offer dual benefits of pest control and food security (Hussain et al., 2023). India's 2020 response involved coordinated aerial spraying and government action along breeding hotspots (Government of India, 2020). Economic analysis reveals wheat yield losses up to 12%, underlining the need for disaster recognition and crop insurance schemes (Chatterjee, 2020; Khan et al., 2023).

Overview of the Methodology

This study adopts a mixed methods approach, combining both quantitative and qualitative research to gain a comprehensive understanding of the connection between climate change, locust outbreaks, and their impacts on agriculture and food security in Rewari district, Haryana. The approach is well-suited to explore both statistical trends and the lived experiences of affected communities.

Data Collection and Location

The research focuses on three randomly selected villages within the Rewari Block of Haryana. This selection allows for targeted analysis while keeping the scope manageable. For the quantitative aspect, historical climate data (covering the period from 1979 to 2020) is sourced from credible institutions like the India Meteorological Department (IMD) and FAO Desert Locust Watch. This data helps identify long-term patterns in temperature, rainfall, and wind speed that may be linked to locust swarm occurrences. Additionally, government records and field observations are used to assess agricultural losses caused by these invasions.

Primary Data and Sampling

To capture the on-ground impact of locust attacks, interview-based questionnaires were conducted with 90 respondents across the three villages. The participants were chosen to represent diverse backgrounds in terms of social, and economic status. The survey included both closed ended questions for quick analysis and open-ended ones to explore individual experiences, allowing a deeper understanding of how locust outbreaks have affected rural livelihoods, especially when combined with challenges like COVID19.

Research Objectives

1. To analyse the relationship between climate change and locust swarm occurrence in the Indian subcontinent

2. To assess the impact of locust infestations on agricultural productivity and food security.

3. To find sustainable ways to manage locusts by combining environmental, technological, and policy strategies.

Research Questions

1. How do climatic factors (temperature, rainfall, wind patterns) influence locust outbreaks?

2. What are the socioeconomic consequences of locust invasions on farmers and food supply chains?

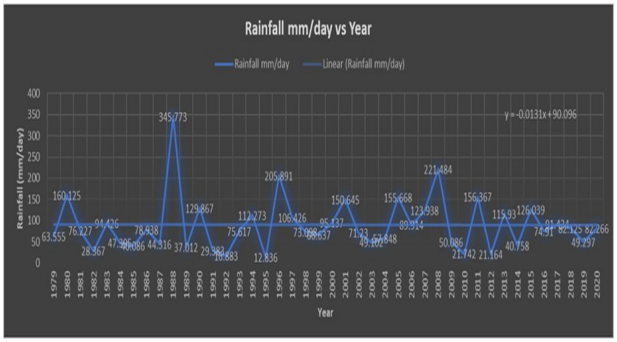
3. How effective are current locust management strategies?

Figure 1: Trend Analysis Graph of Rewari District (Reinafall vs Year)

Findings and recommendations

Trend analysis of the historical rainfall data (19792020) for Rewari, Haryana

Rainfall Trend Analysis: Rewari (19792020)



Key Observations :

Long-term Decline: The linear trend line equation: $y = -0.0131x + 90.096$

This indicates a gradual decline in average daily rainfall (mm/day) over time, pointing to a drying trend in the region.

Qualitative Component Data Analysis Tools and Justification

Data from primary surveys were organized and analysed using Microsoft Excel, leveraging tools such as PivotTables, charts, and regression models to explore relationships between variables. Statistical methods including trend analysis, correlation,

and nonparametric tests were applied to assess patterns and make projections. The use of Excel made it easier to visualize data and detect anomalies. This methodology is appropriate for the research as it balances data driven analysis with humancentric insights, ensuring that both climatic trends and community impacts are addressed comprehensively.

High Variability: Extreme peaks in certain years (e.g., 1988, 1996, 2006). Multiple years with low rainfall (e.g., 19841986, 19911994, 20152020). This pattern suggests inconsistent monsoon behaviour with occasional rainfall surges surrounded by dry years.

Recent Decade (20102020): Mostly below average rainfall. 2013 and 2014 had moderate spikes, but the years after show drought prone conditions.

Rainfall Locust Outbreak Relationship: Desert locust swarms (Schistocerca gregaria) are sensitive to rainfall patterns, especially in arid and semiarid zones. The Rewari rainfall trend contributes to locust risk in the following ways:

Declining Rainfall (Aridification):

- Creates semiarid landscapes, which are ideal for desert locust migration.
- Vegetation becomes patchy, making locusts more mobile and prone to swarm behaviour.

Sporadic Rainfall Spikes: Occasional heavy rains cause rapid greening and growth of grasses/weeds ideal for:

- Egg laying
- Nymph development

Years like 1988, 1996, and 2006, which saw rainfall spikes, may have triggered breeding grounds when followed by warm temperatures.

Rainfall After Drought:

- Long dry spells followed by sudden rain (common in the graph) stimulate egg hatching.
- This creates a "boombust" ecological cycle, perfect for swarm escalation if not checked.

Implications for Agriculture and Locust Management

- The drying trend weakens crop systems and reduces resilience to pests.
- Sudden rainfall increases surprise locust outbreaks, especially pre-monsoon or early monsoon.
- These rainfall anomalies in an increasingly dry climate make Rewari a climate sensitive hotspot for nontraditional locust invasions.

Inference:

The historical rainfall data of Rewari reveals a clear trend of declining and erratic rainfall. This evolving pattern:

- Supports desert-like conditions, ideal for locust transit and feeding.
- Promotes episodic vegetation booms, which act as breeding triggers.
- Enhances the ecological vulnerability of the region to locust swarms, especially when combined with rising temperatures and favourable winds.

Action Needed: Monitoring such rainfall trends is crucial for forecasting locust risks, and integrating this data into early warning systems can prevent agricultural damage in Haryana and beyond.

Temperature and Wind Speed vs Year graph for Rewari (19792020).

Temperature (°C) Trend:

Graph Line Colour: *Blue*

Trendline Equation*: y=−0.0251x+41.888y = 0.0251x + 41.888*

Observation:

- The temperature shows a slight negative slope, indicating a marginal downward trend.
- However, the trend is largely flat, and the temperature stays within the high range of ~3845°C, suggesting persistent heat, especially during pre-monsoon and summer seasons.
- A visible outlier dip around 1987 may be due to data error or climatic anomaly.

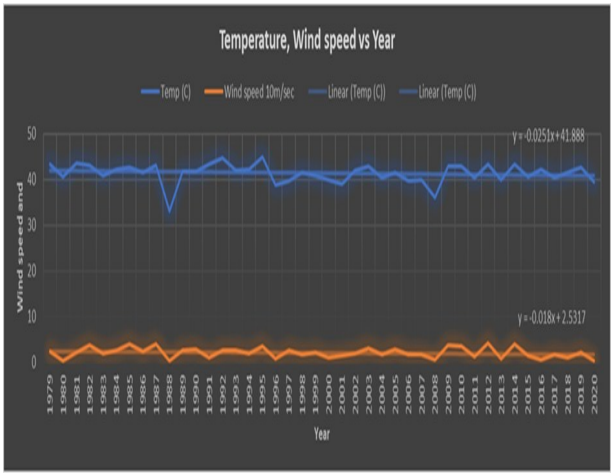


Figure: Trend Analysis Graph of Rewari District (Temperature and Wind Speed vs Year)

Wind Speed (10 m/sec) Trend:

- ***Graph Line Colour:*** *Orange*
- ***Trendline Equation:*** $y=-0.018x+2.5317$
- ***Observation:***

- *T*he wind speed shows a slight declining trend.

- Despite the downward slope, peaks in wind speed are visible in certain years (e.g., 1988, 2011, 2014), indicating intermittent strong wind events.

- Average wind speeds remain above 2 m/s, which can significantly influence locust movement and swarm dispersal.

Climatic Influence on Locust Activity

Role of Temperature:

Desert locusts flourish in hot, dry conditions, with optimal breeding and development occurring at temperatures between 3542°C. In regions like Rewari, consistently high pre-monsoon temperatures can prepare locusts for swarming, especially if followed by rainfall.

Role of Wind Speed:

Locust movement is highly dependent on wind. Strong and sustained winds enable long-distance travel, while sudden gusts can either disperse or introduce swarms. Although the overall wind trend is declining, occasional high wind years facilitate sudden migratory events into regions like Rewari.

Combined Climatic Interaction:

The combination of warm, dry weather, episodic strong winds, and prior rainfall creates ideal conditions for locust breeding, migration, and crop damage.

Conclusion:

Rewari's Suitability for Locust Activity Despite slight downward trends in temperature and wind speed, Rewari's climate remains favourable for locust activity due to persistent high temperatures, episodic wind bursts, and erratic rainfall, making it increasingly vulnerable under shifting pre-monsoon patterns.

Recommendations

Adopt early warning systems integrating real-time temperature and wind data with forecast models. Emphasize surveillance from April to June, when locusts are likely to arrive and conditions are conducive to their spread.

1. Correlation Analysis: Temperature, Wind Speed, and Rainfall (19792020)

Locust outbreaks, particularly those involving Schistocerca gregaria (desert locust), are profoundly influenced by climatic variables such as rainfall, temperature, and wind. Understanding the trends and

- Correlation Matrix Interpretation
- The correlation matrix contextualizes the relationships between temperature, wind speed, and rainfall in the Rewari region (19792020) and ties them into broader climatic and ecological implications.
- Inter-relationships among these variables is critical to assessing vulnerability and forecasting locust invasions. This analysis examines the long-term patterns of these climate indicators in Rewari, Haryana, and analyses their potential role in shaping locust activity in the region.

Correlation Matrix Interpretation

The correlation matrix contextualizes the relationships between temperature, wind speed, and rainfall in the Rewari region (19792020) and ties them into broader climatic and ecological implications.

From an agricultural standpoint, these trends pose a growing threat to food security and rural livelihoods. The findings underscore the urgent need for integrated climate risk assessments and robust locust early warning systems, particularly during the premonsoon period, to mitigate emerging threats in nontraditional invasion zones like Rewari.

Correlation Matrix: Temperature, rainfall and wind speed

	Temp (°C)	Wind Speed (10m/s)	Rainfall (mm/day)
Temp (°C)	1.000	0.667	**0.885**
Wind Speed (10m/s)	0.667	1.000	0.622
Rainfall (mm/day)	0.885	0.622	1.000

Interpretation:

- **Temp & Rainfall:** Strong negative correlation (0.885) - as temperature increases, rainfall tends to decrease.
- **Temp & Wind Speed:** Moderate positive correlation (0.667) - higher temperatures are associated with higher wind speeds.
- **Wind Speed & Rainfall:** Moderate negative correlation (0.622) - stronger winds tend to accompany lower rainfall

Temperature and Rainfall (r = 0.885)

There is a strong negative correlation between temperature and rainfall. This implies that as temperatures rise, rainfall tends to decline in the region.

- **Implication:** Warming conditions, potentially driven by climate change or urbanisation, are likely contributing to reduced precipitation levels. This could lead to drier soil conditions, water scarcity, and reduced crop yields in the agricultural district of Rewari.
- **Locust linkage:** Higher temperatures and lower rainfall can create favourable breeding grounds for desert locusts, especially when followed by sudden rain events that stimulate vegetation growth.

Temperature and Wind Speed (r = 0.667)

A moderate positive correlation is observed between temperature and wind speed. Temperature increases are generally associated with stronger wind speeds.

- **Implication:** Warmer air masses tend to rise, creating pressure differences that increase surface wind activity. These winds may aid the spread of pests and crop diseases, including facilitating locust migration from neighbouring regions.
- **Locust linkage:** Stronger winds, when combined with elevated temperatures, enhance the mobility and range of desert locust swarms, helping them reach inland regions like Rewari that are not traditionally affected.

Wind Speed and Rainfall (r = 0.622)

A moderate negative correlation exists between wind speed and rainfall. As wind speeds increase, rainfall tends to decrease.

- **Implication:** High wind speeds are commonly associated with dry atmospheric conditions or the movement of storm systems that do not deposit significant precipitation locally.
- **Locust linkage:** Lower rainfall accompanied by strong winds supports arid conditions conducive to locust breeding, while also enabling long distance swarm travel. This contributes to the risk of locust incursions into low rainfall zones like Rewari.

Over the past four decades, Rewari has experienced a gradual shift toward a warmer, drier, and windier climate. These evolving conditions marked by declining but sporadic rainfall, persistently high temperatures, and intermittent strong wind shave collectively increased the region's ecological suitability for desert locust invasions. Such climatic dynamics weaken the natural rainfall support system while amplifying the risk of locust outbreaks, particularly during years marked by anomalous weather patterns.

From an agricultural standpoint, these trends pose a growing threat to food security and rural livelihoods. The findings underscore the urgent need for integrated climate risk assessments and robust locust early warning systems, particularly during the premonsoon period, to mitigate emerging threats in nontraditional invasion zones like Rewari. Strengthening surveillance and response frameworks is essential to safeguard both the environment and the socioeconomic fabric of the region.

2. Findings of a Survey conducted in 3 villages of Rewari Block in Rewari district of Haryana.

Three villages, Aakera, Balaswar Ahir and Alwalpur, were chosen for a field survey to assess the impact of locust infestations on agricultural productivity and food security, to understand the socioeconomic consequences of locust invasions on farmers and food security and to understand the effectiveness of the current locust management strategies. The primary occupation of the villagers is agriculture, and a key source of their household incomes as well. Majorly, Wheat, Cotton, Mustard, Bajra, Jowar, Gram (Chana) and Maize are the crops which are currently cultivated in these three villages. These crops are severely affected due to locust attack. The landholding size ranges between 0.60 ha. to 2.1 ha. The recent locust attack happened in 2020 which was a Covid19 year, and farmers faced dual hardships as their livelihoods and socioeconomic conditions were severely impacted.

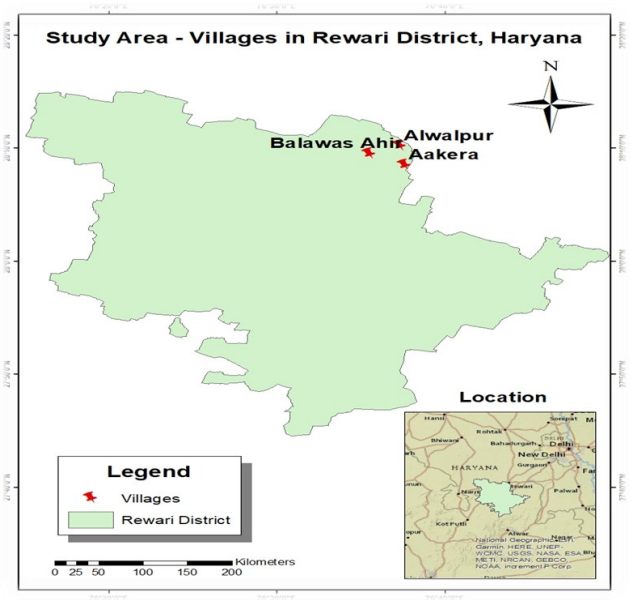


Figure 3: Map of three villages of Rewari District, Haryana where survey was conducted.

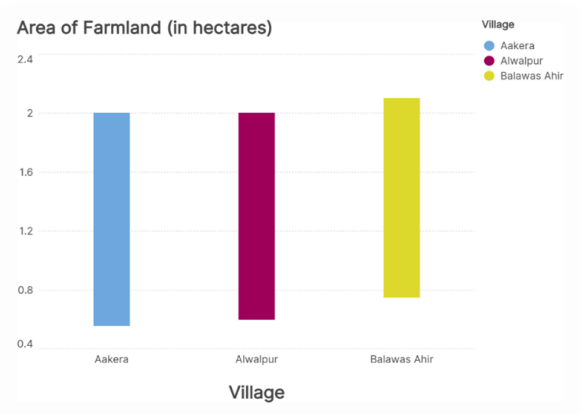


Figure 4: Land holding range of three village

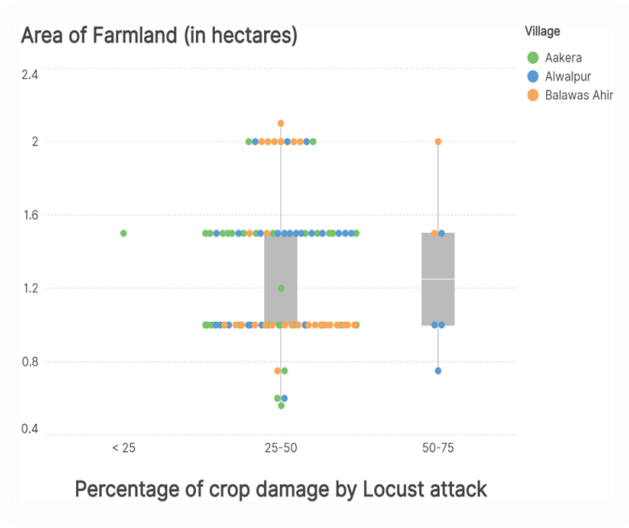


Figure 5: Boxplot of Land holding and % loss. Most of the damage (2550%) has occurred in all three villages. < 25 only in Aakera.

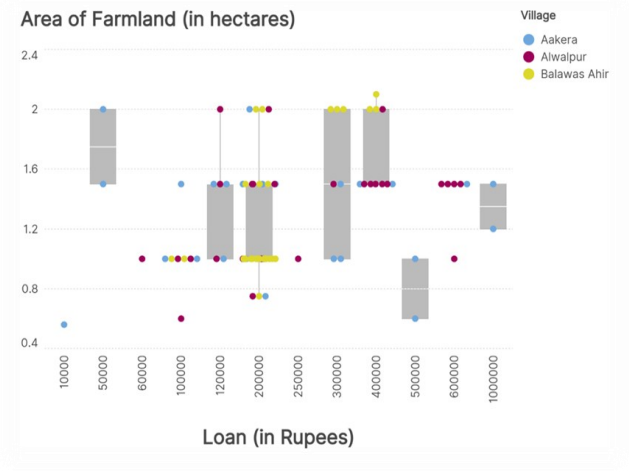


Figure 6: Boxplot of Land holding and Loan amount

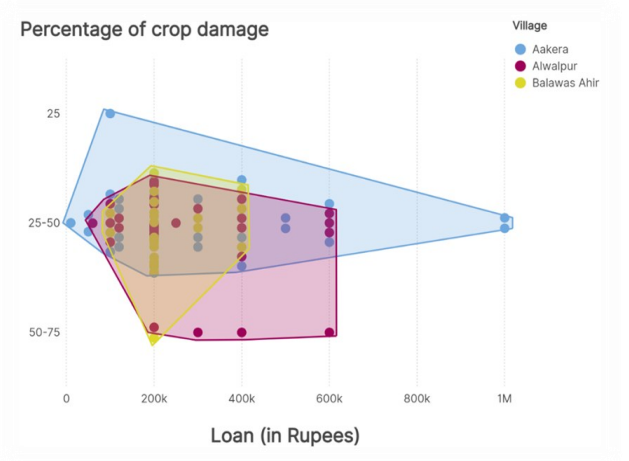


Figure 7: Percentage of Crop damage vs Loan money taken

Aakera village had the widest range of loan amount 10k to 1 million, and land holding as well. Alwarpur village loan range varied between 60k to 600k with land holding up to 2 ha., and in Balawas loan amount varied between 40k to 400k with land holding more than 2 ha. The relation between land holding and loan amount was found weakly related (R square= 0.04, $F(1, 85) = 4.216376$, $p < 0.05$)

The polygon method analysis depicts that Aakera village's crop damage was up to 50% but loan amount was maximum (1 million). Alwarpur suffered greater loss than Akera (up to 75% crop) but their loan amount was up to 600 K and Balawas Ahir village suffered like Alawarpur but their loan amount was up to 400k.

The survey findings indicate that a significant majority of respondents (80%) reported that the locust attack completely damaged their crops. Additionally, 8.9% of respondents experienced heavy crop loss, while an equal proportion (8.9%) stated that their household income was heavily affected. A smaller percentage, 1.1%, reported that their livelihood was severely affected, and another 1.1% fell below the poverty line due to the impact of the locust attack and COVID19 situation. These results highlight the widespread agricultural damage and the varying degrees of economic hardship experienced by affected households.

The analysis reveals that in Aakera village, farmers with land around 1.6 hectares experienced crop damage ranging from severe to complete loss and livelihood was heavily affected. In Alwalpur, although most farmers had similar land size (1.41.6 ha), the impact varied from falling below the poverty line to complete crop loss. Balawas Ahir farmers, with relatively smaller land areas (~1.2 ha), mostly faced complete crop damage and livelihood disruption, but fewer reported falling below the poverty line.

88.9% of households were severely affected and 11.1% were moderately affected by locust attacks. During the interactions with respondents, it was found that the traditional methods such as firecrackers, beating utensils and making loud noises were more effective than pesticide usage. It was economically also more effective as does not require monetary investment. Although Govt. aided in pesticide availability, but it was not appropriate.

Farmers had to take loans to deal with dual impact of Covid19 and locust attack. The survey also highlights the lack of disbursement of monetary compensation to the farmers for locust attack. The administrative machinery could not provide effective solutions and aid other than pesticide spraying at few locations. Farmers had to deal with the menace on their own. Effective government intervention is required to understand the damage caused and declare it as an agriculture emergency. Administrative guidance, early warning system, preparedness and a robust plan to deal with the situation is important.

Conclusion

In recent years, the fight against locust outbreaks has advanced through a mix of traditional knowledge and innovative solutions. Scientists and policymakers are increasingly relying on technologies such as remote sensing, GIS, and GPS to track and predict locust movements with greater precision. . Alongside these tools, there's growing interest in environmentally friendly approaches, such as using natural fungi like Metarhizium acridum to infect and reduce locust populations without harming other organisms (Riaz and Hakeem, 2024).

These strategies offer promising alternatives to chemical pesticides, which often come with serious ecological side effects. Moreover, researchers have studied how locusts damage crops and are working on sustainable control techniques to limit the scale of destruction. Together, these efforts represent a shift toward smarter, greener, and more coordinated management of one of agriculture's oldest threats.

A ray of hope is seen in the opportunity to use Locust as feed for fulfilling protein requirement of the population in order to combat food insecurity. Effective and timely administrative action by tracing locust migration paths by use of drones, spraying of pesticides and disbursement of monetary compensation can create a robust mechanism to deal with this menace. Predictive climate modelling to understand and trace the next occurrence of attack can help better preparedness. Climate change is the main cause of shift in temperature and precipitation pattern which affects the locust's migration across the world.

The shift from traditional dryland cultivation of crops towards cash crops has also led to severe damage of crops. This resulted in food insecurity, economic losses, socio economic consequences and causing livelihood damages. An integrated approach to find solutions by keeping all stakeholders like farmers, locals, government, international organisations, scientists and academicians in consensus can help tackle this issue of locust attack. The field of research is open to new solutions and management strategies.

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Beyond Antibiotics: In Silico Discovery and Enzymatic Insights for H. pylori Eradication

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Executive Summary

Helicobacter pylori is a spiral-shaped, gram-negative bacterium which grows in the mucus layer that coats the inside of the human stomach. It is a considerable burden to public health; infections acquired in childhood can lead to chronic diseases, including gastric ulcers and cancer. The transmission route of this bacterium is poorly understood, but it generally subsists in water (contaminated) and in poor sanitation conditions. There are no exclusive drugs to eradicate H. pylori, but the multidrug gold-standard treatment achieves eradication rates of over 90%. Healthcare is one objective of the United Nations' Sustainable Development Goals. Using biotechnological applications, pathogenic organisms and their protein structures can be studied and brought to use in the healthcare of humankind. The Gmhc (also referred to as HldE, D-beta-D-heptose 7-phosphate kinase) is a protein in the lipopolysaccharide (LPS) biosynthesis layer, primarily part of the Heptose synthesis (ADP-d-glycero-β-d-manno-heptose) pathway in H. pylori. The research focuses on blocking the function of this protein, which will truncate the LPS, resulting in control of the growth of H. pylori. The protein has been studied both in vitro and in silico. A certain new approach was taken by using antimicrobial peptides as the molecules to block the activity of gmhc, by docking these AMPs to the active site of the protein receptor. With the increasing antibiotic resistance, this new approach combats the former problem.

Context & Problem Statement

Helicobacter pylori is a gram-negative spiral bacterium that causes peptic ulcer disease and is associated with an increased risk of gastric cancer. It is the sixth most prevalent cancer in the world and the third leading cause of cancer death. (Rajendran and and Ponnuraj, 2024). In this study, gmhc (D-beta-D-heptose 7-phosphate kinase) HP0858, an enzyme involved in the biosynthesis of lipopolysaccharides that encourages bacterial adherence, self-aggregation. gmhc is a bifunctional enzyme; it acts as a kinase and adenyltransferase. It is a dimeric protein, part of the Heptose synthesis pathway of the core oligosaccharide in the lipopolysaccharide layer of Helicobacter pylori . This pathway has four proteins: gmhA, HldE, and gmhB. This pathway is present in almost all Gram-negative bacteria, as they require heptose sugars in the inner core of their LPS. H. pylori appears to use mainly its Cag type 4 secretion system (CagT4SS0 to also mediate the transfer of heptoses into human gastric epithelial cells and monocytes/macrophages, while Enterobacteriaceae (Shigella and Yersinia) may also enlist T3SS for a similar purpose. The impact of H. pylori resistance on patients' treatment failure is a major concern. Therefore, the development of novel or alternative therapies for H. pylori is urgent. Generally, Antimicrobial peptides (AMPs) are short peptides consisting of 10–60 amino acids with an overall positive charge (generally +2 to +9) and have a substantial proportion of hydrophobic residues (>30%) These characteristics of AMPs (amino acid sequences, net-positive charge, amphipathicity, and very small size) allow APMs to bind to and disrupt the membranes of microorganisms. When we block the activity of gmhc, the LPS layer formation gets disturbed. We have studied the in silico as well as in vitro properties of this protein for a better understanding. The exclusive work with antimicrobial peptides and their compatibility has

also been studied and checked against the gmhc, which acts as a receptor for these peptides. The selected peptides are naturally occurring and have the potential to block the gmhc enzymatic activity. This research can be carried forward by in vitro synthesis of these selected antimicrobial peptides and testing them against the H. pylori culture, to check the minimum inhibitory concentration. Even further to increase the binding affinity, mutations can be generated in gmhc. The advent of in silico methods of bioinformatics, molecular docking, and molecular dynamics simulation provides an extraordinary advancement in the field of drug discovery. These molecular approaches enhance our knowledge regarding biological pathways of protein-peptide, protein-protein, or protein-ligand complexes, which provide insights into the mechanisms of novel interactions. Molecular docking helps scientists to predict the best binding patterns and interactions between compound complexes.

Literature Review

Most strains of H. pylori produce virulence factors that have developed to influence host cell signalling pathways. Among the many distinctive traits of H. pylori, its remarkable ability to survive for decades in the challenging gastric environment due to the host's failure to eradicate the infection is particularly noteworthy. Unlike other viruses and bacteria, H. pylori has developed the capacity to thrive in the stomach's highly acidic environment by converting urea into ammonia through urease, which creates a neutral zone around the bacterium. Current evidence supports the idea that H. pylori has lived alongside humans for tens of thousands of years, with genetic research suggesting that humans have harboured H. pylori for at least 58,000 years (Chmiela et al., 2014). Currently, half of the world's population is infected with this infection. Most people do not show any symptoms. ("Helicobacter pylori (H. pylori) and Cancer - NCI," 2013; Chmiela et al., 2014; Linz et al., 2007; McArthur et al., 2005).

Lipopolysaccharide (LPS) is crucial for the virulence associated with H. pylori infection. LPS is a significant element of the outer membrane in Gram-negative bacteria, typically regarded as toxic and possessing strong immune-modulating and immune-stimulating effects.

Alexander Fleming identified lysozyme in 1922, which initiated the advancement of modern innate immunity. Since that time, antibiotics and antimicrobial peptides (AMPs) have been discovered. The sources of AMPs can be divided into mammals (human host defence peptides account for a large proportion), amphibians, microorganisms, and insects according to statistical data. The docking of such complexes can be performed using various online servers like Cluspro, HDOCK, Hawkdock, Patchdock and so on. Peptide-mediated interactions are attracting growing interest because of their crucial roles in various regulatory processes characterised by dynamic protein interactions.

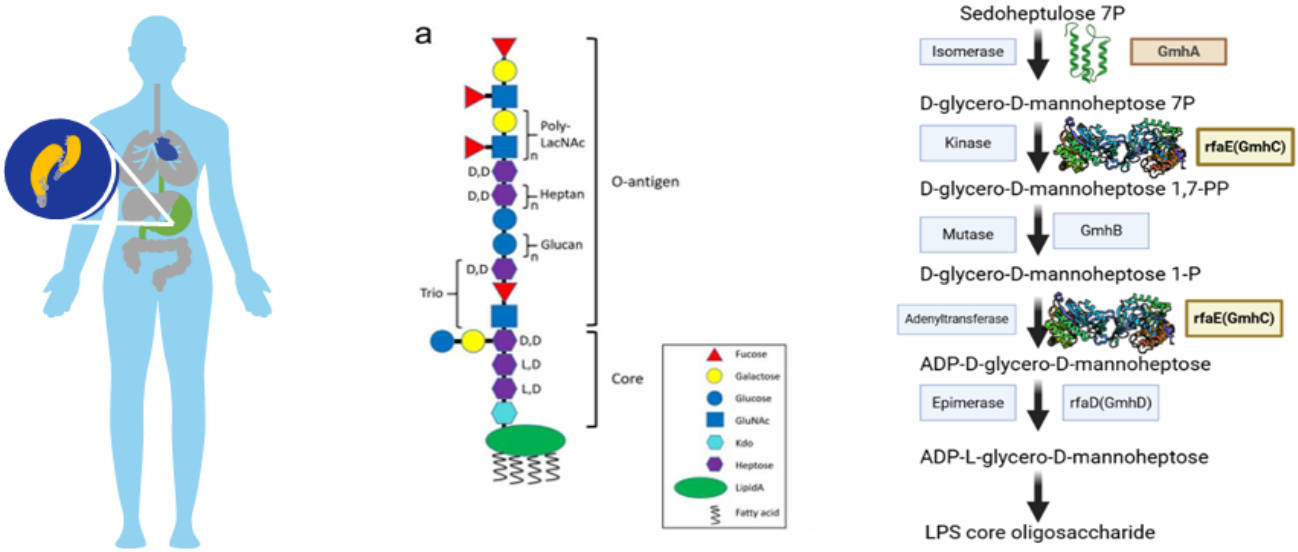


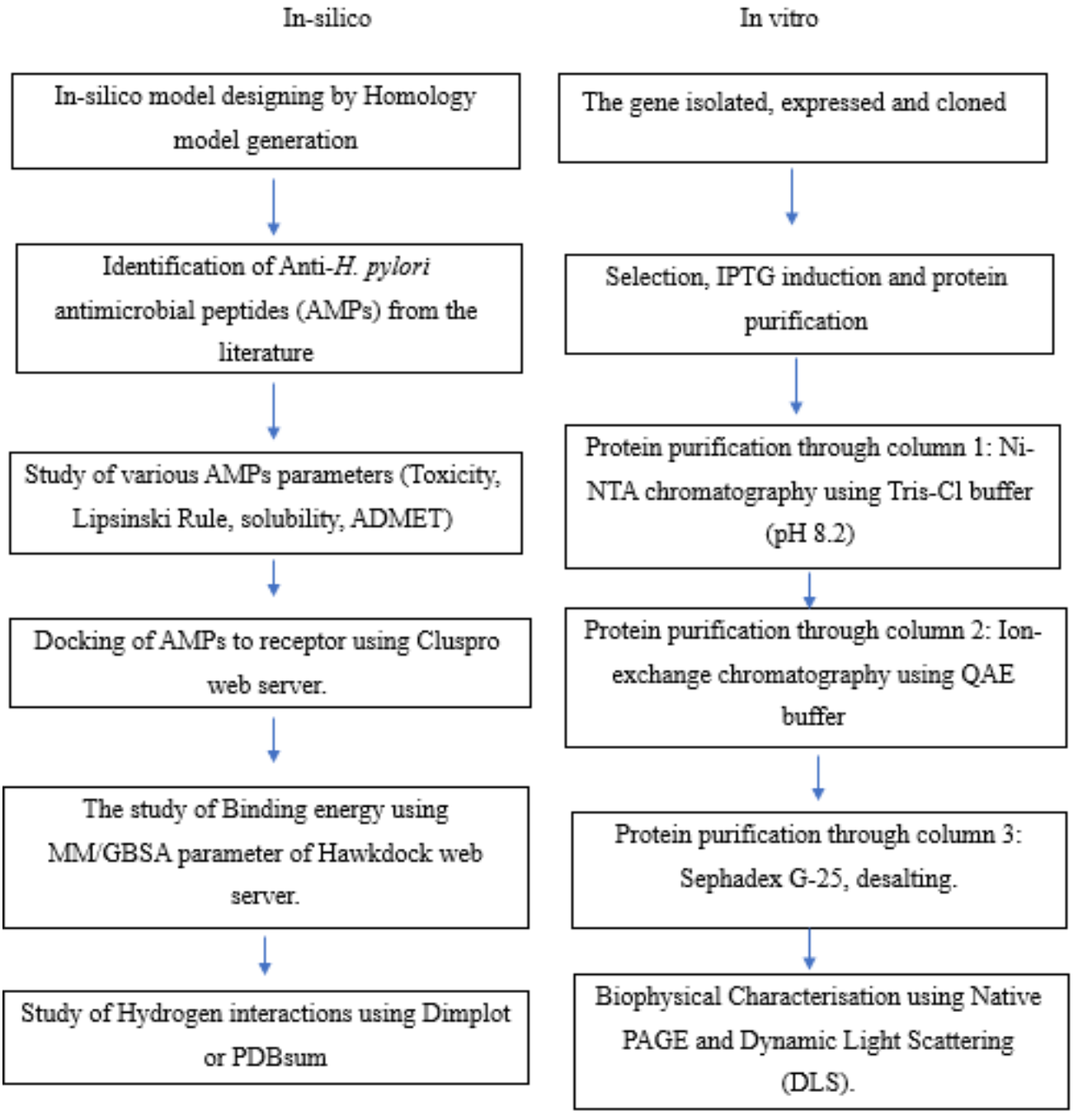
Figure 1 The human stomach infected with H. pylori a) shows the LPS layer of H. pylori, wherein our focus in on the L-glycero D-mannoheptose molecule, which gets synthesised by using Heptose synthesis pathway, represented in right side, where the gmhc enzyme is the focus of study.

The structures of these interactions offer a valuable foundation for their characterisation and manipulation and can serve as a basis for designing targeted inhibitors. The limited number of experimentally determined structures of peptide-protein complexes can be supplemented by a surge of modelling techniques that have emerged in recent years, demonstrating enhanced accuracy and relevance to an expanding range of systems (London et al., 2013).

Research Focus and Methodology

The main objective of the study was to computationally study the bifunctional enzyme gmhc from H. pylori and check the blocking efficiency of antimicrobial peptides when targeted against the gmhc as a receptor. Secondly, in vitro, this gene has been isolated, cloned and expressed into pET28a (+) vector; further, the protein was isolated and studied for biophysical properties.

The methodology for in-silico and in-vitro is as shown in the flowchart.



Key Findings:

Table 1: The sequence template for homology model

PDB ID	Organism	Seq identity (%)	Coverage	QMEAN	Reference
4e8y	*Bukholderia cenocepacia*	42.36	0.62	0.52	Lee et al.,2012
4e8z		39.80	0.65	0.52	
4e8z		39.80	0.65	0.51	

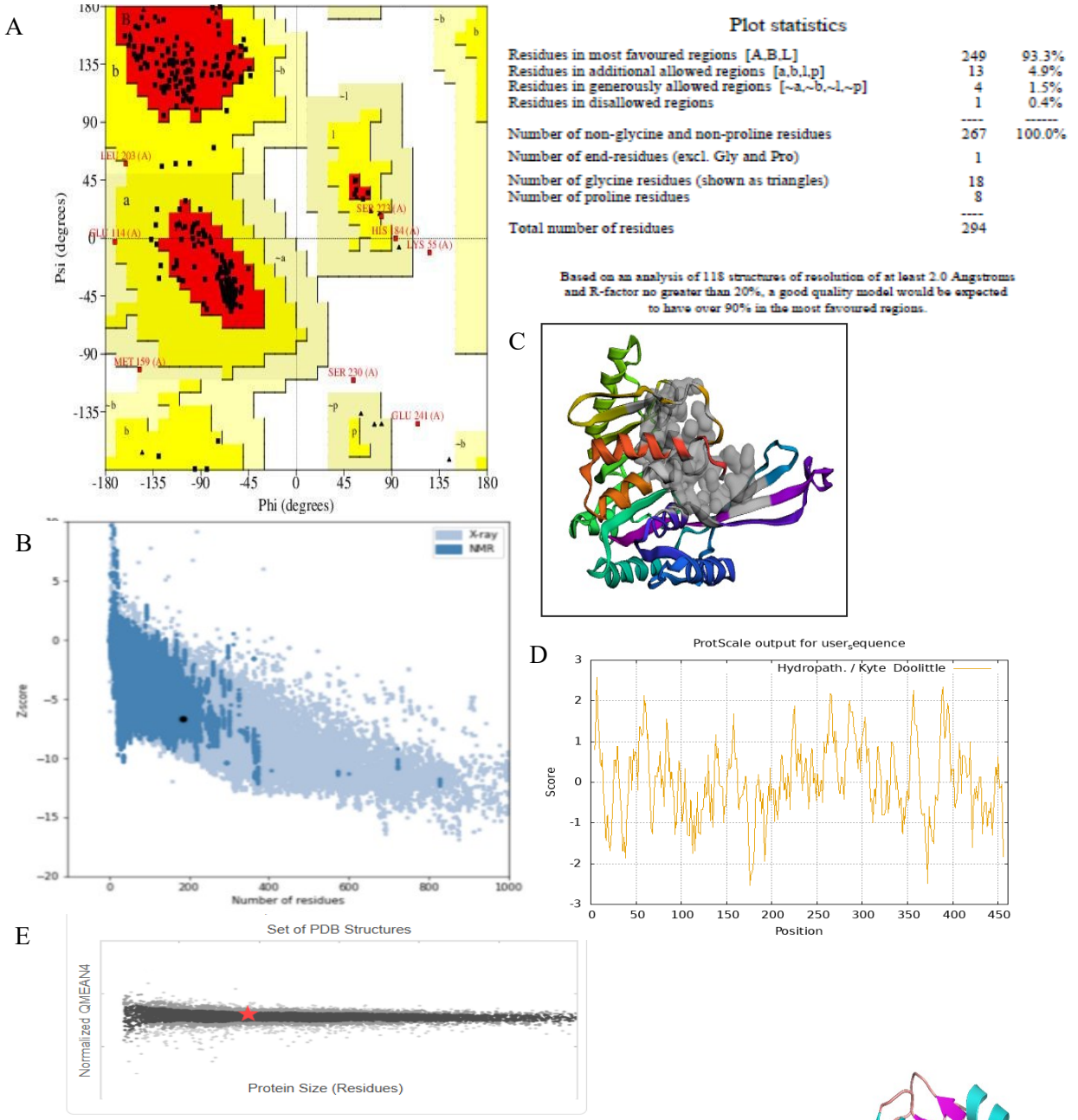


Figure 2 A: The validation of model using Ramachandran Plot. B: The Z Score plot indicating the model representation in present experimental data using ProSA web server. C: The active site prediction using CastpFold server. D: The solubility of protein using kyte and Doolittle paramter in Protscale web server and E: QMEAN score analysis using Expasy, which indicates that the qualitative mean energy of structure is stable.

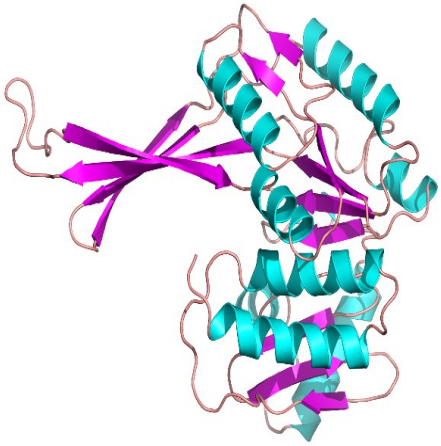
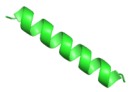
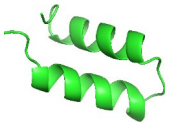
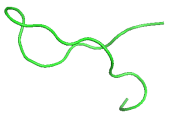
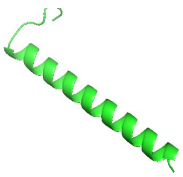


Figure 3: Homology model of gmhc based of 4e8y

Identification of Antimicrobial Peptides (AMPs)

Table 2: AMP selected via literature review to target H. pylori and gram-negative bacteria

Name of Antimicrobial Peptide	Sequence	3D Model	Reference
HF-18	GFFKKAWRKVKKAFRRVL		(Zhou et al., 2022)
Snakin1	GSNFCDSKCKLRCSKAGLADR-CLKYCGICCEECKCVPSGTYGNKHE CPCYRDKKNSKGKSKCP		(Mustafa et al., 2022)
EcAMP1	GSGRGSCRSQCMRRHEDEPWRV-QECVSQCRRRRGGGD		(Mustafa et al.,
SP1-1	RKKRLKLLKRLL		(Dangel et al., 2013)
Pexiganan	GIGKFLKKAKKFGKAFVKILKK		(Neshani et al., 2019) (Ge et al., 1999)
Bulgaricin BB18	KIYRGNVGHCGKSTVDWG-TAIGNGNNAASFL		(Simova et al., 2009) (Neshani et al., 2019)
Bicarinalin	KIKIPWGKVKDFLVGGMKAV-		(Rifflet et al., 2012) (Neshani et al., 2019) (Guzman et al., 2017)
Soly C	FSGGNCRGFRRRCFCTK		(Rigano et al., 2012) (Neshani et al., 2019)
Human cathelicidin LL-37	LLGDFFRKSKEKIGKEFKRIVQRIK-DFLRNLVPRTES		(Leszczyńska et al., 2009) (Neshani et al., 2019)

The docking of all the above AMPs with the target receptor gmhc was performed using the ClusPro server. The top five models were chosen from the server, based on the docking score. For the selection of the best pose, the selected model was analysed using the MMGB/SA parameter of the Hawkdock server. The MMGB/SA score was calculated the energy parameter of the basis of vander Waals interactions, electrostatic bond, Gibbs energy and surface area.

The above table states that **Snakin and EcAMP1** are the most appropriate AMPs, which block the activity of the gmhc receptor in *H. pylori.* The hydrogen bonds were obtained through the PDBsum server. The active sites of the gmhc receptor were stated from the CASTpFold server and literature review. The protruding twisted β-sheet has high electron density due to which is characterised as the active site for binding of the molecule (Lee et al., 2013). In Castpfold pocket Id 1, having a surface area of 769.917 and volume 931.412 considered the active site. In case of Snakin AMP, the amino acid residue common to the active site in gmhc receptor are Ser230, Arg192, Lys250, Glu231, Gly257, Asp13, Arg100, Arg110, whereas in case of EcAMP1, the common residues in active sites are Arg192, Ser230, Glu231, Thr256, Arg100, Arg110. These residues are present in the shallow of the twisted β parallel sheets present in the gmhc 3D model. Hence, the Snakin and EcAMP1 successfully block the activity of gmhc, resulting in the truncation of the LPS layer of H pylori.

Table 3 Keystone table with all the energies of AMP obtained from Hawkdock and No. Of hydrogen bonds from the PDBsum server.

AMPs	VDW	ELE	GB	SA	Total	No. of H2 bonds
HF-18	-69.87	-497.54	523.72	-9.16	-47.85	7
Snakin	-155.43	-949.21	1006.93	-21.54	-119.24	21
EcAMP1	-101.13	-699.79	719.48	-15.05	-96.49	23
SP1-1	-52.28	-536.39	556.55	-8.03	-75.03	17
Bicarinalin	-81.82	-522.72	549.5	-11.17	-66.76	11
Pexiganan	-81.34	-621.79	647.45	-10.88	-66.35	5
Soly C	-97.04	-710.65	729.41	-15.37	-93.64	12
Cathelicidin	-133.46	-786.68	844.04	-19.93	-96.03	18
Bulgarcin	-112.68	-323.44	370.19	-15.99	-81.93	15

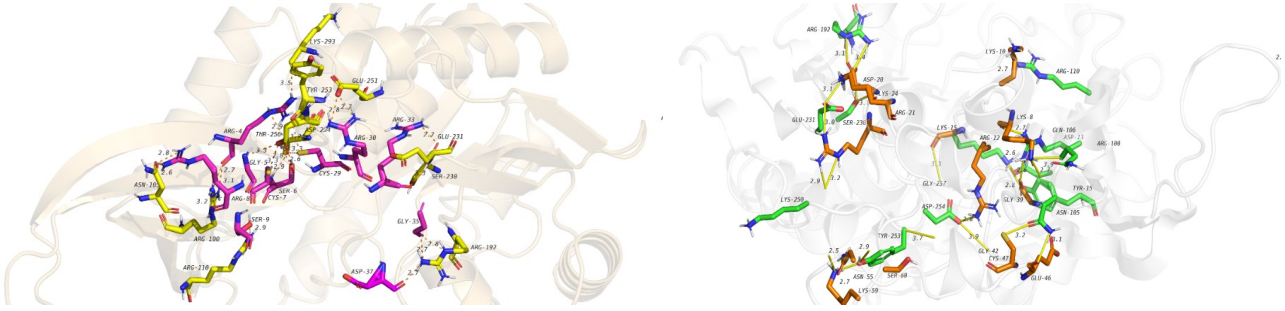


Figure 4 A) Top: The docked model Snakin and gmhC using Cluspro. B) Bottom: The docked model of EcAMP1 and gmhc using Cluspro.

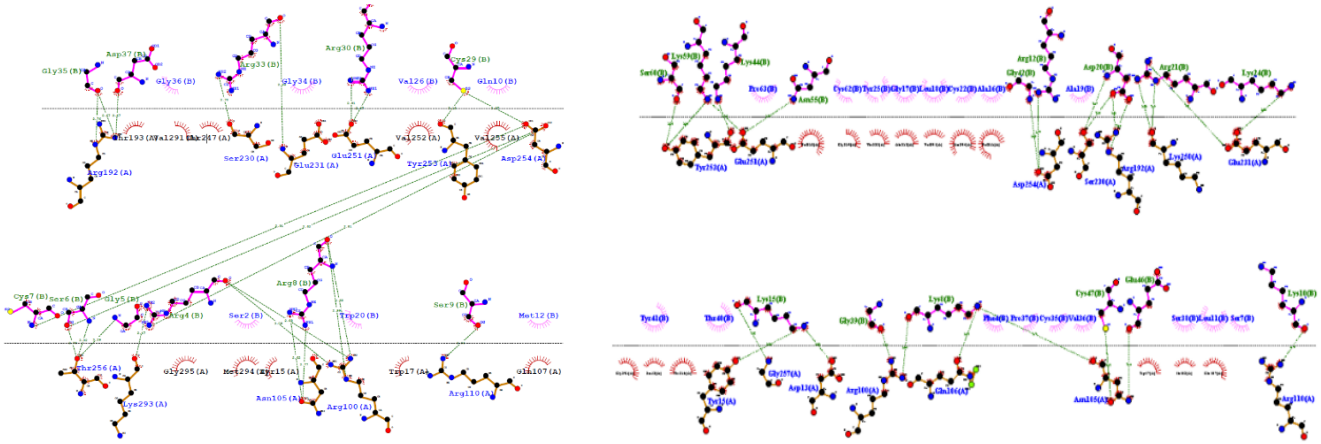


Figure 5 a) Left side: The dimplot showing hydrogen interactions between EcAMP1 and gmhc b) Right: The dimplot showing the hydrogen bond interaction between Snakin and gmhc chain A: Receptor, whereas chain B: Peptide

Purification of gmhc

The protein was successfully purified using Ni-NTA chromatography, ion exchange and desalting experiments. After passing the protein through 3 different columns, the purified protein was obtained.

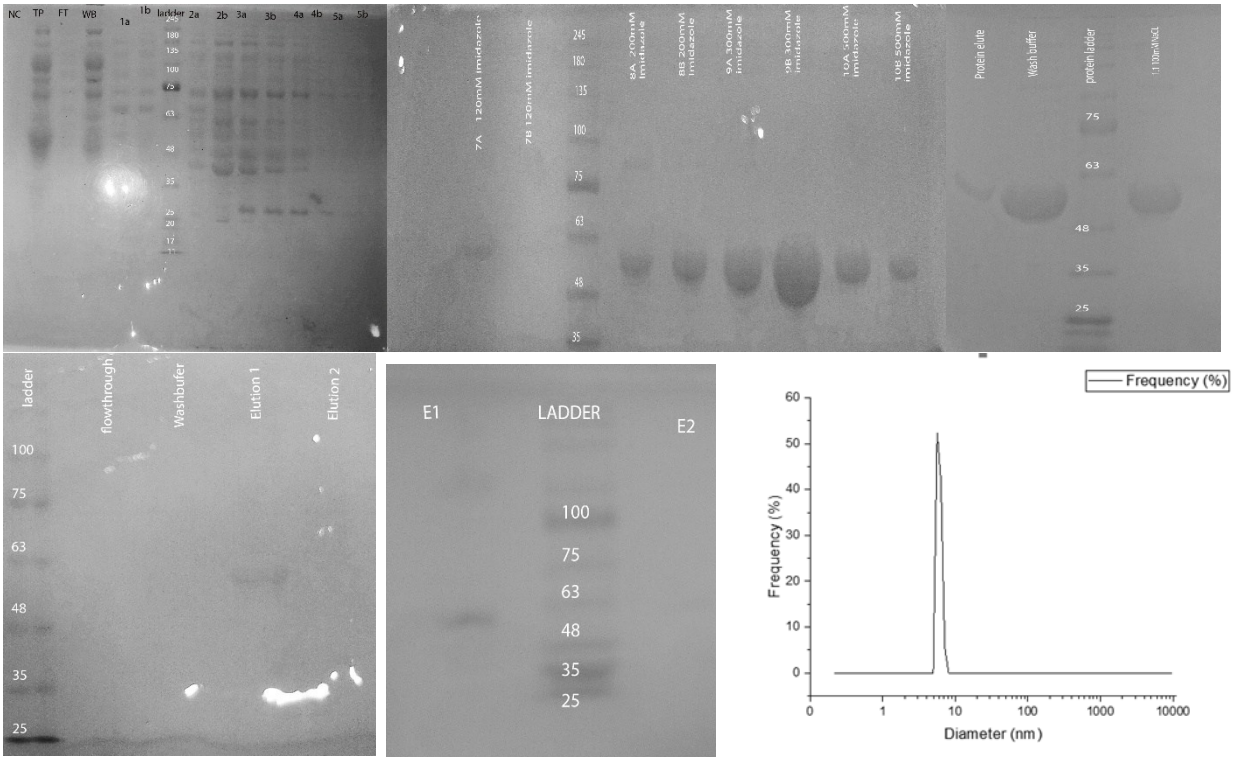


Figure 6 A: The Ni-NTA gel images using Tris-Cl (pH 8.2) buffer. B: The ion-exchange gel image using QAE buffer. C: Sephadex G25 column used for desalting. D: The native PAGE image. E: The DLS graph result, which shows that only a particle is present, as the graph is monodisperse.

To check the oligometricity of the gmhc, native PAGE was studied, which gave a result that the protein is a dimer, but as the concentration of the other band was less, it can be stated that the protein is a monomer. Other experiments need to be performed to confirm the oligometricity of the gmhc; therefore, a Dynamic light scattering experiment was performed. Based on the calculations, are mean is 5.691±0.09nm, whereas the Standard deviation is 0.4680. The Standard error is 0.095538. The Polydispersity Index is 0.006762, which states that the particle is highly monodisperse. 20 different runs were carried out using a single sample of purified gmhc, based on which mean, standard deviation. and Polydispersity index were calculated. Hence, gmhc is a monomer, based on the data of DLS. 5.69 +0.09 nm and Pdi (polydispersity index) is 0.0067 (=< 0.1) and monodisperse.

Conclusion:

This protein is part of the L, D-heptose synthesis pathway, which is an important part of lipopolysaccharide (LPS). Any blockage in the heptose synthesis can lead to truncation in the LPS layer of gram-negative bacteria or *H. pylori*. Hereby, in silico, gmhc homology model was designed as the target receptor. A certain new approach was taken by using antimicrobial peptides as the molecules to block the activity of gmhc, by docking these AMPs to the active site of the protein receptor. EcAMP1 and snakin were selected as the drug molecules which to their rigid binding energy property. **Snakin and EcAMP1** have also been studied before to work against other *H. pylori* proteins. In vitro, the transformed cells were provided for the purification of the protein. The induction of the recombinant protein, gmhc, was carried out by the addition of IPTG. Further, the protein was successfully purified using Ni-NTA chromatography, ion exchange and desalting experiments. After passing the protein through 3 different columns, the purified protein was obtained. The functional studies of the gmhc are a further study to be done. The biophysical properties can also be checked via various studies like NMR, DSA (Differential scanning calorimetry) and many more. The enzymatic studies of gmhc are another step ahead. To increase the efficiency of binding of AMPs, mutations can be created in the receptor gmhc. The peptides can be synthesised and tested in the lab on the H. pylori. Thus, the effective AMP can be experimentally tested on the model organism. In-vitro mutations can be generated in the receptor molecules, leading to a change in the activity of the protein and binding ability of the AMPs.

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2. ADVANCING NATURE-BASED SOLUTIONS FOR ECOSYSTEM RESTORATION AND CLIMATE RESILIENCE

Exploring ecological restoration, natural infrastructure, and ecosystem valuation.

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Reimagining Payments for Ecosystem Services: A Risk-Responsive and Institutionally Aligned Framework

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Executive Summary

Ecosystem services, from water purification to carbon sequestration, are foundational to human wellbeing, yet they remain largely undervalued in mainstream economic systems. Payment for Ecosystem Services (PES) offers a promising framework to bridge this gap by creating financial incentives for the conservation and sustainable management of natural resources. However, existing PES models are plagued by shortcomings: they rely on static valuations, ignore ecological uncertainty, and are often designed in isolation from the institutions responsible for implementation. This paper addresses these gaps by proposing an integrated PES model that combines dynamic valuation, risk-adjusted payments, and institutional efficiency to create a more adaptive, equitable, and scalable approach.

The research sets out three objectives: to explore how valuation mechanisms can evolve over time to reflect ecosystem change, to incorporate ecological risk into compensation structures, and to assess how institutional variables influence PES outcomes. Drawing on a theoretical framework informed by ecological economics, risk modeling, and governance theory, the study constructs a model that captures temporal variability, simulates ecological uncertainty, and adjusts transaction costs based on governance performance.

The findings demonstrate that static models underestimate service values and often misalign incentives. By contrast, this integrated model produces more accurate, fair, and adaptive payment structures. It enables PES schemes to function not only as financial transactions, but as tools for responsive environmental governance. This paper advances the position that PES must be reimagined not as a fixed payment mechanism but as a dynamic policy instrument, one that reflects ecological complexity, embraces uncertainty and strengthens institutions.

Context and Problem Statement

The global decline of ecosystem services poses a critical threat to both environmental sustainability and human development. Forests, wetlands, grasslands and other natural systems provide a variety of services: provisioning, regulating, supporting, and cultural, yet they continue to be degraded due to land use change, deforestation, and unsustainable development.. This disconnect stems from a fundamental market failure: ecosystem services are rarely priced or compensated for, leading to over exploitation and underinvestment in conservation. Payment for Ecosystem Services (PES) has emerged as a response to this failure aiming to internalize environmental benefits individuals or communities who maintain or enhance service flows. Despite this conceptual appeal, real-world PES programs face significant operational challenges. Most rely on static valuation techniques, assuming constant ecosystem service output over time.

They do not account for ecological risk, such as fire, flood, or disease, which can abruptly disrupt service provision. Nor do they reflect the complex institutional terrain in which these programs are implemented. Often, transaction costs are high, monitoring is weak, and local governance systems are fragmented or underresourced. These shortcomings limit both the equity and the effectiveness of PES initiatives, particularly in developing country contexts.

In India, PES remains largely experimental and unstandardized. Although there have been efforts at the state level to pilot PES schemes, notably in Himachal Pradesh, Karnataka, and Sikkim, the absence of a national policy framework, data infrastructure, or institutional coordination has hampered scalability. Most schemes focus only on afforestation or watershed protection and do not incorporate economic risk or governance constraints into the design. This research responds directly to these gaps. It challenges the static assumptions of traditional PES models and proposes an integrated approach that dynamically values ecosystem services, adjusts for risk, and reflects institutional realities. The aim is to bridge theory and practice by developing a model that is analytically robust yet practically implementable. The context demands nothing less: as climate change accelerates and ecological thresholds are breached, mechanisms like PES must evolve to become not only tools of compensation, but instruments of adaptive environmental governance.

Context and Problem Statement

The concept of Payments for Ecosystem Services (PES) emerged as a mechanism to address environmental externalities by compensating individuals or communities for actions that maintain or enhance ecosystem services. Wunder (2005) provided a widely accepted definition, framing PES as voluntary, conditional transactions between service users and providers. Since then, extensive literature has explored its theoretical underpinnings, practical applications, and ethical considerations. At the heart of early PES models lies a neoclassical logic: assign a monetary value to a service, establish a beneficiary-payer relationship, and enforce conditionality. While elegant in theory, this model has faced criticism for oversimplifying ecological systems and neglecting socio-political complexity. Scholars such as Muradian et al. (2010) and Vatn (2010) have argued that PES schemes must go beyond market efficiency to address fairness, power asymmetries, and governance.

A key critique centers on the static nature of PES valuation. Most schemes calculate payments based on one-time assessments, failing to account for temporal shifts in service quality or quantity (G´omez-Baggethun et al., 2010). This results in inefficient or unjust payments, particularly when ecosystem conditions degrade or improve over time. To address this, recent scholarship has advocated for dynamic valuation approaches that evolve with ecological data and stakeholder inputs (Farley & Costanza, 2010; Bagstad et al., 2013). Risk and uncertainty form another major gap. While ecological systems are inherently volatile, most PES contracts ignore environmental risks, treating them as exogenous or irrelevant. However, Ferraro (2008) and Guerry et al. (2015) emphasize that ignoring uncertainty leads to fragile outcomes. Incorporating risk through probabilistic modeling, scenario planning, or Bayesian updating is now seen as essential to the resilience of PES frameworks. The role of institutions has gained increasing attention. Transaction costs, property rights clarity, monitoring capacity, and legal enforceability all shape PES outcomes. Studies by Pagiola et al. (2008) and Verma & Negandhi (2011) show that institutional quality determines both cost-effectiveness and equity. The concept of governance-adjusted transaction costs has emerged to quantify these effects.

This research contributes by integrating these three critical debates valuation, risk, and institutions into a single framework. While previous studies have addressed each individually, few have synthesized them into a coherent, implementable model. In doing so, this paper positions itself at the intersection of ecological economics, risk management, and environmental governance, offering a holistic response to long-standing critiques of the PES paradigm.

Research Focus and Methodology

This research develops an integrated framework for Payments for Ecosystem Services (PES) that addresses the limitations of static, narrowly constructed compensation systems. It brings together three essential pillars, dynamic valuation, risk adjustment, and institutional efficiency,

to reimagine how PES programs can be made more equitable, adaptive, and scalable. The study is guided by three central research questions:

- How can dynamic valuation methods better capture the temporal variability of ecosystem services and enhance the precision of PES compensation structures?
- In what ways do risk-adjusted payment mechanisms improve resilience and fairness in PES contracts under ecological and institutional uncertainty?
- How do governance quality, institutional capacity, and transaction costs affect the implementation and scalability of integrated PES models?

To answer these questions, the study develops a conceptual framework that captures the evolving nature of ecosystem value, accounts for ecological risk, and incorporates institutional costs into PES design. Instead of relying on flat-rate compensation or one-time assessments, the model uses probabilistic techniques to simulate service flow variability and introduces adaptive features that allow payments to evolve with changes in risk and performance over time.

The model also incorporates institutional dimensions—including monitoring capacity, policy clarity, and transaction costs, as variables influencing the feasibility and effectiveness of PES schemes. By grounding the model in available secondary data from Himalayan forest ecosystems, the research demonstrates how theoretical principles can be translated into implementable policy tools. The result is a robust framework that can be tailored to diverse ecological and governance contexts.

Key Findings and Arguments

Conventional PES systems, while conceptually elegant, often lack the sophistication to respond to dynamic socio-ecological systems. One of the key findings of this research is that static PES models typically overgeneralize ecosystem service flows, treating them as homogenous and constant. In reality, service flows are highly variable over time, shaped by factors such as climatic cycles, land use transitions, and ecological degradation. The integrated model developed here demonstrates that PES schemes must reflect this variability through adaptive pricing mechanisms. This shift can significantly improve both payment accuracy and the legitimacy of PES among resource-dependent communities.

Another key contribution is the incorporation of ecological risk into payment design. The study illustrates that unforeseen disruptions, such as forest fires or degradation due to human activity, can drastically alter the capacity of ecosystems to deliver services. Traditional PES contracts either penalize providers in such cases or offer no recourse at all. By embedding ecological risk into the valuation framework, the model enables a more equitable distribution of both incentives and responsibilities. This feature not only protects service providers from external shocks but also encourages proactive ecosystem management **practices.**

The institutional component of the model adds further value. Using governance-adjusted transaction costs, the research shows that implementation success is closely tied to local administrative capacity, enforcement clarity, and property rights recognition. Regions with poor institutional infrastructure experience inflated transaction costs and program delays, whereas those with coordinated governance systems see better alignment between objectives and outcomes. This insight allows policymakers to pre-assess the institutional readiness of regions before deployment, enabling strategic targeting of interventions.

For example, PES pilots implemented in areas without clarified land tenure or coordination between forest and revenue departments have struggled with disbursal delays and compliance issues. In contrast, well-structured interventions supported by local forest user groups and panchayat institutions demonstrate smoother implementation. The integrated model allows these institutional factors to be internalized into payment structures, making PES schemes more adaptive and scalable.

This research argues that PES is not simply a pricing mechanism but a policy architecture. By moving away from fragmented implementation and toward a systems-based approach, this model establishes PES as an instrument of institutional transformation as much as environmental compensation. The integration of ecological valuation, risk responsiveness, and institutional diagnostics marks a departure from minimalist models and brings PES in alignment with the complexities of the Anthropocene.

Policy and Practice Implications

The implications of this research are especially relevant for policymakers, environmental planners, and donor agencies designing or funding PES programs. Three core recommendations emerge, each backed by empirical modelling and contextual evidence.

1. Introduce Adaptive Payment Mechanisms in PES Guidelines

PES policies should explicitly mandate dynamic pricing updates, ideally on an annual or seasonal basis. The ecological data needed for this recalibration, such as land use changes, biomass regeneration, or service-specific performance indicators, are increasingly available through remote sensing, ground based monitoring, and participatory methods. By establishing protocols for periodic review, payment structures can remain aligned with real-time ecosystem function. Adaptive payments also help build trust among beneficiaries, who are more likely to participate if they see a clear link between conservation effort and compensation level.

2. **Integrate Risk Adjustment in Contract Design**

Risk-adjusted payments must become a core design element rather than a theoretical add-on. Contracts should specify conditions under which payments may vary in response to ecological stressors. For example, in regions prone to forest fire or landslides, a base compensation rate can be accompanied by a flexible buffer linked to event probabilities. Tools such as Bayesian updating or Monte Carlo simulations can inform these adjustments using data already collected by environmental departments.

3. Prioritize Institutional Readiness and Governance Assessment

Many PES initiatives fail not because of valuation flaws, but due to institutional constraints. This research quantifies how transaction costs vary with institutional quality and recommends integrating governance-readiness assessments into PES feasibility studies. Policymakers can use simplified governance diagnostics to evaluate whether agencies have the legal clarity, human resource capacity, and monitoring systems necessary to manage PES contracts. Including institutional criteria in project appraisal templates can ensure that investments are channelled into contexts where they are most likely to succeed.

Conclusion

This research advances a central argument: that Payments for Ecosystem Services, if properly designed, can move beyond being symbolic gestures or fragmented transactions. They can become structured interventions that reshape the relationship between state, community, and environment. However, this transformation requires abandoning simplistic assumptions and engaging deeply with the socio-ecological and institutional dimensions of service provision. The integrated model presented here takes a step in that direction. It acknowledges that ecosystem services are not static, that risks are inevitable, and that institutions matter. These acknowledgments are not limitations; they are opportunities. They provide an entry point for policy innovation that is both empirically grounded and normatively robust.

As climate shocks intensify and ecological thresholds near collapse, India, and other rapidly developing economies, must embrace policy instruments that are as dynamic as the challenges they address. PES, if restructured through the lens offered in this paper, can help build governance systems that are anticipatory, not reactive; participatory, not technocratic; and resilient, not brittle.

The next phase of PES must therefore focus not only on environmental valuation but on building capacity for environmental governance. Future work should explore how this model can be adapted for multiple ecosystem types, scaled through digital platforms, and aligned with green financing instruments. The groundwork laid by this study offers both a warning and a possibility: if we misprice nature again, it may not come back. But if we build policies that reflect its real value, economic, ecological, and institutional, there is still time to recover.

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Eco-Hydro Restoration of Wetlands in Blue Carbon Ecosystem of Sundarbans Biosphere Reserve, India

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Executive Summary

The Sundarbans Biosphere Reserve (SBR), the world's largest continuous mangrove ecosystem, faces unprecedented threats from climate change and anthropogenic pressures, particularly affecting its inland freshwater aquatic systems. This study addresses the critical degradation of these water bodies through a comprehensive eco-hydrological restoration framework that integrates geospatial analysis, field data collection, and predictive modelling to enhance water quality, restore biodiversity, and increase carbon sequestration potential. Our multi-faceted approach revealed alarming trends in groundwater quality, with 20% of samples exceeding permissible Total Dissolved Solids (TDS) limits and 30% showing elevated electrical conductivity due to seawater intrusion. The Cl^-/HCO_3^- ratio analysis confirmed varying degrees of seawater influence across sampling sites, with ratios exceeding 6.6 mg/L indicating severe saltwater contamination. Sea level rise analysis spanning 1993-2024 demonstrates a consistent upward trend of around 4 mm/year, projecting 20-30 cm rise by 2050 and threatening 20-30 km² of critical coastal carbon storage areas. The integrated impact assessment reveals that projected sea level rise will result in a carbon loss of 70-80 Mt C by 2050, representing a reduction in total carbon stock and highlighting the urgent need for restoration interventions. Our findings demonstrate that degraded inland aquatic systems are transitioning from carbon sinks to carbon sources, undermining global climate mitigation efforts. Immediate implementation of science-based eco-hydrological restoration strategies is essential to preserve the Sundarbans' dual role as a biodiversity hotspot and critical blue carbon ecosystem. Without urgent intervention, continued degradation will compromise both local socio-economic resilience and global climate stability, making restoration not just an environmental imperative but a climate necessity.

Context & Problem Statement

The Sundarbans Biosphere Reserve (SBR), located at the confluence of the Ganges, Brahmaputra, and Meghna rivers, is not only the world's largest continuous mangrove ecosystem but also a UNESCO World Heritage Site and Ramsar wetland. It spans over 10,000 km², with a diverse array of flora and fauna, including endangered species such as the Royal Bengal tiger, Irrawaddy dolphin, and northern river terrapin. The region provides critical ecosystem services, including biodiversity conservation, carbon sequestration, flood control, and nutrient cycling. However, the ecological and socio-economic significance of the SBR is under threat due to climate change, anthropogenic pressures, and unsustainable resource management practices (Gopal & Chauhan, 2006) (Bhattacharjee & Ahmed, 2022). The key challenges facing the SBR is the degradation of its inland freshwater aquatic systems, essential for local livelihoods, agricultural productivity, and biodiversity, are increasingly impacted by sea-level rise, salinization, and pollution. Evidences highlights that these inland systems, traditionally used for aquaculture and domestic purposes, are now experiencing a decline in water quality and biodiversity.

The transformation of freshwater ponds into brackish water systems has adversely affected fish farming, irrigation, and other water-dependent activities, pushing local communities into economic vulnerability (Fawzy, et al., 2020) (Ghosh, et al., 2021).

The inland aquatic systems of the SBR also hold significant potential for climate change mitigation through carbon sequestration. Studies suggest that aquatic ecosystems can store carbon at rates comparable to or even exceeding terrestrial ecosystems. The historical degradation of these ecosystems, exacerbated by rising temperatures and changing hydrological patterns, has transformed many natural carbon sinks into carbon sources, thereby amplifying global warming impacts (Nellemann, 2009) (Banerjee & Mitra, 2015). To address these multifaceted challenges, there is an urgent need to develop a comprehensive eco-hydrological restoration suggestion. This model must integrate field data, geospatial analysis, and hydrological modelling to enhance water quality, restore biodiversity, and increase carbon sequestration. The restoration efforts may prioritize socio-economic benefits to local communities, through sustainable aquaculture and agriculture, enhancing water security, and building resilience against climate-induced disasters (Das, et al., 2022) (Mitra, et al., 2009). The significance of the proposed restoration strategies is underscored by their alignment with the United Nations Sustainable Development Goals (SDGs). Specifically, these initiatives contribute to Sustainable Development Goals (SDGs). (Hoques, et al., 2006) (Dasgupta, et al., 2014).

Through an integrated approach combining geospatial mapping, field surveys, and predictive modelling, this study aims to establish a robust framework for sustainable restoration and management of the inland aquatic systems in the SBR through case study approach. By doing so, it seeks to ensure the long-term ecological and socio-economic resilience of this globally significant region (Ghosh, et al., 2021) (Bhattacharjee & Ahmed, 2022).

Literature Review

The coastal area serves as the boundary between land and sea, representing a crucial zone of the global oceans from a human perspective. Coastal marine ecosystems, encompassing estuaries, seagrass beds, salt marshes, tidal flats, mangroves, coral reefs, and shelves, offer a rich reservoir of valuable services such as nutrient cycling, pollution detoxification, food production, habitats, as well as recreational and leisure activities (Costanza, et al., 1997).

The Sundarbans, recognized as the largest continuous mangrove forests globally, are exceptionally crucial and exceedingly susceptible to the impacts of climate change due to their intricate geomorphology and environment, coupled with their gradual reduction under rising sea levels. The inundation of inland freshwater bodies by saltwater resulting from cyclones and tidal surges, coupled with the prevalence of diseases, epidemics, and erratic rainfall, significantly contribute to the degradation of these inland aquatic ecosystems as highlighted in various works (Das, et al., 2022). (Chand, et al., 2012) have discussed that the intrusion of saline water due to flooding and rising sea levels poses a threat to inland freshwater ecosystems.

The intrusion of saline water into inland areas is a recurrent phenomenon exacerbated by regular tropical cyclones. The escalating salinity levels, stemming from the limited water exchange, pose a significant threat to the ecosystem. The expansion of brackish shrimp farming not only endangers the mangrove ecosystems but also jeopardizes the agrobiodiversity and aquifer ecosystems of the inland regions (Dasgupta, et al., 2014). Prolonged exposure to saline water in shrimp farms leads to a decline in soil organic matter, subsequently diminishing agricultural productivity (Bazzaz & Sombroek, 1996). In the Indian Sundarbans, inland aquatic bodies form intricate socio-ecological systems deeply intertwined with the cultural fabric of the region, playing a crucial role in delivering vital ecosystem services. These aquatic bodies often suffer from undervaluation and contamination of their water sources. The concentrations of inland aquatic bodies known as pondscapes, which have been demonstrated to harbour rich biodiversity that significantly enhances the overall aquatic biodiversity of the surrounding catchment area compared to lakes, streams, and rivers (Davies, et al., 2008). These aquatic ecosystems are indispensable natural assets for advancing the UN Sustainable Development Goals (SDGs), which are designed

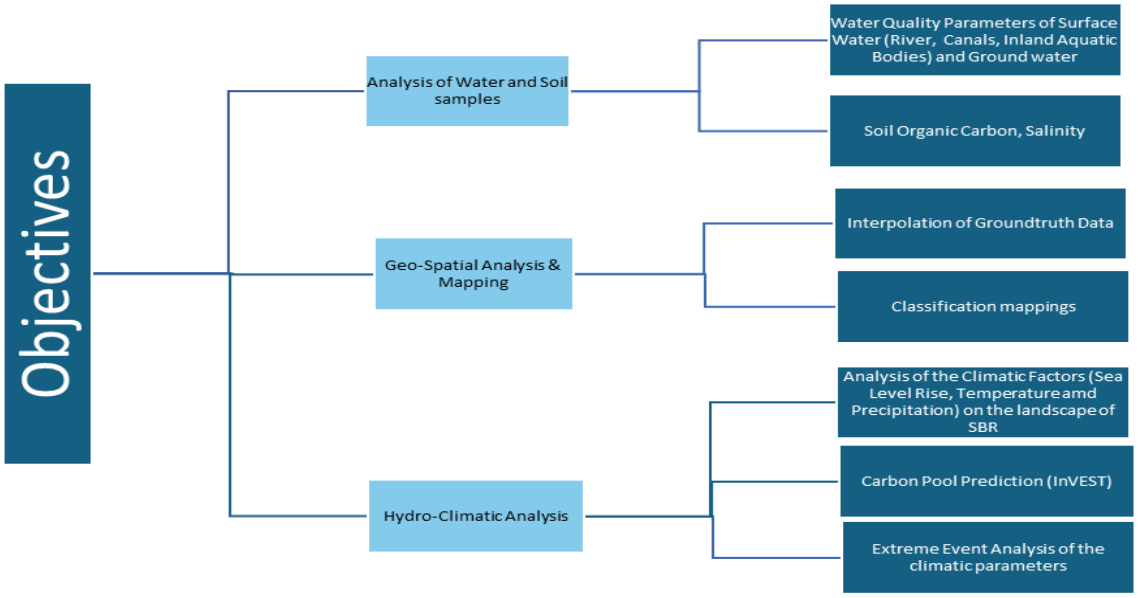
to promote strategies fostering improvements in health, education, inequality reduction, economic growth, global environmental management, and ecosystem conservation. In the context of the Indian Sundarbans, inland aquatic bodies play a pivotal role in the daily lives of the local population, provide beneficial ecosystem services to the communities which needs to be measured.

Research Methodology

This study seeks to explore the degradation of inland freshwater bodies within the SBR and develop a scientifically grounded restoration model. The key research objectives guiding this study are:

- Assessment of Hydro-Climatic changes in Sundarbans Biosphere Reserve (SBR), India.
- Primary data collection of the Soil and Water, to conduct the chemical dynamics.
- To identify the change in the Carbon Dynamics due to Sea level rise.

To accomplish the specified aims and address the research inquiries, a multifaceted approach will be utilized, integrating field surveys, secondary geospatial analysis, and primary soil and water data collection. The methodology is organized into distinct components. The primary segment entails study of secondary geospatial analysis, secondary data analysis and mapping with ground truthing. The process will involve obtaining satellite imagery (e.g., Landsat, Sentinel-2) and additional remote sensing data for the SBR, alongside compiling historical data on land use and land cover (LULC) and Digital Elevation Models (DEM). GIS software like ArcGIS and QGIS will be used to process and categorize the satellite images to detect map the Wetlands and LULC. Both supervised and unsupervised classification methods will be applied, followed by an accuracy evaluation using ground truth information.



The subsequent segment concentrates on field data collection of the ground water and surface water to evaluate the chemical dynamics of the ecosystem and the collected qualitative and quantitative data will be assessed utilizing statistical tools like Excel and Python to evaluate key patterns and effects. The chemical analysis of groundwater samples was conducted using standard laboratory procedures to ensure precision and accuracy. Various physicochemical parameters, including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness, Calcium, Magnesium, Chloride, and Alkalinity, were measured following established analytical techniques.

The results obtained from these chemical analyses provided critical insights into the groundwater quality and were further used for spatial interpolation using the Inverse Distance Weighting (IDW) method to understand spatial variations across the study area. The Inverse Distance Weighting (IDW) interpolation method is a widely used spatial interpolation technique that estimates unknown values based on the weighted average of known data points. Using InVEST model to estimate the change in the Carbon Stock and the future predictions

Key Findings and Arguments

LULC analysis across approx 10,000 km² reveals water bodies dominating (45.5%), followed by mangroves (17.6%) and croplands (16.9%). Wetlands mapping identifies estuarine open water approx 4,000 km²) as the largest component, with aquaculture operations (approx 500 km²) correlating with groundwater salinization patterns observed in chemical analysis.

TDS exceeded permissible limits in 20% of the samples, highlighting concerns related to seawater intrusion and dissolved solids accumulation, which could affect groundwater suitability for drinking purposes. The analysis of calcium and magnesium concentrations showed that 92.5% and 70% of samples, respectively, fell within acceptable limits, while a small percentage exceeded permissible thresholds, suggesting localized hardness issues influenced by aquifer mineral composition. These findings emphasize the need for continuous monitoring and sustainable groundwater management to mitigate potential salinity impacts and ensure long-term water quality in the region. The pH levels across all three islands remain within the acceptable range, indicating stable acidity-alkalinity conditions. Notable differences are observed in Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

The analysis of groundwater samples from the islands reveals a clear trend of increasing Cl^-/HCO_3^- ratios with rising chloride concentrations, signifying varying degrees of seawater influence. Based on established classification criteria, groundwater with a Cl^-/HCO_3^- ratio below 0.5 mg/L is considered unaffected by seawater, whereas samples with ratios ranging from 0.5 to 6.6 mg/L indicate moderate seawater influence, and those exceeding 6.6 mg/L are classified as highly affected by seawater intrusion.

The sea level rise analysis spanning 1993-2024 reveals a consistent upward trend with significant implications for coastal inundation and blue carbon vulnerability corresponding to approx. rate of 4 mm/year, which closely matches the global mean sea level rise rate but represents a substantial threat to low-lying coastal ecosystems. Long-term projections to 2100 indicate an average approx. rate of 4 mm/year, with confidence intervals suggesting potential acceleration under high emission scenarios. This translates to approximately 30 -40 cm of sea level rise by 2100, representing a critical threshold for mangrove survival and coastal carbon storage stability.

Extreme sea level events analysis using the 5th/95th percentile method identified 40 extreme events over the study period. The temporal distribution shows 1990s: limited extreme events, 2000s: moderate increase, 2010s: elevated frequency, and 2020s: continued high frequency, suggesting an acceleration in extreme event occurrence.

The analysis of tidal height data from 1948-2022 provides the longest temporal perspective in this study, revealing subtle but significant changes in tidal dynamics. The linear trend ($y = 0.0038x - 0.45$) indicates a tidal height increase of 0.003-0.004 m/year, contributing to the overall relative sea level rise affecting the Sundarbans. Extreme tidal event analysis shows evolving patterns in both high-tide (≥95th percentile) and low-tide (≤5th percentile) frequencies across decades. The frequency trends suggest potential changes in tidal asymmetry, which could affect sediment transport, nutrient cycling, and carbon burial processes in mangrove ecosystems. These changes may be linked to both sea level rise and morphological changes in the coastal zone. The precipitation analysis (1980-2020) reveals substantial inter-annual variability in average daily rainfall without a clear long-term trend. This variability has important implications for freshwater input to the Sundarbans, affecting salinity gradients that control mangrove species distribution and productivity.

Temperature analysis (1983-2016) shows trends in yearly average maximum, minimum, and mean temperatures. The distribution analysis of daily temperatures reveals the frequency patterns of extreme temperature events, which are critical for understanding thermal stress on mangrove ecosystems. The combined temperature-precipitation analysis reveals complex relationships between these variables, with scatter plot analysis suggesting weak correlations that vary seasonally. The daily temperature and precipitation heatmaps illustrate clear seasonal patterns and inter-annual variations.

Notable features include warmer periods corresponding to drier conditions and cooler periods aligning with higher precipitation, reflecting monsoon dynamics typical of the region. The integrated sea level rise impact analysis combines mean SLR rate of approx. 4 mm/year with median land subsidence of -2.0 mm/year, calculating net relative rise of approx. 6 mm/year projecting 0.2-0.3 m total rise to 2050. DEM-based inundation modelling predicts aprrox 21 km² land submergence by 2050, representing 0.2% of total area but including critical coastal margins with high carbon storage potential. This submergence results in projected carbon loss of approx 70-72 Mt C. The carbon loss represents 11% of total projected net sequestration for 2020-2050, highlighting sea level rise as a critical threat multiplier for blue carbon systems.

Policy and Practice Implications

Three key recommendations emerge from this comprehensive analysis, each supported by robust empirical evidence and designed to address the interconnected nature of climate change, water quality degradation, and carbon loss.

Recommendation 1: Establish Integrated Blue Carbon Management Zones

Policymakers should immediately designate and legally protect integrated blue carbon management zones that encompass both mangrove forests and inland aquatic systems. Our carbon stock analysis demonstrates that sea level rise threatens around 70-72 Mt C of stored carbon by 2050, representing approximate 11% of projected net sequestration. The establishment of these zones should include: mandatory environmental impact assessments for all development projects within 5 km of designated areas; implementation of buffer zones with restricted agricultural and aquaculture activities; and creation of community-based monitoring programs that engage local stakeholders in long-term ecosystem stewardship. The spatial analysis revealing vulnerable land provides precise boundaries.

Recommendation 2: Implement Adaptive Groundwater Management Systems

Given that 30% of water samples exceed electrical conductivity thresholds and 20% surpass TDS limits, immediate implementation of adaptive groundwater management systems is crucial. This should include: deployment of real-time salinity monitoring networks using the Cl^-/HCO_3^- ratio methodology validated in this study; establishment of freshwater harvesting and storage infrastructure during monsoon periods to reduce dependency on increasingly saline groundwater; and development of alternative water sources including treated rainwater harvesting systems for communities showing severe seawater intrusion (ratios >6.6 mg/L). Financial incentives should support community adoption of water-efficient technologies and alternative livelihood strategies that reduce pressure on degraded freshwater systems.

Recommendation 3: Develop Climate-Resilient Restoration Financing Mechanisms

The projected sea level rise rate and accelerating extreme event frequency demand innovative financing approaches that recognize the global climate benefits of Sundarbans restoration. Policymakers should: establish payment for ecosystem services programs that compensate local communities for carbon sequestration and biodiversity conservation activities; create blue carbon credit systems that monetize the net sequestration potential identified in our projections; and develop climate adaptation funds specifically targeting eco-hydrological restoration projects with demonstrated carbon storage benefits. International climate finance mechanisms should prioritize Sundarbans restoration given its global significance for climate regulation of priority protection areas.

These recommendations require coordinated action across multiple governance levels, from local community organizations to international climate policy frameworks. The scientific evidence presented supports immediate policy action, as delays will exponentially increase restoration costs and reduce ecosystem recovery potential. Success depends on integrating traditional ecological knowledge with scientific data, ensuring that restoration efforts enhance both environmental outcomes and community resilience. Regular monitoring using the methodological framework established in this study will enable adaptive management and continuous improvement of restoration strategies.

Conclusion

This research provides critical scientific evidence for the urgent need to implement comprehensive eco-hydrological restoration strategies in the Sundarbans Biosphere Reserve, advancing our understanding of the complex interactions between climate change, water quality degradation, and blue carbon ecosystem stability. The integration of geospatial analysis, field data collection, and predictive modelling has revealed the alarming pace of environmental degradation, with sea-water intrusion affecting 30% of groundwater samples and sea level rise threatening significant carbon storage capacity.

The study's value extends beyond documenting environmental decline to providing actionable solutions that address both local socio-economic needs and global climate imperatives. By quantifying the relationship between sea level rise and carbon loss, this research establishes a clear economic and environmental case for immediate restoration investment. The methodological framework developed here offers replicable approaches for similar coastal ecosystems globally, contributing to the broader scientific understanding of blue carbon system dynamics under climate change. Future research should focus on developing cost-effective restoration technologies, refining carbon sequestration monitoring protocols, and establishing long-term community engagement strategies. Critical knowledge gaps remain regarding the optimal balance between conservation and sustainable resource use, requiring continued interdisciplinary collaboration. The window for effective intervention is rapidly closing, making the implementation of evidence-based restoration strategies not just environmentally beneficial but essential for regional and global sustainability. Success in the Sundarbans will provide a model for coastal ecosystem restoration worldwide, demonstrating that scientific rigor combined with community engagement can address even the most complex environmental challenges.

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Accounting for Nature: A Monetary Assessment of India's Forest Ecosystems

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Executive Summary

Amidst mounting concerns over the relaxation of environmental safeguards in India, this study explores the economic value of the country's forest ecosystems to critically examine the sustainability of current land-use and development policies. Leveraging the System of Environmental-Economic Accounting: Ecosystem Accounting (SEEA EA) framework, the research constructs a national and zonal ecosystem accounting structure for forests, integrating both physical and monetary flows for selected provisioning services—specifically timber and firewood—for the financial year 2022–23. The study adopts a novel valuation methodology, combining predictive estimation and a tailored pricing mechanism to address data heterogeneity across sources. While detailed results are withheld here, the accounting exercise captures changes in forest extent and ecosystem condition, linking these to economic asset values that are often excluded from conventional measures of national income.

To demonstrate the implications of such exclusions, the research introduces two integrated indicators—Forest Gross Ecosystem Product (FGEP) and Forest Adjusted Domestic Product (FADP)—designed to embed forest ecosystem values within national macroeconomic metrics. These indicators highlight how ecological degradation and natural capital dynamics materially alter the economic picture, particularly when regional disparities in forest condition and management are considered.

By reframing forests as economic assets rather than passive environmental backdrops, this study emphasizes the need to treat degradation not only as an ecological issue but as an erosion of national wealth. As India continues to revise forest governance mechanisms, including recent regulatory relaxations, this work advocates for the systematic integration of ecosystem accounts into economic planning. Embedding such valuations can serve as a critical corrective to the underestimation of ecological costs in development decisions and help steer the economy toward a more sustainable and equitable growth trajectory.

Context & Problem Statement

India's recent development trajectory has increasingly prioritised rapid industrial growth and infrastructural expansion, often sidelining environmental safeguards in the process. Policy shifts, including recommendations by the 2014 Subramanium Committee and the amendments introduced through the Forest Conservation Rules (2022), reflect a growing tendency to streamline environmental clearance procedures in favour of economic activity. A key concern is the removal of mandatory consent from local forest-dwelling communities for diverting forest land, thereby weakening decentralised oversight and community-based forest governance, and oilseeds, along with poor utilization of livestock, aggravates the nutritional crisis. Climate vulnerabilities, small and fragmented landholdings, and poor market access further constrain agricultural diversification. Public distribution policies, focusing on cereals, reinforce unhealthy dietary patterns.

This position paper responds to a critical gap: the lack of district-level assessment of the nutritional contribution of agriculture

Such regulatory relaxations risk incentivising large-scale land-use changes that may degrade forest ecosystems, whose long-term economic contributions are often underrepresented in conventional planning. In this context, a robust economic valuation of forest resources becomes essential—not simply as a conservation exercise, but as a foundational input to evaluate the sustainability and opportunity costs of current policy directions.

This study addresses this gap by undertaking an ecosystem-based valuation of Indian forests within the structure of national economic accounts. Using the updated System of Environmental-Economic Accounting: Ecosystem Accounting (SEEA EA), it develops a framework that recognises forests as dynamic economic assets. The SEEA EA represents a shift from earlier static accounts by explicitly incorporating ecosystem condition, extent, and the flow of services—provisions critical to understanding long-term resource sustainability.

By adapting and applying this framework to India's forest resources, the research aims to estimate and integrate these values into macroeconomic indicators. Doing so will enable more informed policy decisions, support the case for ecological accounting in economic planning, and promote strategies that harmonise developmental goals with the preservation of natural capital. Ultimately, this exercise highlights the need to rethink growth metrics to reflect both economic performance and ecological well-being.

Literature Review

The inadequacy of conventional economic indicators in accounting for environmental degradation has long been acknowledged. Scholars have pointed out that when natural resources—particularly forests—are depleted without proper valuation, national income statistics can present a misleading picture of economic well-being. These findings underscore the importance of integrating ecological dimensions into economic measurement systems to ensure that the consequences of natural capital depletion are not overlooked in growth assessments (Repetto, 1989; Torras, 2000).

Within this broader discourse, several researchers have explored methods to better reflect the value of forest ecosystems in national accounts. In the Indian context, studies have highlighted how traditional valuation techniques tend to underestimate the contribution of forests by excluding the full range of services they provide (Gundimeda et al., 2007; Haripriya, 2001). These contributions have sparked ongoing efforts to develop more comprehensive approaches to valuation that account for both market and non-market benefits.

The System of Environmental-Economic Accounting (SEEA), and more specifically its updated ecosystem component—the SEEA Ecosystem Accounting (SEEA EA)—offers a robust structure for integrating ecosystem services and asset values into economic decision-making (United Nations, 2021). The framework's focus on capturing ecosystem condition, extent, and service flows provides a more holistic basis for evaluating the role of ecosystems in supporting economic systems.

Recent applications of the SEEA EA framework in other countries and at regional levels in India suggest its potential to bridge ecological valuation with policy planning (Campos et al., 2022; Maes et al., 2023; Ramachandra et al., 2024). These studies have highlighted broader trends in ecosystem decline and demonstrated how ecosystem accounting can guide more sustainable land-use and resource management strategies.

However, a gap remains in the application of the SEEA EA at the national scale in India. Moreover, there is little discussion on how the framework might be adapted to fit the complexities of India's institutional and ecological landscape. This research aims to address these gaps by applying and refining the SEEA EA to comprehensively value India's forest ecosystems in a manner that aligns with national accounting practices.

Research Focus and Methodology

This study seeks to explore how forest resources in India can be economically assessed and more effectively reflected within national-level accounting systems. The aim is to provide a broad and integrated understanding of the role forests play in supporting economic activity and environmental stability. The research involves developing ecosystem accounts—both physical and monetary—for select forest-related services.

Particular attention is given to generating value estimates for extractive use, reflecting changes in forest conditions and extent over time, and examining how these valuations might inform broader macroeconomic indicators.

In doing so, the study considers how existing accounting approaches can be adapted to better reflect ecological realities, and how ecosystem degradation and resource use may translate into tangible economic terms. Ultimately, the goal is to highlight the significance of integrating forest values into formal economic planning and assess whether current methods of economic measurement adequately account for the contributions and losses associated with forest ecosystems.

The overarching research question guiding this work is - *To what extent can ecosystem accounting provide a more comprehensive and policy-relevant measure of the economic contribution and degradation of forest resources in India?*

The study draws on a variety of national and state-level data sources to construct a comprehensive view of forest resource dynamics for a recent financial year. Key information related to forest stock and ecosystem flows is synthesized from public datasets and institutional reports, allowing for the development of accounts that reflect both the physical and economic dimensions of forest contributions. These sources provide the foundation for tracking the extent and use of forest resources over time.

To address data gaps and temporal inconsistencies, predictive techniques based on observed trends are employed to estimate values where direct figures are unavailable. In particular, trends from the past decade are used to project values for key indicators in the reference year, including those related to ecological disturbances such as forest fires. For these disturbances, estimation techniques rely on consistent historical relationships between event frequency and ecological impact.

The accounting framework used in the study draws broadly from internationally recognized approaches that integrate environmental assets into economic measurement. Both physical and monetary accounts are developed, incorporating stock and flow measures. Following this, valuation strategies are applied to assign economic worth to various resource use categories and ecosystem changes. These techniques incorporate market-based and imputed pricing structures, drawing from observed prices, reported expenditures, and policy documents. Different categories of forest use and change—such as extraction, degradation, or regeneration—are valued using tailored approaches that reflect their characteristics and data availability.

Where direct valuation was not feasible due to data limitations, composite or proxy pricing methods were employed to approximate economic values. The final output includes aggregate metrics designed to integrate these valuations into broader economic analysis. These measures offer a pathway to reflecting forest-related contributions and losses within national-level indicators, aiming to inform more ecologically attuned economic policy.

Key Findings and Arguments

This study undertakes a national-level assessment of India's forest ecosystem by constructing physical and monetary accounts for a recent financial year, guided by the principles of the SEEA EA framework. Through this approach, forests are treated as economic assets that provide measurable benefits to society. The study attempts to quantify changes in forest stock and the economic value associated with these changes, offering a lens to evaluate the broader implications of forest resource use on the economy. By assigning monetary value to ecological flows and changes, the research frames forest ecosystems as natural capital—whose depletion or enhancement carries direct macroeconomic consequences.

The analysis reveals that India's forest ecosystem has undergone measurable physical and economic shifts. While there have been gains in some areas, overall national trends point to a net decline in both forest extent and value. These outcomes are shaped by multiple factors, including resource extraction, land-use change, and ecological disturbances. While certain restoration and regeneration efforts have been recorded, they have not been sufficient to counterbalance the pace of extraction and damage across the country.

Monetary accounts, developed through valuation of select ecosystem services, show a decrease in the overall asset value of forest ecosystems. Though the relative percentage change appears small, the scale of absolute losses is notable, raising concerns about the long-term sustainability of forest resource use.

The contribution of forests to national income, when properly accounted for, stands at a significant share of the economy—even when only a limited set of ecosystem services is considered. This underlines the importance of incorporating forest values into macroeconomic frameworks to better reflect ecological dependencies.

The study also introduces two integrative metrics—Forest Gross Ecosystem Product (FGEP) and Forest Adjusted Domestic Product (FADP)—to capture the forest ecosystem's contribution to national income more effectively. While FGEP quantifies the gross value of ecosystem contributions, FADP adjusts national income by accounting for both the benefits and losses associated with forest stock changes. These measures demonstrate that even a partial inclusion of ecosystem services alters conventional income estimates, offering a more ecologically informed view of development. Disaggregated zonal analysis further illustrates the heterogeneity of forest dynamics across regions. Certain regions exhibit more resilient patterns, with relatively better performance in terms of forest conservation and economic valuation. These areas are likely influenced by a combination of institutional, ecological, and sociocultural factors that support sustainable forest practices. In contrast, other zones show marked declines, suggesting high extraction pressure, insufficient regeneration, and ecological stress. These trends signal the importance of tailoring forest management policies to regional contexts.

Zones emerged with net positive trends in both physical and monetary terms, pointing toward successful conservation and restoration initiatives. While others, despite experiencing a decrease in forest area, recorded notable gains in economic value—possibly due to the quality and density of remaining forest stock. These contrasts highlight the necessity of distinguishing between quantity and quality in ecological assessments. Several other zones experienced moderate to severe losses, with extraction pressures, fire events, and land-use changes driving negative outcomes. In particular, zones recording the sharpest declines in both area and value, underlining the urgent need for targeted intervention in forest governance, fire prevention, and land use planning.

The study also reveals a discrepancy between physical and monetary drivers of forest loss. While physical accounts are primarily influenced by high-volume resource use, monetary losses are more strongly tied to high-value disruptions like forest fires. This contrast reflects the differentiated economic worth of ecosystem components, and underscores the limitations of relying solely on biophysical indicators for policy formulation.

Overall, the findings call attention to the widespread undervaluation of forest resources in conventional economic systems. Even within a limited scope, the inclusion of forest ecosystem values produces measurable divergences from official income estimates, pointing to hidden costs of economic development that often go unrecorded. Adjusting macroeconomic metrics to reflect changes in natural capital can offer a more realistic and sustainable measure of progress.

By integrating ecological valuation into national accounting structures, this study offers a framework for rethinking the role of forests in economic development. The results underscore the importance of region-specific strategies and institutional strengthening to preserve ecosystem services while pursuing growth. As the ecological and economic functions of forests become more interlinked in a changing climate, their inclusion in planning and budgeting frameworks becomes not only desirable but essential for sustainable development.

Policy and Practice Implications

The findings of this study underscore the urgent need for targeted policy measures to address regional differences in forest resource conditions and to promote sustainable forest management practices across India. The economic significance of forests demonstrated here calls for their recognition as critical natural assets within national economic planning. Integrating forest valuation into broader accounting and policy frameworks can help reflect their true contribution, not only in terms of provisioning services but also through ecosystem functions that sustain biodiversity and local livelihoods.

Institutionalizing green economic indicators that capture these values—such as the Forest Gross Ecosystem Product and Forest Adjusted Domestic Product—can support a more comprehensive understanding of the trade-offs between development and ecological health.

This integration would allow policymakers to better track the economic impacts of forest depletion and regeneration, guiding decisions toward sustainability in the long term.

Recent regulatory changes, particularly amendments to forest conservation laws, raise concerns about weakening environmental safeguards and potentially marginalizing communities that depend on forests. Reinstating participatory decision-making processes involving local institutions is critical to ensure more equitable and ecologically sensitive forest governance.

Compensatory afforestation policies, while aiming to offset forest loss, need to be carefully revisited to avoid unintended consequences such as the establishment of monoculture plantations that fail to restore natural biodiversity. Encouraging afforestation efforts that prioritize ecological diversity and are adapted to local climatic and terrain conditions will enhance the long-term resilience of forest ecosystems.

Strengthening the legal and institutional frameworks governing forest management is essential to improve enforcement and reduce illegal or unrecorded resource extraction, which currently contributes to significant ecological and economic losses. Building the capacity of environmental agencies and local forest institutions will be vital to ensure that conservation regulations are effectively implemented.

Overall, the evidence presented points to the need for comprehensive reforms that combine improved data collection, more rigorous monitoring, and adaptive enforcement strategies. Addressing regional disparities through customized approaches, reassessing recent regulatory relaxations, and fostering community involvement can collectively pave the way for more sustainable forest management. By embedding the economic value of forests within planning and governance systems, India can better safeguard its forest ecosystems while supporting inclusive and environmentally sustainable growth.

Conclusion

This study underscores the critical need to fundamentally rethink how forests are valued and incorporated into India's economic planning. By applying the SEEA EA framework to construct detailed physical and monetary accounts for timber and firewood flows, the research provides a nuanced assessment of the state and economic value of India's forest ecosystems for 2022–23. The observed declines in forest area and volume, coupled with significant monetary losses, highlight the urgent challenge posed by unsustainable resource use and inadequate restoration efforts.

The introduction of forest-augmented indicators such as the Forest Gross Ecosystem Product and Forest Adjusted Domestic Product offers a practical pathway to integrate ecosystem services into national accounts, revealing the substantial yet often overlooked contribution of forests to the economy. Regional disparities in forest conditions emphasize the need for location-specific policy responses that address the distinct challenges faced by different zones.

This study advocates a paradigm shift in treating forests as dynamic economic assets rather than passive resources. Current regulatory relaxations that weaken community participation and environmental safeguards must be reassessed to prevent further degradation. Strengthening legal and institutional mechanisms is essential to safeguard forest ecosystems from overexploitation.

Ultimately, embedding natural capital accounting into mainstream economic frameworks is vital for ensuring that India's development remains both economically prosperous and ecologically sustainable. .

The true cost of neglecting forest values extends beyond environmental damage to encompass the erosion of national wealth and resilience, underscoring the imperative for sustainable forest management in securing India's long-term future.

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Study of morphological and physiological parameters of *Azolla sp.* in response to growth parameters and optimisation for carbon capture

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Executive Summary

Carbon capture, utilisation, and storage have received attention lately as a measure to mitigate climate change. However, the artificial routes of carbon capture are economically inadequate to be scaled in the global South. This study presents a novel approach to capture atmospheric carbon via enhanced cultivation of the aquatic fern Azolla, which has one of the lowest biomass doubling times (i.e., 2 to 5 days) among photosynthetic species. Due to Azolla's ability to capture atmospheric nitrogen, the harvested Azolla can be used as a bio-fertiliser, reducing the demand for nitrogenous fertilisers like urea and diammonium phosphate. This could reduce the emissions associated with the production and use of synthetic fertilisers. Besides capturing carbon dioxide, this practice could also reduce the dependence of small and marginal farmers on expensive synthetic fertilisers, making the agricultural community more resilient to the impacts of climate change.

The high growth rate of azolla can be leveraged to sequester atmospheric carbon dioxide (CO_2) through the process of photosynthesis. This study explores a model of enhanced cultivation of azolla through vertical integration and soilless liquid fertiliser to establish year-round carbon capture operations at minimal cost.

Context & Problem Statement

This study represents a pioneering effort in the large-scale, sustainable cultivation of *Azolla*, offering foundational insights for future research in its use as fodder, fertiliser, biofuel feedstock, and a scalable carbon capture solution. Unlike prior studies that primarily relied on synthetic fertilisers or organic solids like soil and cow dung, this research prioritised water-use efficiency and system simplicity. Consequently, solid nutrient inputs were minimised to maintain optimal water quality parameters—such as dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Instead, liquid nutrient solutions derived from processed organic waste streams were developed and standardised, aligning nutrient delivery with environmental sustainability.

A major innovation of this study lies in the implementation of vertically integrated cultivation systems. While vertical farming is common in hydroponics, it has not been extended to aquatic ferns like *Azolla*. This research explored tiered meta-structures to increase land-use efficiency without compromising biomass productivity, marking a novel contribution to the cultivation of shade-tolerant aquatic species. In contrast to algae, which require high solar radiation and costly photobioreactor systems for vertical scaling, *Azolla* demonstrates inherent compatibility with low-light conditions, making it suitable for stacked or rooftop farming models. The operational simplicity and adaptability of the proposed system are crucial for scalability, especially in contexts lacking reliable electricity, arable land, or high-tech infrastructure.

By eliminating dependence on soil characteristics and electrical input, the study lays the groundwork for decentralised, low-tech *Azolla* farming across varied geographies and socio-economic contexts. This approach has significant implications for rural livelihoods, peri-urban farming systems, and climate-resilient agriculture. Most importantly, the study highlights a substantial research gap in using *Azolla* explicitly for carbon capture. Historically, interest in *Azolla* has focused on its utilitarian value, overlooking its potential as a nature-based climate mitigation tool. Yet, geological records indicate that ancient *Azolla* blooms played a major role in past atmospheric carbon drawdowns. Building on this premise, the present study advocates for the strategic use of *Azolla* in carbon capture operations, potentially at a gigatonne scale a perspective that could shift the global research agenda on aquatic ferns.

This study thus provides the first practical framework for standardised, scalable, and low-impact *Azolla* cultivation systems that could support certification for carbon credits and contribute meaningfully to meeting international climate goals under the Paris Agreement. Future research can build on this exploratory work by optimising vertical integration designs, enhancing nutrient cycling using waste streams, and quantifying carbon sequestration rates under varied climatic and structural conditions.

Literature Review

The genus *Azolla* (*Azo*: to dry; *ollyo*: to kill) (Lumpkin and Plucknett, 1980) is a small-leafed aquatic fern that doubles itself in a mere time of 2 to 5 days. It is a small-leafed, floating aquatic fern native to the tropics, subtropics, and warm temperate regions of Africa, Asia, and America. (Sabetraftar *et al.*, 2013) (Bujak and Bujak, 2024) Among cyanobacteria-plant associations, the relationship between Azolla and *Anabaena-azollae* stands out as unique. The Azolla symbiosis with Anabaena is the only known permanent symbiosis, living in Azolla throughout all its life stages. It gets passed down from one generation to the next, whether it produces sexually or vegetatively.

Azolla is an excellent source of biofertilizer because of its rapid biomass doubling time and therefore widespread distribution. (Jama *et al.*, 2023) Azolla as a biofertilizer can mitigate the CO_2 emissions which would otherwise be produced from fossil fuels that are being utilised in producing inorganic fertilisers such as urea. It alters the soil microbial communities as well (Widiastuti, 2017). Azolla as a biofertilizer offers a promising way in order to achieve better nitrogen use efficiency (NUE) by utilising the biological nitrogen fixation (BNF) potential. (Yao *et al.*, 2018)

When the process of trans-esterification is performed and Fatty Acid Methyl Esters (FAME) are obtained from *Azolla/ Anabaena azollae,* the lipids, particularly C16:0, C18:2 & C18:3, meet the essential fuel criteria required in the EN14214 standards of biodiesel, which includes the Cetane Number (CN), fuel density & the iodine value. Due to this distinct chemical composition, Azolla becomes a great & environmentally friendly resource for the production of biofuel.

Azolla – Anabaena symbiosis was used to treat wastewater as it grows by fixing nitrogen from the atmosphere, and therefore it can be expected that even when the N is consumed, still P removal can take place (Shiomi and Kitoh, 1987). As *Azolla,* the aquatic fern, can grow on wastewaters, it makes it an attractive species for utilisation as bioenergy (Miranda *et al.*, 2018). *Azolla* can act as a decontaminant as it binds in very high concentrations with heavy metals and with effectiveness (Cohen-Shoel *et al.*, 2002)

Research Focus & Methodology

The research objectives and underlying research questions for the study have been enumerated as under:

1. To optimise the composition, dose and frequency of nutrient addition, and standardise feasible strategies for integrated pest management
2. To empirically quantify the CO_2 captured through biomass growth
3. To analyse plant physiology and establish macro and micro-parameters of *Azolla* health and productivity

.On successful completion of standardisation and optimisation of operations at small-scale implementation, operations were scaled to medium scale by vertically integrating *Azolla* containers on top of each other, with a median distance of 0.25 m between two vertical levels.

A meta-structure for large-scale *Azolla* cultivation was constructed, with financial sponsorship from the Emerson Centre of Excellence for Sustainability Studies. While initially, the meta-structure was planned to have a capacity of $1tCO_2yr^{-1}$, due to space constraints within TERI SAS premises, the approved meta-structure had a cumulative carbon capture capacity of about 635 $kgCO_2yr^{-1}$, under optimal operating conditions

Table 3.1: *Summary of structural details of the carbon capture meta-structure*

Specification	Details
Available area	6.7 m x 3.1 m
Structure footprint	6.5 m x 3 m
Inter-level height	2 m
Design water load (per level)	1650 kg
Cumulative design water load	8250 kg
Effective azolla area	82.5 m^2
Annual carbon capture capacity	635.25 kg

The process of calculating captured CO_2 from the fresh weight of the harvested biomass is as follows:

- **Fresh weight of harvested *Azolla* (FW):** The *Azolla* is harvested once the double bedding condition is reached. The excess water is allowed to drain out, and the fresh weight of the biomass is recorded.
- **Dry weight of *Azolla* biomass (DW):** DW=0.07 x FW [Fresh weight samples are dried every week to obtain an average ratio of dry to fresh weight. For our study, the observed ratio is 0.07.]
- **Carbon content of biomass (CB):** CB=0.42 x DW [The carbon content of the dry biomass is estimated through ultimate analysis. The carbon content of azolla is fairly constant, regardless of species and growing conditions. For our study, we have assumed a carbon content of 42%, pending empirical tests on harvested azolla samples (Bocchi and Malgioglio, 2010).]
- **Captured CO_2:** CC=3.67 x CB [The captured atmospheric CO2 can be quantified by the stoichiometric relationship between atomic carbon and molecular carbon dioxide.]
- **The empirical equation thus becomes:** CC=0.107898 x FW

Chlorophyll a and b occur in higher plants, ferns and mosses. Chlorophylls c, d, and e are found in algae and certain bacteria. Chlorophyll is extracted in 80% acetone, and the absorbance at 663nm, 652nm and 645nm is read in a spectrophotometer. Using the absorption coefficients, the amount of chlorophyll is calculated.

Table 3.2: *Readings of the lower phase*

Absorbance (nm)	Reading 1	Reading 2	Reading 3
645	0.277	0.300	0.283
652	0.394	0.408	0.394
663	0.703	0.724	0.710

Table 3.3: *Reading of the upper phase*

Absorbance (nm)	Reading 1	Reading 2	Reading 3
645	0.072	0.064	0.069
652	0.094	0.087	0.091
663	0.154	0.148	0.155

Table 3.4: *Chlorophyll a and b values of both the phases*

Phases	Chlorophyll a	Chlorophyll b
Lower Phase	0.414	0.162
Upper Phase	0.088	0.043

Calculations:

Calculate the amount of chlorophyll present in the extract (mg chlorophyll per gram of tissue) using the following formula:

a. Chlorophyll a (mg/g) = 12.7 (A_{663}) – 2.69 (A_{645}) × V/1000 × W

B. Chlorophyll b (mg/g) = 22.9 (A_{645}) – 4.68 (A_{663}) × V/1000 × W

C. Total chlorophyll (mg/g) = 20.2 (A_{645}) – 8.02 (A_{663}) × V/1000 × W

Where, *A= Absorbance at specific wavelengths; V= Final volume of chlorophyll extract in 80% acetone; W= Weight of the fresh tissues extracted*

Key Findings & Arguments

Chlorophyll analysis was performed using the protocol mentioned in the resources and methods section, and the following were the results.

As given under the equations under the preceding section, the following graph indicates the quantum of biomass harvested from the meta-structure in the period from 08.03.2025 to 28.05.2025, spanning a period of 81 days, with a cumulative harvest of 177.41 kg wet *Azolla* biomass, and consequently a direct air capture quantum of 19.142184 $kgCO_2$.

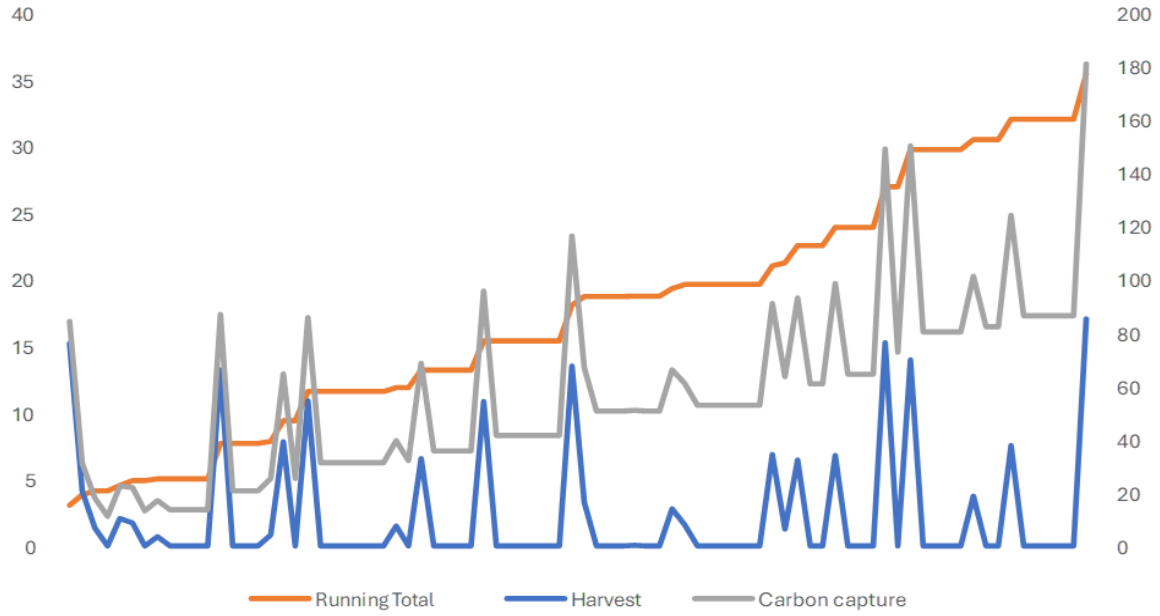


Figure 3.1: *Graph of running total, harvest and carbon capture*

The corresponding fresh weight harvest rate becomes 30.420 g/m^2-day against the optimal figure of about 200 g/m^2-day. Learning curves as well as local limiting factors have to be taken into consideration while evaluating the efficacy of such exploratory studies.

High Performance Conditions:

A7, A8, A12 – All used Soil + Fresh Cow Dung + No Netting. Vigorous, sustained growth.

Moderate Performance:

A2, A5, A13 – Soil + Fresh Dung + Partial Netting: Steady but slower growth.

A3, A9 – No Soil + Fresh Dung + Full Netting: Poorer performance

Low/Failed Performance:

A1 – No inputs: complete failure.

A4 – Fermented dung: yellowing, stagnation.

A6, A10, A11 – Biofertilizer-only: poor sustainability.

Variable-Specific Analysis

- **Soil Presence:** Essential for nutrient buffering and microbial activity. All high-performing trials included soil.
- **Fertiliser Type:** Fresh cow dung was most effective. Fermented dung and biofertilizer were suboptimal.

  Shade Netting: Partial shade (30–40%) was optimal. Full shade suppressed growth. No shade led to overheating above 36–37°C.
- **Solar Radiation:** Needed for proliferation. Overexposure (>37°C) caused yellowing.

Emergent Patterns and Thresholds

- Best Growth: Soil + Fresh Dung + Full Sun (up to ~36°C ambient).
- Growth Inhibition: Begins above ~37°C or under >50% shade.
- Color Loss: Low light, nutrient stress, or thermal stress.

- Frond Decay: Ammonia buildup, dehydration, or zero inputs.

Proposed Next Steps – Phase 2 Trials

B1 – Soil + Fresh Dung + 30% Shade Net: Optimal configuration.

B2 – Soil + Fermented Dung + Partial Net: Test impact of anaerobic input.

B3 – Soil + Fresh Dung + White Diffuse Film: Investigate light spectrum.

B4 – Soil + Fresh Dung + Biofertilizer: Test synergy.

B5 – Soil + Fresh Dung + Mist Cooling: Thermal resilience.

B6 – Soil + Fresh Dung + Azospirillum Inoculation: Nitrogen fixation enhancement.

Policy & Practice Implications

The empirical findings from sustained Azolla cultivation across diverse microclimates offer actionable insights with profound implications for Indian policy-making. Given India's heavy reliance on fertilizer imports, pressing energy security concerns, and global climate commitments, Azolla emerges as a strategic biological asset capable of addressing multiple policy priorities simultaneously.

Fertilizer Import Independence: India currently imports over 30% of its urea and significant quantities of phosphorus- and potassium-based fertilizers, placing a considerable burden on the national exchequer and exposing agriculture to global supply volatility. *Azolla,* with its proven capacity for atmospheric nitrogen fixation via symbiosis with *Anabaena azollae*, provides a sustainable and scalable alternative to synthetic nitrogen fertilisers.

Government policy can encourage decentralised Azolla cultivation through the National Mission for Sustainable Agriculture (NMSA) frameworks, linking it to local Krishi Vigyan Kendras (KVKs) and Panchayati Raj institutions. Incentivising Azolla production and integration into paddy fields, vegetable farms, and livestock systems can significantly reduce nitrogen fertiliser demand. Inclusion of Azolla-based biofertilizers in the PM-PRANAM scheme (Promoting Reduction of Nitrogenous Input Application for Minimising Fertiliser Subsidy) could catalyse farmer uptake and align with nutrient-use efficiency targets.

Biofuel Production and Energy Transition: India's National Bio-Energy Policy aims to boost biofuel production, especially second-generation (2G) feed stocks, to reduce dependency on fossil fuels and mitigate rural energy poverty. Unlike food-based biofuel crops, Azolla does not compete for arable land or freshwater, and it thrives on nutrient-rich wastewater, enhancing its viability in peri-urban and rural wastewater recycling systems.

Policy instruments such as the National Bio-Energy Mission can support pilot-scale Azolla-to-biofuel initiatives, especially in conjunction with rural biogas programs or municipal waste-to-energy schemes. Additionally, subsidies or viability gap funding for Azolla-based bio-digesters in Gram Urja Swaraj schemes can integrate energy self-sufficiency.

Carbon Capture and Climate Policy Alignment: This aligns with India’s Long-Term Low Emission Development Strategy (LT-LEDS), which emphasises nature-based solutions and ecosystem restoration. The rooftop and structural pool trials demonstrate the potential for urban and peri-urban carbon capture infrastructure based on living biomass, a model not yet tapped in India’s climate action portfolio.

Incorporating *Azolla* cultivation into India’s Green Credit Programme and afforestation-linked carbon trading platforms could unlock new incentives for individuals and communities. Moreover, *Azolla’s* role in nutrient cycling, shade moderation, and biotic stress resistance offers co-benefits for climate-resilient agriculture under PM-KUSUM and MGNREGS-supported eco-restoration works.

Conclusion

While the dominant majority of studies on azolla focus on its multitudinous uses as fodder, fuel and fertiliser, there is a research gap in the context of using azolla as a means for enhanced carbon capture. The limited scalability of azolla cultivation operations over the past few decades can be attributed to the intent of research carried out in the context of azolla morphology, physiology and utilisation. None of the extant studies focus on the widespread utilisation of azolla for the primary purpose of combating global warming, which can catalyse the scalability of azolla cultivation operations to a gigatonne order of magnitude.

Future studies on similar topics include, but are not limited to, the following areas of research:

- Genetic enhancement of azolla species for greater tolerance to extreme temperature and humidity conditions in local micro-climates
- Imparting a certain degree of salinity tolerance to the azolla species
- Backwards integration for resource efficiency can be streamlined to allow for decoupling of necessary resources, such as freshwater, from anthropogenic requirements. Studies in this domain can focus on the cost-effective desalination of ocean water using renewable energy technologies such as parabolic/paraboloid solar thermal collectors.
- Spore extraction technologies can be developed to increase the ease of inoculation and transportation in the event of the initialisation of operations at a new location.

The present study offers an exploratory approach for standardisation, optimisation and eventual certification of enhanced azolla cultivation processes for the generation of carbon credits and subsequent offsetting of greenhouse gas emissions through planned end use of the harvested biomass. Future research can be built on the foundation of this face validity study on the potential of this tiny fern to draw down greenhouse gases, while providing co-benefits pertaining to social, economic, and environmental dimensions.

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1. Mangroves and Ponds as Natural Barriers: Protecting Freshwater for Millions in a Climate-

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Executive Summary

The Sundarbans delta, supporting 4.6 million people, faces a critical water security crisis due to accelerating subsurface water salinisation driven by sea-level rise (3.14 mm/year), cyclones, and embankment failures. This research provides the first evidence quantifying mangroves as essential natural buffers against saltwater intrusion. A study of subsurface water samples across the region revealed an important relationship, which holds statistically: mangrove patches prevent saltwater intrusion and help in maintaining salinity levels in subsurface water.

Along with this, surveys of households confirmed ponds as vital socio-ecological infrastructure for irrigation, domestic use, aquaculture, and cultural practices. However, communities reported severe decline: multiple observations were made regarding increased frequency in drying of the ponds, waning water quality and aquatic life, and their failure to serve as dry season reserves. Crucially, most residents were unaware that mangrove loss increased flooding and salinity problems they ranked as severe.

Our position is unequivocal: Mangrove restoration as coastal buffers, integrated with improved pond systems and community outreach, offers the most effective, equitable, and sustainable pathway to safeguard freshwater security in the Sundarbans and similar climate-vulnerable deltas. Ignoring this nature-based approach risks catastrophic water scarcity for millions.

Problem Statement

Coastal deltas globally, home to over 500 million people, are on the frontlines of climate change. The Sundarbans, a UNESCO World Heritage site and the world's largest contiguous mangrove ecosystem, epitomises this vulnerability. Its inhabitants face an existential threat: the rapid salinisation of their primary freshwater source – subsurface water. Accelerated relative sea-level rise (50% faster than global averages), intensifying cyclones, and pervasive embankment breaches are driving saltwater into underground aquifers, contaminating drinking water and irrigation supplies. This crisis forces communities to purchase water or rely on deep, expensive borewells, deepening poverty in a region where 44% already live below the poverty line.

The salinisation crisis overlaps with acute socio-environmental vulnerabilities. Declining river sediment flows weaken embankments, while upstream freshwater diversions reduce flushing of estuarine salts. Subsurface water over-extraction exacerbates saltwater intrusion. Crucially, the degradation of mangrove forests – natural coastal defences – removes a critical barrier against saline inundation. The problem transcends environmental degradation; it is a profound threat to human health, food security via salinized agricultural land, economic stability, and cultural survival.

Despite widespread recognition of mangrove benefits for surface wave attenuation, a critical knowledge gap persisted: evidence delineating mangroves' specific role in mitigating subsurface water salinisation in complex deltaic systems like the *Sundarbans* was absent. Furthermore, the potential of integrating traditional water systems (household ponds) with mangrove conservation for holistic water security remained unexplored. This research directly addresses these gaps, providing actionable scientific evidence for nature-based adaptation.

Literature Review

Nature-based Solutions (NbS) have emerged as a vital paradigm for climate adaptation, emphasising ecosystem protection, restoration, and management to address societal challenges while benefiting biodiversity. Coastal NbS, particularly mangrove conservation and restoration, are globally recognised for reducing wave energy, storm surge impacts, and erosion. Extensive literature documents mangroves' role in surface water dynamics and coastal protection post-2004 tsunami. However, understanding of their subsurface hydrological functions, specifically concerning subsurface water salinity regulation, remains underdeveloped.

Subsurface water salinisation in deltas is a well-documented but escalating problem, driven by sea-level rise, reduced sediment flows, over-extraction, and physical infrastructure failure. Monitoring techniques (hydraulic head measurements, geophysical surveys, tracer analysis) confirm saltwater intrusion pathways, yet studies integrating ecological buffers like mangroves into salinisation models are scarce. Research specific to the Sundarbans details alarming salinity gradients, species shifts indicating salt stress (e.g., decline of *Heritiera fomes*), and embankment vulnerabilities. While acknowledging mangroves' overall protective value, existing Sundarbans literature lacks empirical quantification of their direct impact on aquifer salinity and fails to integrate community-managed freshwater ponds into resilience strategies.

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This research bridges these critical gaps. It builds upon NbS theory and coastal hydrogeology but provides novel evidence: clarifying the mangrove width -subsurface water salinity. It uniquely integrates hydrogeological analysis with socio-ecological assessment of household ponds, positioning both as complementary NbS for integrated delta water security, thus advancing beyond purely ecological or purely engineering approaches prevalent in current literature.

Research Focus & Methodology

The research approach combined scrutiny of the subsurface water quality with qualitative socio-ecological assessment of the ponds, which are a feature observed in almost every single household of the region. Forty subsurface water samples from tubewells/borewells were collected. Geographic coordinates enabled spatial analysis using QGIS to map distances. Well depth and operational years were recorded via user interviews. A Multiple Linear Regression (MLR) model quantified relationships. Community understanding of ponds was assessed via structured surveys with respondents across the islands, selected using snowball sampling due to logistical constraints and the

near-universal presence of household ponds (ensuring topic relevance).

The questionnaire covered environmental awareness, pond uses, ecological value, livelihood importance, observed changes, and socio-cultural significance. This mixed-methods design was essential. The MLR provided robust evidence of the mangrove-salinity relationship while the perception survey captured the irrefutable yet vulnerable role of ponds a crucial, community-managed NbS component revealing real-world vulnerabilities and socio-cultural dimensions absent from purely physical data. Combining these approaches generated a broad understanding of NbS efficacy for delta water security.

Key Findings

A. Mangroves are Highly Effective Natural Barriers against subsurface water salinisation:

1. **Robust Statistical Evidence:** Regression analysis revealed a highly significant negative relationship between mangrove patch width and sub-surface water salinity. This finding provides proof of mangroves directly mitigating saltwater intrusion into aquifers in the Sundarbans.
2. **Spatial Context:** While proximity to saline sources generally correlated with higher salinity (intuitive negative correlation), the influence of mangrove width demonstrates that physical distance alone is insufficient; the presence and extent of this natural vegetation barrier is the primary factor controlling subsurface salt intrusion in this deltaic environment.

B. Household Ponds are Vital but Climate-Threatened Socio-Ecological Infrastructure:

1. **Multifunctional Lifelines:** Surveys confirmed ponds are near-universal (virtually every household) and serve diverse, critical functions: irrigation, domestic chores, aquaculture, and cultural/religious practices. They are embedded in daily life and local economies, with maintenance costs reflecting use intensity.
2. **Strong Ecological Awareness:** Communities highly value ponds' ecological roles, with the majority in agreement that they support biodiversity and the importance of pond-side trees for shade and wildlife habitat.
3. **Severe Climate Impacts:** Despite their value, ponds are failing under climate stress. A strong consensus of respondents agrees with the following: ponds are drying up more frequently, and there is a reduction in the quality of the water, as well as fauna and flora species in the pond. Critically, ponds do not provide reliable backup water during dry periods due to their design and vulnerability to drought. This highlights a dangerous vulnerability in community water security.
4. **Cultural Transition:** While the ponds' cultural importance was affirmed, only a few reported active ritual use, suggesting a shift from practical social spaces towards symbolic heritage, partly driven by environmental constraints. However, they remain vital seasonal spaces for children.
5. **Critical Awareness Gap Undermines Resilience:** Despite identifying cyclones, flooding, embankment breaches, soil salinity, and water scarcity as severe problems, most did not view the reduction in the quanta of mangrove cover as an alarming or even an important loss. This disconnect is of concern, given the evidence that mangroves directly mitigate these very threats (flood attenuation, salinity buffering). This lack of awareness hinders community engagement in vital conservation efforts.

These findings fundamentally shift the discourse on Sundarbans water security. Mangroves are not just biodiversity havens or surface wave buffers;

they are quantifiable, essential infrastructure for protecting the freshwater lifeline beneath the ground. The significant relationship provides actionable science for restoration. Concurrently, household ponds represent a widespread, community-owned NbS for rainwater harvesting and multiple uses, but their current vulnerability to climate impacts (drying, salinisation during storms) constitutes a major risk.

The critical disconnect between community experience of climate threats and understanding of mangrove benefits represents a significant barrier to building resilience. Therefore, effective adaptation requires an integrated NbS approach: strategically restoring mangroves as bio-shields, combined with rehabilitating ponds as climate-resilient water reservoirs (e.g., increasing depth, preventing saline inflow), all underpinned by targeted education linking mangrove conservation directly to the protection of homes, freshwater, and livelihoods. Relying solely on engineered solutions is prohibitively expensive and ignores the proven, multi-benefit potential of these synergistic natural and traditional systems. This integrated strategy offers the most sustainable and equitable pathway to safeguard the future of delta communities.

Policy and Practice Implications

The empirical evidence demands urgent integration of mangroves and ponds into the core of Sundarbans' water security and climate adaptation strategies. Policymakers, disaster management authorities, and conservation agencies must act on these findings:

A. Mandate and Implement Strategic Mangrove Buffer Zones:

Action: Enact and enforce policies designating and protecting mangrove buffers along vulnerable coastlines and estuaries adjacent to critical freshwater aquifers and settlement zones, based on the identified technical optimum. Prioritise restoration in areas with high salinity intrusion and narrow existing buffers.

Co-benefits: Mangroves provide extensive co-benefits beyond salinity reduction. They serve as crucial carbon sinks, storing up to four times more carbon per hectare than tropical rainforests, making them vital for climate change mitigation. These coastal forests act as natural buffers against storm surges, tsunamis, and coastal erosion, protecting inland communities and infrastructure from extreme weather events. Ecologically, mangroves function as nurseries for numerous marine species, supporting fisheries that millions of people depend on for their livelihoods. They filter pollutants and excess nutrients from water, improving coastal water quality. Many mangrove areas also support ecotourism, providing sustainable economic opportunities for local communities while preserving these critical ecosystems. Additionally, mangroves help stabilise shorelines through their complex root systems and contribute to subsurface water recharge in coastal areas, further enhancing their value for both environmental protection and human well-being.

B. Integrate and Upgrade Household Ponds into Climate-Resilient Water Security Systems:

Action: Launch programs for **integrated pond rehabilitation** focusing on: (a) increasing depth and storage capacity (e.g., de-silting, controlled excavation); (b) improving lining to reduce seepage; (c) constructing saline intrusion barriers (e.g., small, mangrove-reinforced berms); and (d) promoting climate-resilient aquaculture. Provide technical support and micro-finance for upgrades, prioritising ponds critical for community clusters.

Evidence Basis: The universal household reliance on ponds for diverse needs, coupled with the documented high vulnerability, necessitates investment to enhance their resilience as a vital, decentralised water source complementing. subsurface water.

Co-benefits: Improves food security (aquaculture), supports livelihoods, enhances local biodiversity, and provides supplementary irrigation, reducing pressure on subsurface water.

C. Launch Community-Led Education and Awareness Campaigns Linking Mangroves to Security:

Action: Develop and implement widespread community awareness programs co-created with local stakeholders. These must clearly communicate the direct evidence linking mangrove width to reduced subsurface water salinity (using local examples and data) and demonstrate how mangroves mitigate cyclones, flooding, and embankment breaches the very threats communities rank as severe. Integrate this into school curricula and local governance (Panchayat) initiatives.

Evidence Basis: The critical gap identified: communities suffering salinity/flooding but not linking it to mangrove loss impedes conservation support. Education is essential for fostering stewardship and ensuring the long-term success of mangrove buffer policies and NbS programs.

Co-benefits: Empowers communities with knowledge, fosters ownership of conservation efforts, builds social cohesion around environmental action, and supports sustainable livelihood development linked to healthy ecosystems.

Conclusion

This research delivers a critical scientific and practical advance for climate-vulnerable deltas: mangroves are empirically proven, quantifiable natural infrastructure for protecting subsurface water the freshwater lifeline for millions from saltwater intrusion. The identification of the significance of mangrove buffer

in reducing salinity provides a precise, science-based target for maximising salinity reduction. Concurrently, household ponds, while culturally embedded and multifunctional, face severe threats from climate change, exposing communities to water insecurity despite their presence.

The core message is clear: safeguarding freshwater in the Sundarbans, and analogous deltas globally, requires an integrated NbS approach. This must combine the strategic restoration of mangrove bioshields based on empirical thresholds with the climate-proofing of traditional pond systems, all reinforced by community education that translates scientific evidence into local understanding and action. Ignoring this integrated approach perpetuates reliance on fragmented, often unsustainable and inequitable engineering solutions. Embracing it offers a cost-effective, multi-benefit pathway to build resilience, protect biodiversity, secure livelihoods, and uphold cultural values. Future work must address temporal salinity dynamics and incorporate detailed hydrogeological data to refine models. However, the evidence presented here provides an unequivocal foundation: investing in mangroves and resilient ponds is an urgent imperative for securing the future of deltaic populations facing the escalating impacts of climate change.

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3. RETHINKING URBAN SUSTAINABILITY THROUGH CLIMATE GOVERNANCE

Focusing on climate-smart cities, semi-urban planning, and built environment resilience.

POSITION PAPERS

Enabling Factors of Climate Smart Urban Governance in Pimpri Chinchwad
Anuja Ramesh Ramugade

Assessing Climate Risk Exposure in the Built Environment
Naheed Yasin Islam

Reimagining Wastewater Governance for Small Semi-Urban Towns in India
Rishika Rajkumar

Integrating Indigenous Materials and Techniques into India's Climate-Resilient Architecture
Rishu Gupta

Understanding the Income-Pollution-Gender Dynamics in the Indian Context: An Application of the Gender-Environmental Kuznets Curve
Daisy

Enabling Factors of Climate Smart Urban Governance in Pimpri Chinchwad

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Executive Summary

As India advances toward its 2047 development vision, climate-smart urban governance in fast-growing Tier II cities becomes more important than ever. This position paper is based on the in-depth case study of Pimpri-Chinchwad, Maharashtra a mid-sized industrial city that has emerged as a one of the national leaders in climate smart city assessments conducted by NIUA. Despite facing similar challenges faced by other Tier II cities including financial constraints, the Pimpri Chinchwad Municipal Corporation (PCMC) has embraced an ambitious sustainability agenda backed by integrated planning, climate budgeting, citizen engagement, and polycentric governance.

Employing a mixed-methods research design including policy analysis, expert interviews, field observations, and a citizen survey this study identifies six enabling factors behind PCMC's success: national policy alignment, sustainable financing, networked capacity-building, collaboration with non-state actors, visionary leadership, and institutional coordination. This paper argues that Tier II cities with their relative institutional flexibility and evolving infrastructure offer a window of opportunity for transformative, inclusive, and replicable climate strategies. Replicating these enabling factors could ensure climate smart development for other growing Tier II cities.

Context and Problem Statement

India's urban transformation is central to its developmental trajectory. With over 40% of its population projected to live in cities by 2036, urban centres face mounting pressure to reconcile infrastructure demands with environmental sustainability. It is observed that nearly 44% of India's rapidly growing carbon emissions have urban origins, emanating from transport, industry, buildings and waste (Global Compact Network India et al., 2019). Climate action discourse remains largely skewed toward Tier I megacities like Mumbai, Bengaluru, and Delhi often neglecting the complex, fast-evolving realities of Tier II cities.

Pimpri-Chinchwad, situated in Maharashtra's Pune Metropolitan Region, exemplifies the potential of a Tier II city to drive impactful climate governance. An industrial powerhouse once known as "Detroit of the East" due to presence of a strong automotive industry PCMC has rapidly transitioned into a planning-driven urban entity with robust public transit, decentralized waste systems, and extensive green cover. Recognized as a 4-star city under the ClimateSmart Cities Assessment Framework (CSCAF), PCMC's achievements demand deeper examination.

The problem this paper addresses is the lack of empirical understanding of climate governance dynamics in Tier II Indian cities contexts marked by uneven administrative capacities, fragmented planning, and constrained financing. How do such cities align with national and global climate frameworks? What are the barriers and enablers in transitioning toward low-carbon, climate-resilient urban systems?

It also fills a literature gap by expanding the empirical base beyond Tier I cities in global north to understand how "second-tier" cities in global south are actively shaping India's climate future.

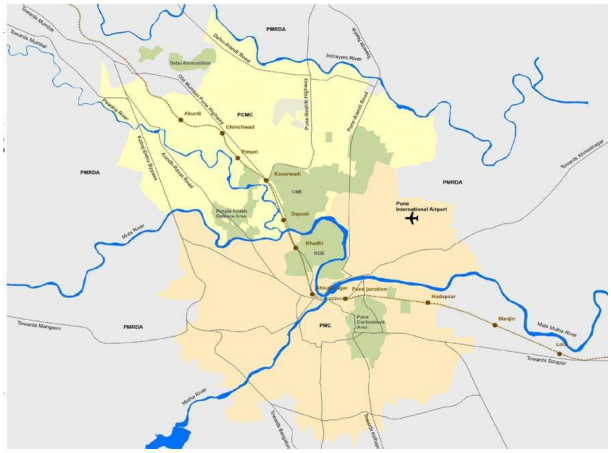


Figure 1 Map of the Twin Cities of Pune and Pimpri Chinchwad (Source: PCMC Revised Draft Development Plan 2025)

Literature Review

This literature review examines the evolving field of urban climate governance, focusing specifically on the Global South and Tier II cities in India. Three key themes emerge: (1) the dual role of cities in contributing to and addressing climate change; (2) the expanding, yet constrained role of Urban Local Bodies (ULBs); and (3) the specific challenges and opportunities facing India's Tier II cities.

Climate Change and Cities

Cities are both drivers and victims of climate change. They account for a significant share of greenhouse gas emissions due to concentrated populations, infrastructure, and energy consumption. In India, urbanisation is often the result of reclassifying rural settlements, not just migration or natural expansion (Kundu, 2011). This leads to fragmented and uneven development, often lacking the infrastructure needed for effective climate action. Luqman, Rayner, and Gurney (2023) highlight how per capita emissions rise with urban expansion, though denser cities tend to have lower per capita emissions underscoring the potential of compact urban development as a mitigation strategy.

Indian cities are especially vulnerable to climate risks such as extreme heat, flooding, and water scarcity. A review by Singh et al. (2021) found that while many Indian cities have begun adaptation efforts, these are often sectoral and reactive rather than integrated or forward-looking. Yet, interventions like green infrastructure can provide "triple wins" by aligning adaptation, mitigation, and development goals. However, studies by Chu and Michael (2022) caution that climate planning in India often lacks inclusivity, overlooking the needs of low-income groups, women, and the elderly. Gupta et al. (2019) similarly stress the importance of community engagement and participatory governance in building resilient cities.

Despite challenges, cities hold transformative potential. Meerow and Stults (2016) argue for a balance between academic visions of resilience and the more pragmatic, risk-based views of local officials. Bridging this gap is crucial for implementing effective and context-sensitive urban climate strategies.

Urban Climate Governance and ULBs

Urban climate governance has grown increasingly complex, shaped by local actions, national frameworks, and global networks. Van der Heijden (2019) emphasises that decentralisation, funding, and policy autonomy are key enabling factors for local climate action. However, cities in the Global South, particularly in India, often face administrative and fiscal constraints.

In India, ULBs are central to implementing climate measures from managing waste to promoting clean energy. Yet, as Stehle et al. (2020) note, their effectiveness varies depending on institutional support and political alignment. Khalid and Okitasari (2023) show that while several Indian cities have developed Climate Action Plans (CAPs), many lack financial backing, integration across departments, and clear accountability mechanisms. Yadav et al. (2024) point to emerging polycentric governance structures and policy innovations that are gradually enhancing local capacity for climate leadership

ULBs are also rooted in India's constitutional framework, which gives them legal mandates for environmental management. Pilkhane (2013) highlights how these institutions can leverage traditional community-based practices for modern climate challenges. As the frontline actors, ULBs must be equipped with greater autonomy, resources, and legitimacy to lead climate resilience efforts effectively.

Tier II Cities: Opportunities and Challenges

Tier II cities in India are urbanising rapidly, offering a unique opportunity to pursue sustainable development before unsustainable systems become entrenched. Jain and Babu (2025) propose a Green City Framework

that aligns environmental goals with economic and social growth. Cities like Nagpur and Faridabad are already adopting smart water systems (Parkhe, 2022), while Bhopal is seeing increased interest in green buildings (Grover, 2015). Yet, this growth is

not without challenges. Purohit (2023) warns of rising pollution, informal settlements, and service delivery pressures. Nonetheless, many Tier II cities retain flexibility to innovate. Bhubaneswar's disaster preparedness, Indore's decentralized water treatment, and Surat's integration of health and climate planning (Chu, 2015) demonstrate the diverse, context-specific approaches these cities are taking.

Literature Gap and Problem Statement

While urban climate governance research has expanded, it remains skewed toward large cities in the Global North and Tier I metros with established climate agendas (Van der Heijden, 2019). This has created a gap in understanding how smaller, less-resourced cities like India's Tier II cities navigate climate action. There is a critical need for more empirical studies that explore the constraints and innovations emerging in these overlooked urban spaces. Additionally, theoretical frameworks by Floater et al. (2016) and Gupta et al. (2019) stress co-benefits and participatory resilience, while the concept of polycentric governance (Yadav et al., 2024) frames the multi-actor reality of contemporary urban planning.

PCMC aligns with this trend but also diverges in its approach. Its evolution from fragmented sectoral action to cross-sectoral climate governance reflected in their recent policies like the Green City Action Plan and climate budgeting represents a paradigmatic shift. PCMC serves as an ideal testbed one that illuminates the potential and complexity of climate governance in India's urban middle order.

Research Focus and Methodology

This position paper seeks to explore the following research question: **What are the enabling factors behind PCMC's climate-smart development?**

By identifying these enabling conditions, the study seeks to contribute to the broader understanding of how Tier II cities in India can move beyond constraints and act as proactive agents in the climate governance landscape.

Research Objectives

To address the research question, the study is guided by two interrelated objectives:

- To analyse the alignment of PCMC's city-level policy architecture with indicators outlined in the national CSCAF.
- To assess citizen awareness and engagement in local climate initiatives under PCMC's governance.

Methodology: This research employed a qualitative-dominant, mixed-method case study design. It combined policy document analysis (12 city-level plans), expert interviews (7), citizen surveys (46 respondents from Pimple Saudagar), and field observations (3 project sites). The aim was to triangulate data across formal policy, implementation practice, and public perception.

Data Collection Tools:

- Policy review: CSCAF-based thematic coding of development plans, mobility strategies, biodiversity actions, and climate budgets.
- Expert interviews: Semi-structured, covering themes of energy, mobility, waste, water, and environment.
- Surveys: Measuring concern, awareness, adoption of sustainability behaviours, and perceptions of GCAP.
- Field visits: BRT corridor, Moshi waste depot, and Harit Setu green corridor.

Data Analysis:

A comparative radar chart was used to assess the alignment between policy intentions and outcome-based indicators from the CSCAF. Thematic analysis of expert interviews revealed key governance enablers and barriers. Additionally, descriptive statistics from citizen surveys highlighted perception gaps and behavioral trends related to climate action. This methodology allowed for a systems-level understanding of PCMC's climate governance integrating institutional dynamics, participatory aspects, and policy-performance gaps.

Key Findings

PCMC's progress in climate resilience and urban sustainability stems not just from project-based interventions but from a systemic alignment of policies, finance, partnerships, leadership, and institutional coordination. This chapter presents key initiatives and outcomes through the lens of six enabling factors.

Policy Alignment with National Frameworks and Missions

PCMC has strategically aligned its urban planning and environmental action with national mandates such as the National Clean Air Programme (NCAP), AMRUT and Smart Cities Mission. This has enabled access to central funds, technical guidance, and benchmarking tools like CSCAF. An analysis comparing PCMC's pre-2023 policy documents with CSCAF outcome scores revealed a moderate to strong alignment. Only outcome-based CSCAF indicators were used to assess whether policies translated into measurable results.



Figure 2 Comparisons between CSCAF Performance and Policy Focus of Pre-2023 plans of PCMC (Source: Author's Analysis)

Two lines were mapped: outcome scores (green) and policy alignment (orange). Areas where implementation outpaced policy included air pollution monitoring, flood risk management, C&D waste, and biodiversity often driven by leadership or external support. Conversely, sectors like water supply efficiency, non-revenue water, and renewable energy showed stronger policy than implementation, indicating barriers like funding or coordination.

Post-2023 radar chart data shows a clear shift, with increased policy focus on previously weak areas such as water systems and energy. The spread of policy engagement across more sectors reflects PCMC's move toward integrated and future-oriented climate governance.

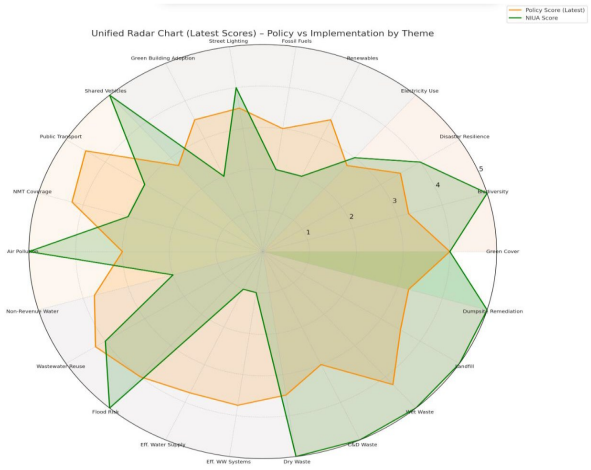


Figure 3 Comparison between CSCAF Performance and Post-2023 Cross Sector Policies of PCMC

In air quality management, PCMC adopted NCAP protocols and implemented them through localized interventions like road-wetting vehicles, real-time air monitoring, and fuel-switch incentives. These efforts have led to measurable improvements in air quality, as validated by CSCAF outcomes and monitoring and sampling analysis done by Maharashtra Pollution Control Board (MPCB, 2024). The Heat Action Plan, Graded Air Quality Response Plan, and Monsoon Plan further reflect the city's responsiveness to national frameworks, translating them into localized action with measurable results in disaster resilience and climate adaptation.

The Green City Action Plan (GCAP), developed in collaboration with International Finance Corporation (IFC) and Advances Practices for Environmental Excellence in Cities (APEX) has become the city's core GHG mitigation plan. The priority measures in the plan are spread across built environment and energy, transportation, waste and water. However, the citizen perception survey reveals that citizen awareness of this plan remains low (only 22% in the survey were aware), indicating the need for stronger communication strategies.

Sustainable Financing via Green Bonds and Climate Budgets

PCMC has pioneered innovative finance mechanisms to fund its sustainability goals: In FY 2025–26, it became the first city in Maharashtra and fifth globally to embed a Climate Budget into its municipal budget, allocating ₹1,962.72 crores toward sustainability-focused sectors out of a total ₹6,251 crores (PCMC, 2025).

Projects under the theme of sustainable urban mobility such as Harit Setu project will be financed through 200 Crore green municipal bonds and public-private investment models, reducing reliance on conventional revenue streams.

Knowledge Networks with GIZ, UNEP, IFC, and Others

PCMC's progress has been shaped significantly by engagement with international knowledge partners. The GCAP and climate budgeting exercises were developed with support from IFC, UNEP, and GIZ, introducing global methodologies for GHG accounting, resilience mapping, and impact tracking. These networks have facilitated technical assessments, capacity-building workshops, and access to international best practices, which are now embedded into PCMC's planning documents and departmental strategies.

In addition, PCMC has also joined the Global Covenant of Mayors for Climate and Energy an international agreement uniting city worldwide that preparing action plans for climate-related disasters. Participation in the agreement will enable the PCMC to exchange experiences and knowledge with cities across the globe. It will provide technical assistance, training, and access to internationally proven solutions for tackling climate change challenges. (Pune Times Mirror, 2025)

Non-State Actor Partnerships: ITDP, Prasanna Desai Architects, and Civil Society

PCMC has built effective collaborations with local and national non-state actors. ITDP has guided the design and implementation of non-motorized transport (NMT) infrastructure, including complete streets, cycle tracks, and pedestrian-friendly zones. The Harit Setu Master Plan, conceptualized by Prasanna Desai Architects, integrates green corridors with mobility solutions, demonstrating urban design's role in resilience planning. Waste segregation and home composting campaigns have been driven by resident associations and school networks, resulting in 94% landfill diversion and a strong CSCAF waste score. Despite limited awareness of formal policies (e.g., only 22% of citizens aware of GCAP), perception snapshot from one of the neighbourhood of PCMC shows that 74% support for metro and waste segregation, 70% use energy-efficient appliances, 52% have rooftop solar whereas 57% practice home composting. These numbers indicate that convenience and accessibility, enabled by civic partnerships, are key to sustainable lifestyle shifts.

Leadership Continuity under a Climate-Champion Commissioner

The sustained progress of PCMC's climate agenda is significantly attributed to Municipal Commissioner Shekhar Singh, whose tenure has been marked by introduction of the Sustainability Cell with six dedicated verticals, mainstreaming the climate budget, emphasis on data-driven and outcome-linked governance.

His leadership has provided strategic continuity in a typically fragmented urban governance landscape. The push toward anticipatory planning, rather than reactive measures, reflects a visionary leadership approach. PCMC's high performance on CSCAF and its integration into broader global climate networks underscore the importance of leadership as a critical enabler of institutional reform.

Institutional Coordination through Interdepartmental Integration

One of PCMC's key strengths lies in its internal coordination mechanisms including the most important Sustainability Cell, housed within the municipal structure, operates across six thematic verticals (waste, mobility, air quality, water, energy, and resilience), ensuring cross-departmental synergy. The Moshi Waste Depot is a model of multi-sector integration linking transportation, health, solid waste, and environmental departments to manage end-to-end waste operations.

Coordination between transport (BRTS, metro), environment (urban forestry, air quality), and IT departments (real-time monitoring, e-ticketing) has enhanced service delivery while reducing emissions. However, the water sector continues to face challenges. Survey data shows 65–70% of residents are unaware of rainwater harvesting, smart metering, or wastewater reuse indicating limited visibility of institutional efforts in this domain. This aligns with radar chart findings where water-related outcomes lag behind policy intentions. Improving interdepartmental coordination in the water and energy sectors, and ensuring these efforts are visible to the public, will be critical for closing the implementation gap .

Policy and Practice Implications

Local urban action that aligns with national frameworks and goals such as the NCAP or Smart Cities Mission tends to yield more consistent and scalable outcomes. This alignment ensures continuity of initiatives even during changes in local leadership or government, and facilitates smoother access to state-level support when needed. The case of PCMC demonstrates how embedding national policy priorities into local planning strengthens accountability, reduces resistance to scaling, and increases resilience in implementation. Other cities should consider institutionalizing similar alignment mechanisms like CSCAF audits, Comprehensive Environmental Pollution Index (CEPI) tracking, or sector-specific climate action plans within their own policy planning cycles. However, regulatory alignment alone is not sufficient. Public finance must also be reoriented to support climate goals. PCMC achieved this through the creation of a climate budget and the issuance of municipal green bonds. Incorporating climate considerations into fiscal systems does more than earmark funds it enhances transparency, attracts external investment, and ensures that spending is tied to measurable outcomes. Scaling the climate budget model to other cities is crucial not only because it embeds accountability into budgetary governance, but also because it drives outcome-focused planning, unlocks new financial pathways, and reinforces sectoral integration. For this to succeed, cities will need targeted capacity building, particularly within municipal finance and sectoral departments, to track, monitor, and manage climate-linked expenditures effectively. Equally important is the role of partnerships and non-state actors in enabling climate action. PCMC's collaboration with international institutions such as GIZ, UNEP, and IFC brought in global technical expertise, knowledge-sharing mechanisms, and innovative methodologies that strengthened local climate planning. Embedding these forms of collaboration into national urban programs can institutionalize a more outward-looking and adaptive planning culture. Cities must also allocate dedicated staff capacity to manage external engagements and translate global tools into local solutions. In addition, partnerships with civil society, technical institutions, and design consultants have helped PCMC bridge the implementation gap, particularly in initiatives requiring broad citizen outreach such as waste segregation, composting, or green mobility. These actors serve as important delivery arms where local governments face resource or manpower constraints. Finally, the presence of a climate-focused leader such as Commissioner Shekhar Singh IAS has been vital in maintaining strategic momentum, embedding long-term vision, and steering reform across departments. For other cities, building leadership whether through individuals or institutional champions is essential to ensure that urban climate planning is collaborative, systematic, data-driven, and inclusive of residents, whose participation remains central to translating policy into meaningful change.

Conclusion

Pimpri Chinchwad's experience demonstrates that Tier II cities, despite limited resources, can lead on climate-smart urban governance when strategic alignment, innovative financing, and participatory models are in place. PCMC's success lies in its integration of national frameworks, climate budgeting, global-local partnerships, citizen involvement, and strong institutional leadership. The city's shift from sectoral to systemic governance reflects a replicable model for other fast-growing Indian cities seeking inclusive, low-carbon, and resilient development. However, bridging gaps in citizen awareness, interdepartmental coordination (particularly in water and energy sectors), and implementation visibility remains essential for scaling such models nationally.

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Assessing Climate Risk Exposure in the Built environment

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Executive Summary

This study explores the climate-related vulnerabilities facing the Indian real estate sector, with a focus on both transition and physical risks across its supply chain. Anchored in the Task Force on Climate-related Financial Disclosures (TCFD) framework, the research aims to assess how evolving climate policies, such as energy codes and green building norms, pose transition risks to real estate operations. In parallel, it evaluates physical climate hazards, including flooding, heat stress, and drought in critical Indian districts where a real estate company maintains assets.

Using scenario analysis tools such as ThinkHazard, Climate Impact Explorer, and the Climate Change Knowledge Portal, the study models climate impacts under two contrasting pathways: SSP1 2.6 (optimistic) and SSP5 8.5 (pessimistic) for the years 2030 and 2050. The analysis identifies significant district-level vulnerabilities: Chennai faces heightened risks of flooding and heat stress; Ernakulam is prone to flooding; Bengaluru confronts chronic water scarcity; and Gandhinagar is exposed to multiple climate hazards.

A focused financial impact analysis for Bengaluru projects a 14% increase in water bills by 2030, driven by regulatory tariff changes, demonstrating the economic consequences of climate stress. The findings underscore the importance of early risk identification to support climate-resilient infrastructure planning, informed investment decision making, and alignment with India's long-term low-carbon growth trajectory. Proactively addressing these risks is no longer optional; it is essential for future-proofing real estate assets in a climate-constrained world.

Context & Problem Statement

Despite growing recognition of climate change as a critical concern, there remains a limited understanding of how both transition and physical climate risks concretely manifest within the Indian real estate sector. While global efforts increasingly prioritise decarbonising the built environment, much of the existing literature and practice has been shaped by experiences in developed economies, where institutional capacity, enforcement mechanisms, and access to green finance are relatively stronger. This leaves a substantial knowledge gap in emerging markets like India, where real estate is not only a major contributor to national emissions but also a key enabler of rapid urban growth and infrastructure development.

This issue matters profoundly in the Indian context. Environmentally, the country faces acute climate threats such as extreme heat, erratic rainfall, flooding, and water stress that have direct implications for building safety, occupant health, and urban liveability. Socially, the real estate sector shapes the living and working environments of millions, and climate-resilient infrastructure is essential to protect vulnerable populations.

Economically, the sector represents a major source of employment and investment, yet it is increasingly exposed to risks that could disrupt construction timelines, inflate operational costs, and devalue assets. Politically, India's national commitments

under the Paris Agreement, including net zero by 2070 and updated Nationally Determined Contributions, are driving stricter regulatory oversight, which makes it imperative for developers to align with evolving standards.

However, the sector still lacks integrated risk assessment approaches that combine forward-looking scenario analysis, localised hazard data, and policy evaluation. There is also a gap in practical tools that help real estate players translate climate targets into business strategy and operational resilience. This research responds to those gaps by mapping transition risks across the supply chain and analysing district-specific climate vulnerabilities using scenario-based methods. It aims to generate actionable insights that can inform better decision-making, drive climate-aligned investments, and support the long-term resilience of urban infrastructure in India.

Literature Review

The real estate sector accounts for about 34 percent of global energy-related CO_2 emissions, driven by both embodied carbon from materials like cement and steel and operational emissions from building energy use. The sector is currently off track to meet the Paris Agreement's 2030 emissions reduction target, placing it under growing pressure to decarbonise rapidly (2024/25 Global Status Report for Building and Construction).

- **Transition Risk Analysis for Real Estate Initiatives in India for the Real Estate sector (UNEP FI, 2023):**

In India, regulatory frameworks such as the Energy Conservation Building Code (ECBC) and Eco Niwas Samhita (ENS) aim to enhance energy efficiency in commercial and residential buildings. Voluntary schemes like the Star Rating Program and the Energy Label for Homes promote benchmarking. Emerging tools like the Carbon Credit Trading Scheme indirectly impact real estate by regulating upstream sectors like steel and cement. Meanwhile, SEBI's BRSR framework and global standards like TCFD and GHG Protocol are pushing developers toward transparent climate disclosures (Bureau of Energy Efficiency, no date),

There is a growing shift in market preferences toward energy-efficient and climate-resilient buildings, often supported by green certifications like GRIHA and LEED. These structures not only reduce operating costs but also improve access to incentives. Regulatory programs such as ECBC and national initiatives like UJALA promote efficient HVAC and lighting systems. Rooftop solar readiness is also gaining momentum through mandates in ECBC and Model Building Bye Laws (Bureau of Energy Efficiency, 2011), (MoHUA, 2016).

Transition risks, as defined by TCFD, fall under four key categories: policy and legal risks from evolving standards; technology risks linked to obsolete systems; market risks due to shifting demand and rising costs; and reputational risks from poor climate performance (Task Force on Climate-related Financial Disclosures, 2017)

Each phase of the real estate supply chain—from raw material extraction and transport to construction, operation, and end of life—carries its own emissions footprint. High emission inputs like cement and aluminium remain difficult to replace, while transportation and construction add further embodied carbon. Circular practices such as retrofitting and reuse are emerging but remain limited in scale (**The supply chain detailing is based on stakeholder consultation)

- **Physical Risk Analysis for Real Estate**

To assess long-term exposure to physical risks, this study adopts the IPCC's SSP–RCP framework. Scenario analysis enables firms to assess asset exposure to climate risks under different future conditions and develop adaptive strategies. Real estate is location-bound and long-lived, making it highly sensitive to extreme weather and chronic environmental stress. (Task Force on Climate-related Financial Disclosures, 2017). Scenario analysis helps developers evaluate asset vulnerability under varying climate futures.

The study uses the Climate Vulnerability Index (CVI) and peer-reviewed data to identify at-risk districts. Chennai faces high exposure to flooding and heat (State Planning Commission, Tamil Nadu, 2024). Ernakulam is prone to flooding, exacerbated by poor drainage (Xavier et al., 2019; Cherian et al., 2024). Bengaluru suffers from chronic water stress due to unregulated urbanisation (Raghuram, 2024). Gandhinagar is a multi-hazard hotspot, facing floods, heatwaves, and droughts with limited adaptive capacity (Times of India, 2024).

Together, these findings underline the need for real estate developers to integrate both transition and physical climate risks into planning, design, and investment strategies.

Research Focus and Methodology

Objectives:

- To identify transition risks across the Real Estate supply chain and conduct a scenario analysis to assess the vulnerability of districts hosting company assets.
- To recommend mitigation strategies for transition and physical risks
- To conduct a financial impact assessment of a physical climate risk to the company

Overview of Methodology:

1. Scenario Analysis

Company XXX, a real estate firm with 25 assets across four Indian states, faces exposure to physical climate risks including flooding, extreme precipitation, rising temperatures, and water stress. Due to limited asset-level climate data, the analysis uses district and state-level indicators, aligning with TCFD's guidance to begin with broad, qualitative scenario assessments. Two climate scenarios—SSP1 2.6 (optimistic) and SSP5 8.5 (pessimistic)—are applied across 2030 and 2050 to explore how climate change could impact the portfolio over time. While it does not estimate financial losses, the study offers a foundational risk outlook to guide long-term resilience planning. Future iterations may include geospatial mapping and third-party climate tools for more precise analysis.

Use of Tools to obtain values

ThinkHazard provides present-day assessments of natural hazard risks like floods, droughts, and cyclones using a simple four-level rating system. It draws from global datasets and is ideal for early-stage planning and site screening. The site can be accessed here.

The Climate Impact Explorer (CIE) models how climate risks such as heat stress, drought, and water scarcity may evolve under different global warming levels (+1.5°C, +2°C, +3°C). Based on SSP scenarios like SSP1 2.6 and SSP5 8.5, it integrates climate and sector-specific models to support forward-looking adaptation planning. The site can be accessed here.

The Climate Change Knowledge Portal (CCKP) offers both historical climate trends and high-resolution projections of future risks, including temperature and precipitation changes. It supports scenario-based planning under SSP1 2.6, SSP2 4.5, and SSP5 8.5, making it valuable for detailed, region-specific resilience strategies. The site can be accessed here.

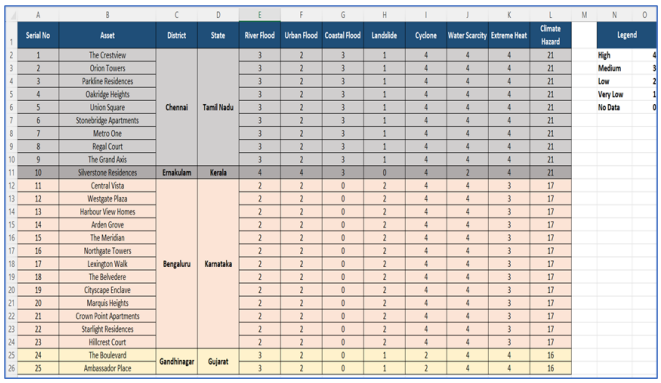
1. ThinkHazard:

ThinkHazard is a location-based tool that assesses natural hazard risks such as floods, droughts, and cyclones using a simple rating scale from very low to high. It supports early-stage planning by helping identify physical climate risks relevant to asset durability, insurance considerations, and site design in the real estate sector.

Methodology of ThinkHazard: The tool classifies hazards into four risk levels—very low, low, medium, and high—using global scientific datasets from sources like NASA and the Global Flood Database. These risk levels are determined based on hazard probability and intensity, in line with international disaster modeling standards (GFDRR, no date)

Indicators chosen: River flood, Urban flood, Coastal flood, Landslide, Cyclone, Water scarcity, Extreme Heat.

*Indicators in Think Hazard are chosen based on the Literature Review on hazards affecting districts where assets are located.



Serial No	Asset	District	State	River Flood	Urban Flood	Coastal Flood	Landslide	Cyclone	Water Scarcity	Extreme Heat	Climate Hazard
1	The Crestview	Chennai	Tamil Nadu	3	2	3	1	4	4	4	21
2	Orion Towers			3	2	3	1	4	4	4	21
3	Parkline Residences			3	2	3	1	4	4	4	21
4	Oakridge Heights			3	2	3	1	4	4	4	21
5	Union Square			3	2	3	1	4	4	4	21
6	Stonebridge Apartments			3	2	3	1	4	4	4	21
7	Metro One			3	2	3	1	4	4	4	21
8	Regal Court			3	2	3	1	4	4	4	21
9	The Grand Axis			3	2	3	1	4	4	4	21
10	Silverstone Residences	Ernakulam	Kerala	4	4	3	0	4	2	4	21
11	Central Vista	Bengaluru	Karnataka	2	2	0	2	4	4	3	17
12	Westgate Plaza			2	2	0	2	4	4	3	17
13	Harbour View Homes			2	2	0	2	4	4	3	17
14	Arden Grove			2	2	0	2	4	4	3	17
15	The Meridian			2	2	0	2	4	4	3	17
16	Northgate Towers			2	2	0	2	4	4	3	17
17	Lexington Walk			2	2	0	2	4	4	3	17
18	The Belvedere			2	2	0	2	4	4	3	17
19	Cityscape Enclave			2	2	0	2	4	4	3	17
20	Marquis Heights			2	2	0	2	4	4	3	17
21	Crown Point Apartments			2	2	0	2	4	4	3	17
22	Starlight Residences			2	2	0	2	4	4	3	17
23	Hillcrest Court			2	2	0	2	4	4	3	17
24	The Boulevard	Gandhinagar	Gujarat	3	2	0	1	2	4	4	16
25	Ambassador Place			3	2	0	1	2	4	4	16

Legend	
High	4
Medium	3
Low	2
Very Low	1
No Data	0

Figure 1: Data obtained from ThinkHazard for region specific exposure to physical hazard

2. Climate Impact Explorer:

The Climate Impact Explorer (CIE), developed by Climate Analytics, is an online platform that visualises how climate change may impact regions through key physical risks such as heat, drought, floods, and crop loss. It supports adaptation and resilience planning by enabling users to assess risks under varying global warming levels.

Methodology of Climate Impact Explorer: CIE integrates CMIP6 Global Climate Models with sector-specific models from ISIMIP to simulate the effects of climate change on agriculture, water, and ecosystems. It presents projections for warming thresholds (+1.5°C, +2°C, +3°C) based on SSP scenarios like SSP1 2.6 and SSP5 8.5. Results are bias corrected, averaged across models, and offer region-specific insights grounded in scientific research. (Climate Analytics, no date)

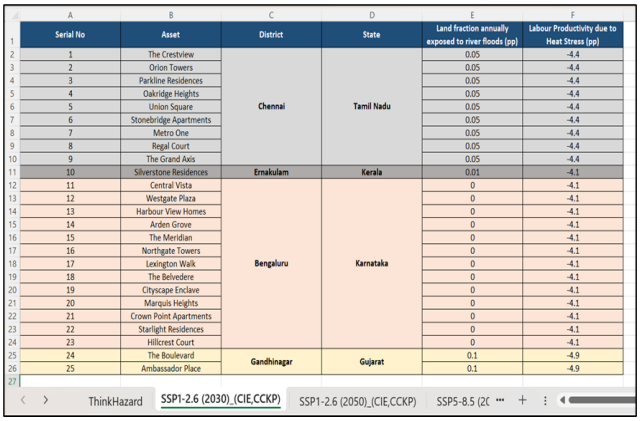
Indicators chosen: Land fraction annually exposed to river floods, Labour productivity due to heat stress

*Indicators in CIE and CCKP are chosen based on stakeholder consultation.

**We note the values on how the chosen indicator acts out, in a particular state, in an SSP1 2.6 and SSP5 8.5 scenario by 2030 and 2050.

3. Climate Change Knowledge Portal

Developed by the World Bank, the Climate Change



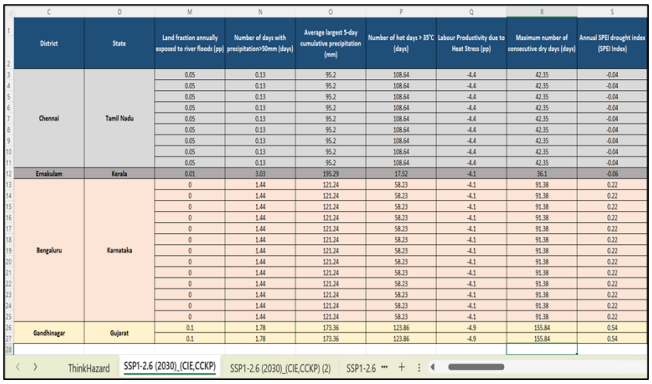
Serial No	Asset	District	State	Land fraction annually exposed to river floods (pp)	Labour Productivity due to Heat Stress (pp)
1	The Crestview	Chennai	Tamil Nadu	0.05	-4.4
2	Orion Towers			0.05	-4.4
3	Parkline Residences			0.05	-4.4
4	Oakridge Heights			0.05	-4.4
5	Union Square			0.05	-4.4
6	Stonebridge Apartments			0.05	-4.4
7	Metro One			0.05	-4.4
8	Regal Court			0.05	-4.4
9	The Grand Axis			0.05	-4.4
10	Silverstone Residences	Ernakulam	Kerala	0.01	-4.1
11	Central Vista	Bengaluru	Karnataka	0	-4.1
12	Westgate Plaza			0	-4.1
13	Harbour View Homes			0	-4.1
14	Arden Grove			0	-4.1
15	The Meridian			0	-4.1
16	Northgate Towers			0	-4.1
17	Lexington Walk			0	-4.1
18	The Belvedere			0	-4.1
19	Cityscape Enclave			0	-4.1
20	Marquis Heights			0	-4.1
21	Crown Point Apartments			0	-4.1
22	Starlight Residences			0	-4.1
23	Hillcrest Court			0	-4.1
24	The Boulevard	Gandhinagar	Gujarat	0.1	-4.9
25	Ambassador Place			0.1	-4.9

Figure 2: Data obtained from CIE for 2 indicators

Knowledge Portal (CCKP) offers open access data on past climate trends, future projections, and sectoral vulnerabilities. It supports informed decision-making for site selection, design, and resilience planning in sectors like real estate.

Methodology of Climate Change Knowledge Portal: CCKP uses historical data from CRU TS v4.08 and ERA5, combining station data with reanalysis models for accuracy. Projections are based on CMIP6 GCM outputs under SSP1 2.6, SSP2 4.5, and SSP5 8.5 scenarios. These are bias corrected and statistically downscaled to 0.25° resolution using quantile mapping. Results are presented as multi-model ensembles with median values and uncertainty ranges to guide regional adaptation strategies (World Bank, no date).

Indicators chosen: Number of hot days > 35°C, maximum number of consecutive dry days, Annual SPEI drought index, Average largest 5-day cumulative precipitation, Number of days with precipitation >50mm.



District	State	Land fraction annually exposed to river floods (pp)	Number of days with precipitation>50mm (days)	Average largest 5-day cumulative precipitation (mm)	Number of hot days > 35°C (days)	Labour Productivity due to Heat Stress (pp)	Maximum number of consecutive dry days (days)	Annual SPEI drought index (SPEI Index)
Chennai	Tamil Nadu	0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
		0.05	0.13	95.2	108.64	-4.4	42.35	-0.04
Ernakulam	Kerala	0.01	3.03	195.29	17.52	-4.1	36.1	-0.06
Bengaluru	Karnataka	0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
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		0	1.44	121.24	58.23	-4.1	91.38	0.22
		0	1.44	121.24	58.23	-4.1	91.38	0.22
Gandhinagar	Gujarat	0.1	1.78	173.36	123.86	-4.9	155.84	0.54
		0.1	1.78	173.36	123.86	-4.9	155.84	0.54

Figure 3: Data obtained from CCKP for 5 indicators

Critical limitation: Data is available for the state level in CIE and CCKP. District-level granularity is absent. Hence, data obtained for the state is assumed to be true for the district. To overcome the limitation to a certain extent, a literature review is performed to understand if the indicators grouped under precipitation risk, water scarcity risk, temperature risk, and climate hazards risk hold true for the district. If the risks are core to the district, the values are based on a review of literature, and core indicators remain true for the district.

Normalisation of views: To enable consistent comparison across indicators with different units and scales, this study applies min-max normalisation. This scales all values between 0 and 1, ensuring no single indicator dominates due to its original range. For metrics where lower values imply higher risk (e.g., heat-induced labour productivity loss), reverse normalisation is used to maintain correct risk direction. This standardisation is key for integrating diverse climate indicators into a unified assessment framework for climate-resilient planning.

Normalised indicators are then organised into four risk dimensions: precipitation, water scarcity, temperature, and climate hazards. Relevant indicators within each category are summed to generate composite scores, capturing the cumulative climate stress in each domain. This approach allows for balanced and comparative multi-hazard risk analysis.

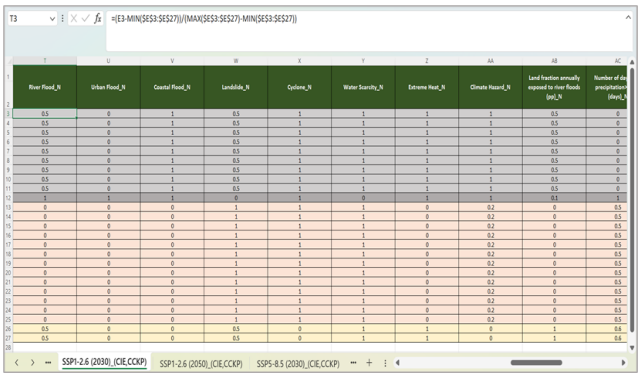


Figure 4: Normalisation of all indicators taken from ThinkHazard, CIE, CCKP

Financial implications of climate risks (water stress):

Water Withdrawal Trend and Projections: Company data shows an 8% increase in third-party water withdrawal from FY 2023 (6,23,607 KL) to FY 2024 (6,73,709 KL). Assuming this 8% annual increase continues, total withdrawal by 2030 is projected at 10,69,041 KL/year. With 25 assets, this translates to:

- 2024: 2,245.69 KL/month per asset
- 2030: 3,563.47 KL/month per asset

City Focus: Bengaluru – Water Stress and Tariff Impact: Bengaluru is selected for financial impact analysis due to chronic water stress, exacerbated by urban growth and climate change (Mohan et al., 2024). In 2025, BWSSB revised tariffs after 11 years, aiming to promote water efficiency (Deccan Herald, 2025).

3. NON-DOMESTIC (Clause 36(IV), Bangalore water supply regulations, 1965):

Sl.No.	Present Slab-wise consumption of water (In Kilo litres)	Present Tariff/KL (In Rs.)	Revised Slab-wise consumption of water (In Kilo litres)	Revised Tariff/KL (In Rs.)
1	MINIMUM 0-10	500.00 50	MINIMUM 0-10	600.00 60
2	10-25	57	10-25	70
3	25-50	65	25-50	80
4	50-75	76	50-75	95
5	75 & Above	87	76-100	98
6			100 & Above	99
Sanitary Charges for Non-domestic connection		25% of water supply charges per month	The existing sewerage charge of 25% on water charges will be increased by an additional 6.25% every quarterly and increase up to 25% at the end of the year 2025-26	

Figure 5: Revised Water Tariff_BWSSB (Water Tariff-2025)

Water Bill Calculations (Monthly, per asset):

- 2024 (old tariff): ₹1,93,730
- 2030 (old tariff): ₹3,08,377
- 2030 (revised tariff): ₹3,51,359

Result: A 14% increase in the monthly water bill from the 2030s old to revised tariff reflects rising financial pressure linked to regulatory action on water use in a water-stressed region.

Key Findings and Arguments

Transition Risks

1. Identification of Transition Risks in the Real Estate Sector: Direct Risks

Transition Risks	Related Policies/ Regulations and their reasoning
Policy & Legal	ECBC and MBBL become enforceable when notified locally; non-compliance may lead to penalties, legal action, and loss of approvals
	BRSR reporting is mandated by SEBI; non-compliance risks legal scrutiny and penalties.
	Delay in adopting ECBC-mandated systems (HVAC, lighting) may cause legal non-compliance and retrofit costs.
Market	PAT and CCTS increase the costs of materials like cement and steel, indirectly raising construction expenses.
	Failure to align with green norms (e.g., ENS) may reduce market competitiveness in energy-conscious regions.
Reputation	Poor or missing BRSR reporting weakens brand credibility and investor trust.
	Lack of ENS adoption may harm perception among eco-aware consumers.
	Absence of green certifications (GRIHA, LEED) may reduce buyer interest, incentives, and long-term value.
Technology	Outdated systems (non-efficient HVAC, DG sets) may lead to obsolescence, forced retrofits, and compliance issues.
	Not planning for rooftop solar (per ECBC, MBBL) may reduce adaptability and increase future retrofit costs.

2. Identification of Transition Risk along the supply chain of Real Estate

As the construction sector shifts toward low emissions, transition risks arising from policies, markets, and technologies affect every stage of the supply chain. These risks can influence project costs, timelines, and long-term value.

Raw Material Processing and Manufacturing: High Emissions at the Source

Real estate materials like cement, steel, aluminium, and glass are carbon-intensive and hard to decarbonise. While developers aren't directly regulated, policies like the Carbon Credit Trading Scheme (2026) will increase upstream costs, exposing developers to indirect market risk via higher prices and procurement uncertainty.

Material Transportation and Logistics:

In regions like Delhi NCR, air quality regulations (e.g., GRAP) suspend construction and restrict truck entry during pollution spikes. While this helps reduce emissions, it causes project delays, income loss for workers, and cash flow issues. Under RERA, developers face legal liabilities if delays impact delivery timelines, making external environmental policy a policy and legal risk with potential financial and reputational consequences.

Construction and Site Assembly

Transition risks here include:

- **Policy and Legal Risk** from mandatory compliance with ECBC and MBBL
- **Technology Risk** from phase-outs of outdated systems (e.g., diesel gensets)
- **Market Risk** due to higher costs for compliant technologies
- **Reputation Risk** if projects lack green certifications like LEED or GRIHA, affecting buyer interest and incentives

3. District Vulnerability Assessment via Scenario Analysis

The following section presents district-wise climate risk profiles for 2030 and 2050 under low (SSP1 2.6) and high (SSP5 8.5) emissions scenarios. Graphs and tables compare literature-identified risks with scenario-based projections, helping developers assess how location-specific vulnerabilities evolve and plan climate-resilient investments accordingly.

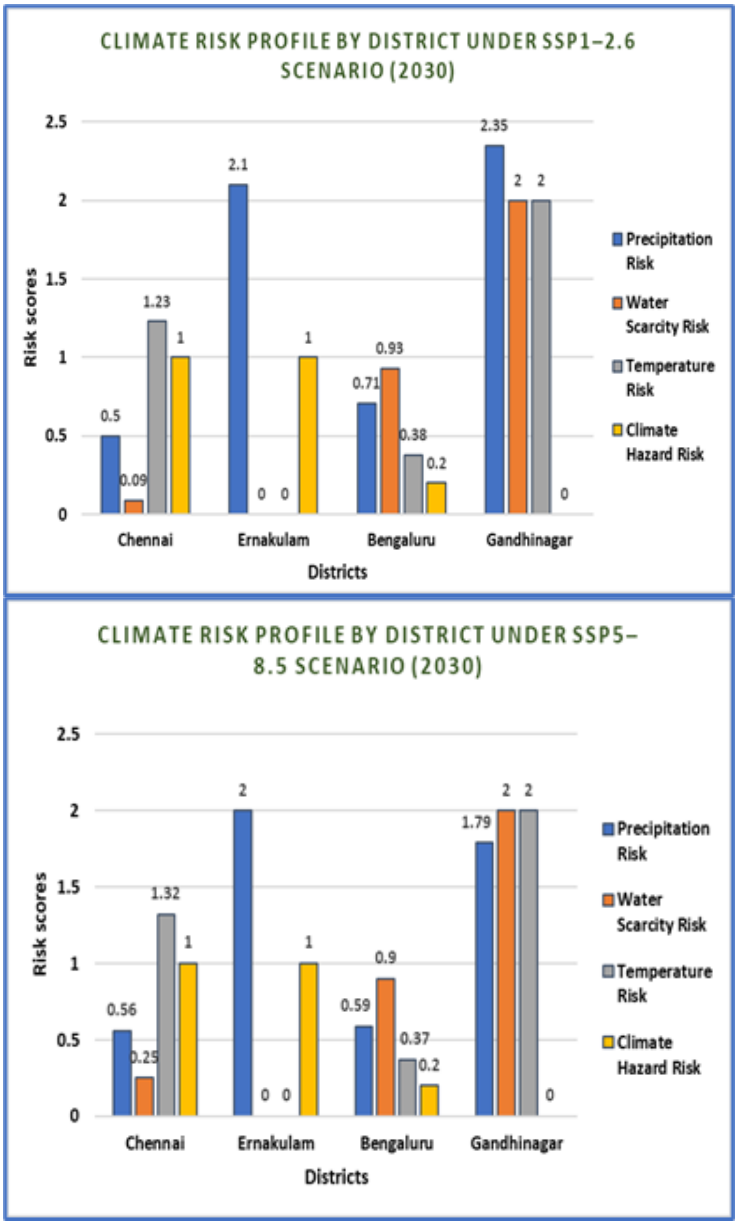


Figure 6: Climate Risk Profile by district under SSP1 2.6 & SSP5 8.5 Scenario (2030)

4. Financial impact of water stress

Regulatory changes and revised tariffs in water stressed areas can significantly impact real estate costs. In Bengaluru, a projected 14% hike in monthly water bills by 2030 highlights the near term financial impact on developers.

Construction and Site Assembly

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Physical Risks

3. District Vulnerability Assessment via Scenario Analysis

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Table 1: District-wise Comparison of Literature-Identified Climate Risks and Projected Risk Changes under SSP1–2.6 and SSP5–8.5 Scenarios by 2030

District	Literature-Identified Risks	Precipitation Risk	Water Scarcity Risk	Temperature Risk	Climate Hazard Risk	Conclusion
Chennai	Flood, Cyclone, Heat	Moderate in SSP1; **increases** in SSP5	Very low in both SSPs	High in SSP1; **increases** in SSP5	Consistently high	Core risks remain **flooding and heat**; intensity grows in SSP5
Ernakulam	Flood, Heavy Rainfall, Cyclone, Drought	High in both SSPs	Very low in both SSPs	Negligible in both SSPs	Consistently high	Flood and rainfall risks **persist**; drought underrepresented in projections
Bengaluru	Urban Flood, Drought, Cyclone, Water Stress	Moderate in both SSPs	**High in both SSPs**, aligning with literature	Moderate and steady	Moderate	Water stress is the **dominant risk**, consistent across pathways
Gandhinagar	Precipitation Variability, Water Stress, Heat	High in SSP1; **slightly reduced** in SSP5	**Very high in both SSPs**, indicating chronic scarcity	**Extremely high** in both scenarios	Consistently high	A **multi-hazard hotspot** with sustained risk across all emissions pathways

The district-wise analysis shows Chennai faces escalating flood and heat risks, especially under high emissions. Ernakulam remains vulnerable to flooding, though drought risks are underreported. Bengaluru consistently shows severe water stress across scenarios. Gandhinagar emerges as a multi-hazard hotspot with high exposure to heat, water scarcity, and rainfall variability.

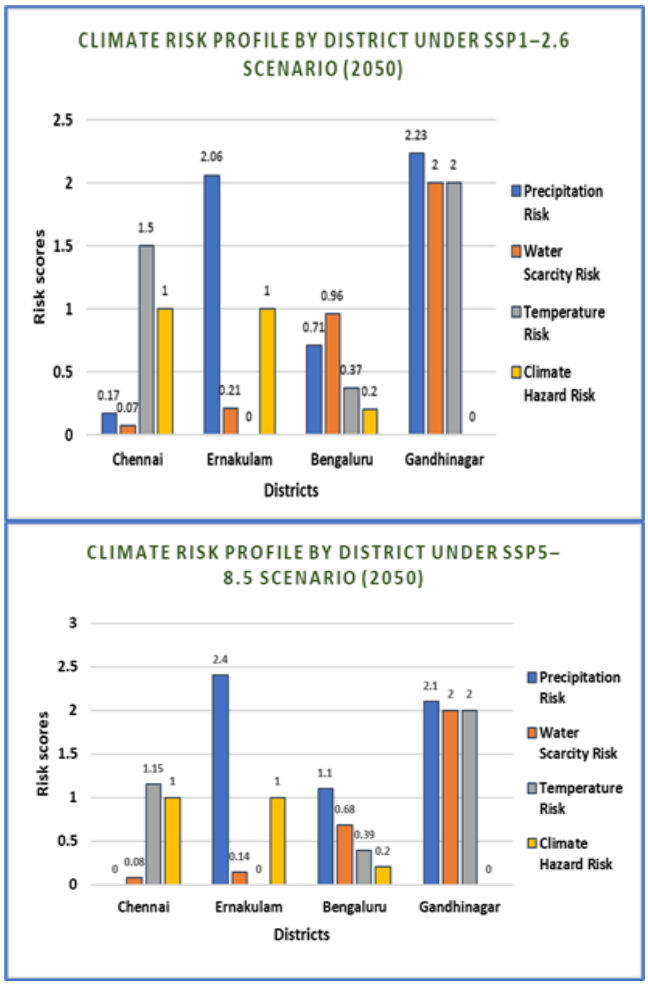


Figure 7: Climate Risk Profile by District under SSP1 2.6 & SSP5 8.5 Scenario (2050)

By 2050, climate risks will intensify across all districts. Chennai sees heightened flood and heat threats under high emissions. Ernakulam remains prone to floods, with drought still underrepresented. Bengaluru's chronic water stress persists across scenarios. Gandhinagar continues as a multi-hazard hotspot with consistently high, overlapping risks.

4. Financial impact of water stress

Regulatory changes and revised tariffs in water stressed areas can significantly impact real estate costs. In Bengaluru, a projected 14% hike in monthly water bills by 2030 highlights the near term financial impact on developers.

Policy and Practice Implications

Physical Risks

1. Key Takeaways

Heat, floods, and water stress directly affect construction, labour productivity, and water availability—demanding adaptive design and resilient operations. (ACI, 2010; ComplianceQuest, 2023).

2. Recommendations:

- Enforce climate responsive design (shading, ventilation, thermal mass).
- Mandate water reuse and rainwater harvesting in high stress zones.
- Integrate green infrastructure for flood management.

Transition Risks

I. Key Takeaways

Evolving policies and material shifts pose cost, compliance, and reputational risks—developers must stay ahead of the curve.

Table 2: District-wise Comparison of Literature-Identified Climate Risks and Projected Risk Changes under SSP1–2.6 and SSP5–8.5 Scenarios by 2050

District	Literature-Identified Risks	Precipitation Risk	Water Scarcity Risk	Temperature Risk	Climate Hazard Risk	Conclusion
Chennai	Flood, Cyclone, Heat	Very low in both SSPs	Remains very low	Decreases in SSP5	Remains constant	**Heat remains a dominant risk**, while lower precipitation risk may not reduce flood vulnerability, as urban flooding is often driven by poor drainage and infrastructure limitation overall risk profile stays high.
Ernakulam	Flood, Drought, Cyclone, Heavy Rainfall	Increases in SSP5	Very low in both SSPs	Remains negligible	Remains consistently high	**Flood-related risks continue to dominate**; drought underrepresented in projections despite strong presence in literature.
Bengaluru	Flood, Drought, Cyclone, Water Stress	Increases in SSP5	Remains high	Increases in SSP5	Remains constant	**Water stress remains chronic**; slight relief in precipitation risk may reflect variability in rainfall, but heat and cumulative stressors remain significant.
Gandhinagar	Precipitation Extremes, Water Stress, Heat	Decreases in SSP5	Remains high	Remains high	Remains constant	**Remains a multi-hazard hotspot** with persistent, high risk across emissions scenarios; mitigation efforts have limited impact on extreme conditions.

2. Recommendations:

- Develop standards for bio-based materials (bamboo, timber, biomass) (UNEP and Yale CEA, 2023)
- Ensure early adoption of ECBC, MBBL, and green certifications.
- Promote ESG disclosures to enhance credibility and attract green finance.

Conclusion

This research highlights the critical importance of recognising both transition and physical climate risks within the real estate sector. Mapping these risks across the supply chain and conducting district-level scenario analysis offers valuable insights into how climate vulnerabilities manifest spatially and evolve. In doing so, it provides a practical foundation for developers, investors, and policymakers to align infrastructure development with long-term climate resilience and regulatory readiness.

The core message is that climate risk is no longer peripheral to real estate—it must be integrated into core decision-making processes. Developers who proactively address these risks are better positioned to safeguard asset value, ensure compliance, and maintain competitiveness in a carbon-constrained future. Incorporating climate data into site selection, design, and water management strategies is no longer optional but essential. Future efforts should focus on refining risk assessments through geospatial modelling and expanding financial analysis across more geographies. There is also a need for greater adoption of adaptive technologies, especially in water stressed regions, to ensure operational continuity and regulatory alignment. As climate challenges intensify, such forward looking approaches will be key to building a resilient and sustainable real estate sector

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Reimagining Wastewater Governance for Small and Semi-Urban Towns in India

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Executive Summary

The Kodaganar River originates from the eastern slopes of the Palani Hills, flows through the town of Vedasandur in Dindigul district, Tamil Nadu, India, before joining the Kaveri River. Although a greywater drainage system was constructed in Vedasandur in the early 2000s, the absence of a wastewater treatment facility has led to the direct discharge of untreated greywater into the river through 22 drain end points (DEPs).

This study assesses the water quality in the Kodaganar River and the wastewater that is discharged into it by analysing key water quality parameters, including pH, dissolved oxygen (DO), biochemical oxygen demand over three days (BOD_3), chemical oxygen demand (COD), faecal coliforms, total suspended solids (TSS), nitrate-nitrogen (NO_3-N), electrical conductivity, total alkalinity, phosphorus and chloride. Longitudinal sampling was conducted at eight strategic locations along the river - upstream, within Vedasandur, and downstream (including the inlet and outlet of the Alagapuri Dam). Wastewater samples were collected from the 11 drain endpoints (DEPs) that have significant flow and discharge directly into the river.

The results revealed critically low DO levels downstream (as low as 0.7 mg/l), high faecal coliform concentrations (up to 108,000 CFU/100 ml), and sustained ionic pollution through the town stretch. A QUAL2Kw model was developed and calibrated (with a fitness of 0.9036) to simulate pollutant dynamics, revealing the limited self-purification capacity of the river and the compounding role of the Alagapuri Dam in trapping pollutants.

This position paper argues that current governance mechanisms are inadequate to address the specific wastewater challenges faced by India's small towns. It recommends urgent investment in decentralised wastewater treatment units (DWWTs), the establishment of town-level river health governance bodies, and the institutionalisation of water quality modelling in local planning frameworks.

Context & Problem Statement

India's rivers, both major and minor, are under increasing pressure from urban expansion, industrial discharge, and inadequate sanitation infrastructure. While much of the national attention has focused on greater river systems such as the Ganga and Yamuna through flagship programmes like the Namami Gange Mission, smaller rivers and semi-urban areas remain under-monitored and poorly understood. This neglect is particularly problematic as smaller towns are now among the fastest-growing urban centres in India, with urbanisation and demographic pressures outpacing institutional capacity and infrastructural planning.

Vedasandur, located in Dindigul district, Tamil Nadu, is emblematic of this overlooked geography. With a population of approximately 14,000, the town falls under the jurisdiction of a Town Panchayat. The town generates close to 1.5 million litres of greywater per day, most of which originates from household activities such as bathing, laundry, and dishwashing. Unlike metropolitan areas, Vedasandur lacks even a basic sewage treatment facility. In the early 2000s,

the town initiated the construction of a drainage system intended primarily for stormwater. However, in the absence of any wastewater treatment facility, this network has evolved into an informal conduit for domestic greywater and sewage, which is discharged either directly into the Kodaganar River or onto adjacent open land through identified drain end points (DEPs).

This study seeks to fill this critical knowledge gap by generating baseline data on the Kodaganar River's water quality, identifying critical points of pollution, and proposing mitigation and intervention strategies. The broader objective is to demonstrate why and how wastewater governance in small towns must evolve to include science-based planning, decentralised infrastructure, and inter-agency coordination.

Executive Summary

River water pollution is a major global environmental concern, affecting both developed and developing countries. In India, the situation is particularly critical, with approximately 70% of the available surface water reported to be polluted, leading to serious ecological, public health, and economic consequences (Panda et al., 2018).

The primary contributors to riverine pollution in India include the continuous discharge of untreated or inadequately treated sewage, industrial effluents containing hazardous chemicals, agricultural runoff, mining activities, oil spills, and solid waste dumping. Nutrient enrichment from these sources also leads to eutrophication, further degrading water quality (Williams, 2018). In addition, open defecation and the improper disposal of biomedical waste introduce significant physical, chemical, and microbial contaminants into river systems (Panda et al., 2018).

Only 578 sewage treatment plants (STPs) across the country were found to comply with the regulatory standards set by the State Pollution Control Boards (SPCBs) and Pollution Control Committees (PCCs). Only 23% of the installed treatment capacity met the consented discharge parameters (CPCB, 2021). This highlights the gap between infrastructure availability and operational efficiency. In many cases, even functional treatment plants fail to deliver effective treatment, resulting in the continued discharge of inadequately treated or untreated wastewater into rivers.Riverine pollution significantly alters the chemical and biological characteristics of water, directly impacting its quality and ecological balance. One of the most critical consequences is the reduction in dissolved oxygen (DO) levels, primarily caused by elevated biological oxygen demand (BOD) and chemical oxygen demand (COD) resulting from the influx of sewage, industrial effluents, and organic waste. BOD serves as an indicator of organic pollution. As organic matter increases, BOD levels rise, leading to a corresponding decrease in DO (Panda et al., 2018). This oxygen depletion creates hypoxic conditions that can severely impair the survival of aquatic organisms, disrupt trophic structures and reduce biodiversity (Khan et al., 2021).

Proper treatment of sewage and industrial effluents prior to their discharge into water bodies is essential for mitigating river pollution. Despite initiatives such as the Ganga Action Plan and the adoption of technological tools, pollution levels continue to rise. This is largely due to the inadequate treatment capacity of sewage treatment plants (STPs), weak regulatory enforcement, and persistent non-compliance by industries (Singh et al., 2022).

Addressing these challenges require an integrated management approach that considers both natural processes and anthropogenic influences (Iqbal et al., 2019). Key strategies include expanding and upgrading sewage and effluent treatment infrastructure, enforcing pollution control regulations more stringently, and ensuring industry accountability through regular monitoring. Additionally, increasing public awareness, encouraging community participation, and leveraging advanced technologies – such as digital platforms for real-time river monitoring – can significantly enhance conservation efforts.

Numerous modelling tools have been developed to simulate water quality in rivers and support policy decision-making. Among them, QUAL2K and its updated variant, QUAL2Kw, developed by the United States Environmental Protection Agency (USEPA), are widely used for one-dimensional, steady-state simulations. QUAL2Kw accounts for complex biochemical interactions such as oxygen dynamics, nutrient cycling, and sediment oxygen demand, and includes an automatic calibration algorithm (PIKAIA)

that enhances model robustness (Noor et al., 2024). Studies in India (Parveen & Singh, 2016; Idris et al., 2016) have used QUAL2K to model segments of the Yamuna, Godavari, and Musi rivers, primarily in urban contexts.

However, the application of such models in smaller towns and for lesser-known rivers remains limited. There is a significant knowledge gap in understanding pollution transport and ecosystem responses in semi-urban contexts, where infrastructure is often informal, and point-source mapping is complex. Babamiri et al. (2021) demonstrated the model's flexibility by applying QUAL2Kw in the Abbasabad River, Iran. Their findings affirmed the model's applicability in assessing pollutant concentrations, decay rates, and intervention scenarios.

This study contributes to this underexplored domain by applying QUAL2Kw to simulate real-time pollution dynamics in the Kodaganar River. The approach is particularly significant because it demonstrates how a small dataset, collected under field constraints typical of semi-urban India, can be used to calibrate a reliable predictive model. In doing so, it offers a practical, low-cost blueprint for other small towns to follow. It also supports a broader rethinking of sanitation policy to integrate data-driven tools into decentralised governance systems.

Research Focus and Methodology

The central aim of this study is to assess the impact of untreated wastewater discharge from the town of Vedasandur on the water quality of the Kodaganar River and to explore the potential for mitigation using water quality modelling. This objective is grounded in the recognition that most small towns in India discharge greywater and sometimes blackwater directly into nearby water bodies without any treatment. Given the absence of formal wastewater management systems in such locations, the study focuses on three specific research objectives:

The specific objectives of this study are:

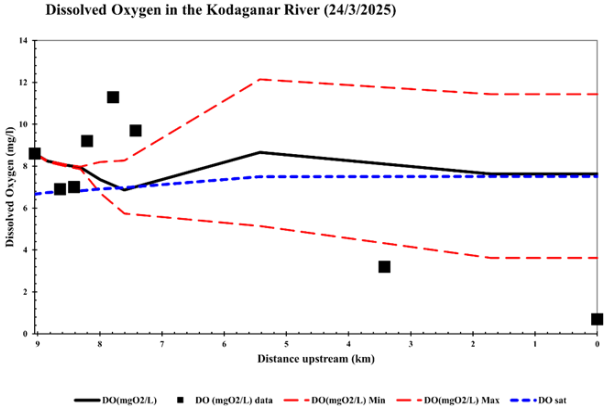
- To assess the impact of sewage discharge from the town of Vedasandur on the surface water quality of the Kodaganar River downstream.
- To identify critical points of pollution along the Kodaganar River resulting from drain outfalls within Vedasandur.
- To propose mitigation strategies to reduce and prevent the pollution of the Kodaganar River caused by untreated sewage discharge from Vedasandur.

The research design is based on a mixed-methods approach combining field data collection, laboratory analysis, and simulation modelling. Water quality sampling was conducted in March 2024 during the dry season to capture the worst-case scenario when river flow is minimal, and pollutant concentrations are likely to be highest. Eight sampling locations were chosen along the river—one upstream of the town, five within the town stretch, and two downstream of the Alagapuri Dam. In addition, wastewater samples were collected from eleven DEPs identified as having significant flow volumes.

The water samples were analysed for 14 parameters, including pH, electrical conductivity (EC), dissolved oxygen (DO), biochemical oxygen demand over 3 days (BOD_3), chemical oxygen demand (COD), faecal coliform (FC), total suspended solids (TSS), nitrate-nitrogen (NO_3-N), total phosphate, chloride, and alkalinity. Flow velocity measurements were taken at each river reach using the float method, and river cross-sectional profiles were estimated using a combination of field observation and Google Earth-based measurements.

The QUAL2Kw model was calibrated using its built-in PIKAIA genetic algorithm, which automatically estimates reaction rates and coefficients to optimise the fit between simulated and observed values.

1. **Severe decline in Dissolved Oxygen (DO)**



The model achieved a strong overall fitness score 0.9036. While independent model validation could not be conducted due to the lack of a separate dataset, the calibrated QUAL2Kw model provides a functionally representative baseline for how the Kodaganar River system behaves under existing conditions.

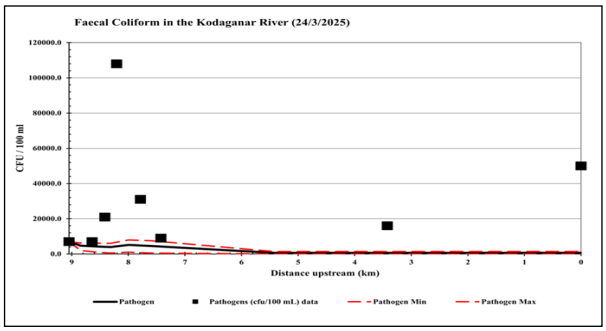
Key Findings and Observations

The empirical and modelling components of the study reveal an alarming pattern of water quality degradation in the Kodaganar River as it passes through Vedasandur. These findings underscore the severe environmental and public health risks posed by the current wastewater discharge practices and challenge the perception that small rivers possess sufficient self-purification capacity to mitigate untreated pollution loads.

Dissolved oxygen levels in the Kodaganar River exhibit a marked decline downstream of Vedasandur, reaching critically low concentrations near the Alagapuri Dam outlet. A minimum DO concentration of 6 mg/l is required for Class A water (drinking without treatment), and 5 mg/l for Class B (bathing purposes) (CPCB, 2008). Observed values downstream of the town fall well below these thresholds, with DO declining to 3.2 mg/l at the dam inlet and a dangerously low 0.7 mg/l at the dam outlet, indicating hypoxic conditions unsuitable even for Class D, which is water quality criteria for the purpose of propagation of wild life and fisheries). This pronounced DO sag reflects the cumulative impact of untreated greywater discharge from the 22 identified drain end points in Vedasandur.

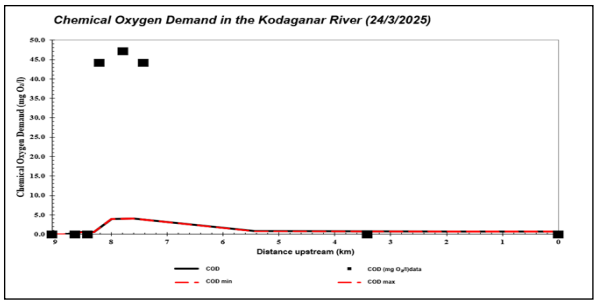
2. **Extremely high microbial contamination**

Faecal coliform concentrations far exceed CPCB standards throughout the river stretch. For Class A, B and C waters, faecal coliform counts should not exceed 50, 500 and 5000 CFU/100 ml, respectively (CPCB, 2008). Even the lowest concentration of faecal coliform (7000 CFU/100 ml) exceeds the concentration set for Class C waters (i.e., drinking water source after conventional treatment and disinfection). The study recorded 108,000 CFU/100 ml at RVS4, a site at which river water already carries the wastewater discharged from 4 DEPs with substantial flow, and where open defecation is consistently seen at the rocks within the river and by the banks. The persistently high levels of faecal coliform downstream confirm microbiological contamination well above acceptable limits for any designated use class. This is especially alarming given that some of the local population consume untreated river water downstream and that even within the town, the local population engage in fishing. These are activities that pose significant public health risks under such contamination levels (Skariyachan et al., 2015).



3. **Progressive increase in organic and chemical pollution**

Chemical oxygen demand (COD) levels were generally low or undetectable across upstream and midstream sites, but spiked sharply from RVS4 to RDS6. This correlates with the high concentration of faecal coliforms at RVS4 due to the confluence of 4 drain end points with substantial flow of greywater. Sustained elevated COD values between RVS4 and RDS6 suggest continuous organic loading over that segment. Though not part of CPCB criteria, COD serves as an indicator of pollution (Maitera et al., 2010).



Notably, electrical conductivity (EC) and alkalinity also showed significant fluctuations. EC peaked at 3900 µS/cm within the semi-urban stretch, reflecting high levels of dissolved ions - likely from detergents and cleaning agents. Alkalinity showed a dip at the reservoir inlet (178 mg/l), followed by a modest increase at the outlet (224 mg/l), suggesting carbonate-bicarbonate buffering processes affected by sedimentation and microbial respiration in stagnant waters.

4. Role of the Alagapuri Dam in exacerbating pollution

In addition to pollution load, the presence of the Alagapuri Dam further compounds the problem. Dam construction exerts complex and dynamic effects on river water quality, particularly influencing the river's natural self-purification processes (Wei et al., 2009). In the short term, reservoirs formed by dam tend to trap and accumulate pollutants, especially organic matter, which upon decomposition, consumes oxygen. This is exacerbated by the stagnant flow conditions, which significantly reduce aeration and hinder the exchange of oxygen between water and the atmosphere (Tyagi and Aggarwal, 2014)

Although some degree of self-purification may occur over time, long-term pollutant deposition and organic accumulation often lead to persistent oxygen depletion and degradation in water quality. The observed hypoxic conditions at the dam outlet suggest diminished self-purification capacity and illustrate the combined effect of unchecked sewage inflow and dam's role in impairing natural aeration processes.

5. Broader implications for semi-urban wastewater governance

The findings have implications that go beyond Vedasandur. First, they reveal that pollution in small rivers is not incidental or minor - it is severe, spatially concentrated, and persistent. Second, they suggest that scientific tools like QUAL2Kw, when combined with strategic sampling, can provide a strong basis for planning and monitoring.

Policy and Practice Implications

The findings of this study underscore the urgent need for targeted, scalable, and scientifically grounded interventions to improve wastewater governance in small semi-urban towns like Vedasandur. This section outlines five key recommendations - each informed by empirical evidence from the study and aligned with broader policy priorities under the Swachh Bharat Mission.

1. Establish a dedicated river management authority

There is an urgent need for the appointment of a responsible authority at the town level to oversee wastewater discharge and river health. The body should be empowered to monitor pollution sources, enforce wastewater regulations, and ensure regular data collection.

2. Establish Decentralised Wastewater Treatment Units (DWWTs)

One of the most actionable and cost-effective solutions is the implementation of decentralised treatment systems near high-flow DEPs. These systems - such as DEWATS (Decentralised Wastewater Treatment Systems), constructed wetlands, or phytoremediation zones—can significantly reduce BOD, COD, and faecal coliform loads before greywater reaches the river. In the Vedasandur context, out of the 11 drain end points that have substantial flow of wastewater into the river, a few have significantly greater discharge. Therefore, they can be prioritised for pilot DWWTs. These systems require minimal land and electricity, and their modular design makes them ideal for incremental scaling.

3. Integrate Water Quality Modelling into Local Planning

This study demonstrates that tools like QUAL2Kw can be effectively applied even in low-data contexts to identify pollution hotspots and evaluate potential interventions. Local governments should be trained to use such tools in their planning processes. A one-time investment in capacity building, training and software access can yield long-term planning benefits.

4. Prioritise Behavior Change and Public Engagement

While infrastructure is critical, behavioural change is equally important. Public awareness campaigns should be launched in local languages to discourage direct discharge of wastewater and promote hygienic practices. Schools and community groups can be involved in river clean-up drives, water quality testing, and street plays to raise awareness.

5. Strengthen Regulatory Enforcement and Data Transparency

Lastly, there is a need to enforce existing environmental regulations more stringently. There should be periodic water quality monitoring stations along the Kodaganar and the publishing of results online. Transparency and data-sharing can empower local communities and civil society organisations to hold authorities accountable.

It can also foster healthy competition between towns under schemes like Swachh Survekshan or AMRUT rankings, encouraging them to take proactive measures.

Conclusion

This study offers compelling evidence that semi-urban settlements like Vedasandur can no longer be treated as peripheral in India's water governance discourse. Through a combination of rigorous field-based water quality assessment and simulation modelling using QUAL2Kw, the research demonstrates how untreated domestic greywater has critically impaired the Kodaganar River's ecological function. The study reveals that even in the absence of industrial pollution, persistent discharge of untreated household effluents, especially when combined with infrastructural bottlenecks like flow stagnation caused by dams, can push small rivers toward ecological collapse. The case of Vedasandur exemplifies a systemic failure in wastewater governance: institutional fragmentation, inadequate investment, absence of treatment infrastructure, and lack of scientific tools in local planning. Yet it also presents an opportunity. The detailed mapping of drain endpoints and identification of pollution hotspots provide a tangible starting point for intervention. The successful calibration of the QUAL2Kw model in a low-data setting demonstrates that scientific tools are not beyond the reach of small-town administrations. Such tools need to be adapted and made accessible.

The Kodaganar River is not an isolated case. Hundreds of small rivers across India are witnessing similar trajectories of decline, often undocumented and unaddressed, with a complete absence of data on the water quality parameters. This research provides a replicable framework for identifying, assessing, and intervening in such contexts. Moving forward, it is essential that these approaches are considered within development policy, sanitation, and environmental regulation. Only then can India begin to secure the health of its rivers, both great and small.

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Integrating Indigenous Materials and Techniques into India's Climate-Resilient Architecture

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Executive Summary

India's construction sector contributes significantly to its carbon footprint, driven largely by the widespread use of energy-intensive materials like concrete and steel. With the dual pressures of climate change and rapid urbanization, there is an urgent need for contextually grounded, low-carbon alternatives in the built environment. This research critically examines the potential of indigenous building materials and techniques rooted in regional climatic adaptations and cultural traditions as scalable solutions for sustainable architecture in India.

The study adopted a multi-method approach combining a thematic literature review, Life Cycle Assessment (LCA), in-depth case study analysis, and 47 semi-structured interviews with architects, engineers, artisans, policymakers, and other key stakeholders across eight categories. Findings reveal that techniques such as rammed earth, Kath-Kuni, lime plaster, and bamboo-based systems demonstrate not only strong environmental performance but also the potential to support rural livelihoods, preserve traditional knowledge, and reduce urban heat stress.

LCA results confirm that indigenous materials have 60-80% lower embodied carbon compared to conventional alternatives. However, policy and certification frameworks, educational curricula, and market dynamics remain misaligned with these sustainable options. Artisans, though willing, face skill erosion and economic marginalization without institutional support.

This paper argues for repositioning indigenous architecture as a modern climate solution rather than a nostalgic practice. To enable this shift, actionable reforms are needed in building regulations, procurement policies, architectural education, and certification mechanisms. By integrating traditional knowledge systems into mainstream policy and practice, India can craft a climate-resilient urban future that is both ecologically sound and socially inclusive.

Position: Indigenous construction practices are not obsolete relics, but viable, climate-smart solutions for India's sustainable development. A shift in perception, policy, and pedagogy is essential to unlock their full potential.

Context and Problem Statement

The Indian construction industry, while central to national development and employment, is currently locked into unsustainable practices that have high environmental and social costs. The sector relies heavily on resource-intensive materials such as cement, steel, and fired bricks, which contribute disproportionately to greenhouse gas emissions, accounting for nearly 40% of global CO_2 emissions when combined with the built environment globally. In India's context, this problem is further compounded by the uncritical adoption of uniform, modernist building solutions that ignore local ecological conditions, cultural diversity, and traditional craftsmanship.

This one-size-fits-all model of urban development is steadily erasing centuries-old architectural practices that were deeply adapted to local climates and materials. Vernacular building systems ranging from Kath-Kuni construction in Himachal Pradesh to rammed earth and lime-based architecture in Tamil Nadu offer not only thermal comfort and reduced carbon footprints, but also strong linkages to local livelihoods, gender-inclusive skill systems, and community resilience. Despite these advantages, such indigenous techniques remain severely underutilized in mainstream construction.

The issue at hand is not merely technological or aesthetic, it is fundamentally structural. Indigenous architecture suffers from deep-seated biases in policy, perception, and pedagogy. These systems are often labelled as "primitive," lacking the aspirational value associated with modern cement-and-glass structures. Consequently, traditional artisans face declining demand for their skills, while policy frameworks remain skewed towards industrialized materials due to codification gaps and lack of performance metrics for local alternatives.

Further, current sustainability certification mechanisms such as GRIHA or LEED India tend to prioritize modular, pre-approved materials that fit within global green building narratives, often sidelining hyperlocal, biodegradable, and culturally rooted materials simply because they lack Environmental Product Declarations (EPDs) or standardized documentation. Architectural education too remains largely disconnected from ground-level practices, offering little exposure to students on climate-responsive vernacular systems beyond token electives or isolated workshops.

This research responds to a critical knowledge and policy gap by examining the structural, environmental, and socio-cultural feasibility of mainstreaming indigenous materials and techniques within India's sustainable construction agenda. Through interdisciplinary inquiry and stakeholder engagement, it addresses the pressing question of how to re-integrate time-tested knowledge systems into 21st-century architectural and policy frameworks. The need is not just to preserve architectural heritage, but to mobilize it actively in the service of India's climate goals, housing shortages, and employment challenges.

In this context, indigenous architecture is not a nostalgic throwback but a transformative opportunity, one that remains vastly untapped due to institutional blind spots, skewed market incentives, and weak regulatory support.

Literature Review

The academic discourse on sustainable architecture increasingly underscores the urgent need to move away from high-carbon construction practices towards environmentally and culturally responsive alternatives. Globally, the construction sector is responsible for nearly 39% of greenhouse gas emissions, with materials like cement alone contributing 8% to total CO_2 output (Bhavsar & Sangapurkar, 2018). In India, the expansion of urban infrastructure and the dominance of carbon-intensive materials such as cement, steel, and fired bricks present acute environmental challenges. Scholars argue that this dominant model often marginalizes ecological sensibilities, particularly during the construction phase, which is now recognized as a critical node of embodied emissions (Rahigude et al., 2022; Kulshreshtha et al., 2020).

Against this backdrop, vernacular architecture in India offers a compelling counter-narrative rooted in centuries of regional adaptation and material frugality. Described by Oliver (1997) as "architecture without architects," indigenous techniques such as Kath-Kuni in the north, bamboo frameworks in the northeast, and rammed earth constructions in the south exemplify passive design, local resource optimization, and climatic responsiveness (Kant & Lakra, 2023; Gautam, 2008). These practices, often dismissed as antiquated, have demonstrated measurable sustainability benefits through Life Cycle Assessment (LCA) studies. For example, materials like lime, adobe, and compressed stabilized earth blocks (CSEB) exhibit significantly lower embodied energy and carbon compared to modern industrial alternatives (Mathur et al., 2024).

The integration of LCA methodologies has enabled a scientific appraisal of indigenous materials, translating traditional ecological wisdom into standardized sustainability metrics.

Yet, as several researchers note, these assessments remain underrepresented in mainstream policy frameworks, due to the absence of Environmental Product Declarations (EPDs) and limited data repositories (Tezeswi & MVN, 2022; Sharma et al., 2023). Furthermore, certification systems like GRIHA and LEED often privilege imported, processed materials over vernacular solutions, revealing a disconnect between regulatory benchmarks and localized sustainability (Choudhary, 2016).

Beyond technical evaluations, indigenous architecture also sustains socio-cultural ecosystems. Construction processes historically functioned as communal events preserve artisan skills and foster rural livelihoods (Grove, 1996; Bordoloi & Muzaddadi, 2015). However, modern education and market systems have sidelined this knowledge, resulting in an intergenerational disconnect and economic marginalization of traditional craftsmen. Despite scattered initiatives by NGOs like the Hunnarshala Foundation, systematic integration into curricula and planning guidelines remains limited.

This study positions itself at the intersection of these academic and practical debates, seeking to bridge the gap between traditional wisdom and contemporary architectural demands. It contributes to existing scholarship by empirically validating indigenous methods through LCA, examining structural viability through stakeholder perspectives, and advocating for their inclusion within mainstream urban and regulatory discourse. In doing so, it challenges the assumption that progress in architecture must rely solely on technological innovation, instead advancing a pluralistic, culturally embedded vision of sustainable construction in India.

Research Focus and Methodology

This study is situated at the intersection of sustainable architecture, indigenous knowledge, and environmental policy. It addresses three primary research objectives:

(1) To identify and document indigenous building materials and techniques across various regions of India

(2)To assess the environmental impact and carbon footprint of these materials; and

(3) To evaluate the feasibility of incorporating indigenous practices into contemporary architectural designs.

To achieve these aims, a qualitative-dominant mixed methods design was adopted. This approach was selected due to the contextual, place-based, and deeply cultural nature of indigenous construction techniques, which cannot be adequately captured through purely quantitative methods. The research framework is grounded in exploratory and descriptive inquiry, incorporating stakeholder narratives, case studies, and Life Cycle Assessment (LCA) as complementary tools.

Primary data collection involved 47 semi-structured interviews with eight stakeholder groups: architects, engineers, artisans, contractors, sustainability consultants, policymakers, homeowners, and students. Interviewees were purposively sampled for their direct involvement in sustainable or vernacular construction practices. Digital platforms like LinkedIn and Google Meet were used to engage professionals and policymakers, while field visits enabled in-person interviews with artisans and community builders.

For Objective 1, documentation of region-specific practices like Kath-Kuni, adobe, lime masonry, and bamboo-lime composites were achieved through literature review, field observation, and artisan interviews. This mapped indigenous methods to ecological zones and material cycles.

Objective 2 was met using comparative Life Cycle Assessment, structured by ISO 14040 and ISO 14044 standards. Secondary data from Environmental Product Declarations (EPDs) and scholarly literature were triangulated with qualitative insights from practitioners. Key LCA indicators like embodied energy, global warming potential (GWP), and waste generation were assessed using MS Excel-based modelling.

To fulfil Objective 3, feasibility analysis was conducted through thematic coding of interview transcripts and triangulation with empirical case studies such as the Banasura Hill Resort, Indira Paryavaran Bhawan, and Palava City. This helped identify practical, institutional, and regulatory constraints, as well as

success factors enabling integration of indigenous methods into modern architectural workflows.

Thematic analysis revealed recurring concerns about market acceptance, codification, skill erosion, and policy exclusion. Quantitative LCA results substantiated the environmental advantages of indigenous materials over cement, steel, and fired bricks, making a compelling case for recentring vernacular architecture in India's sustainable construction paradigm.

This mixed-method framework combining empirical rigor with cultural sensitivity ensured that the research captured the technical, ecological, and human dimensions of indigenous architecture, offering both analytical depth and practical relevance.

Key Findings and Arguments

This research presents critical empirical evidence demonstrating the untapped potential and systemic barriers associated with adopting indigenous building materials and techniques in India's transition toward low-carbon architecture. The findings are grounded in qualitative insights from 47 semi-structured interviews, field observations, and Life Cycle Assessment (LCA) data, thematically analyzed to respond to the study's three objectives.

- Indigenous Knowledge Exists, But Remains Underutilized

The study revealed a high degree of awareness among architects and sustainability consultants regarding indigenous construction methods such as Kath-Kuni, compressed stabilized earth blocks (CSEB), bamboo framing, and lime plastering. However, actual application remains limited due to client preferences, institutional bias, and market inertia. While 75% of architects reported familiarity, only a fraction actively integrates these materials in practice typically within niche eco-conscious projects or academic settings. By contrast, engineers and contractors displayed greater skepticism about performance metrics and scalability.

This gap between knowledge and implementation underscores the need for robust dissemination platforms and accessible design guidance that translate traditional techniques into contextually viable, scalable solutions.

Table 1: Familiarity with Indigenous Materials by Stakeholder Group

Stakeholder Group	Percentage Familiar with Indigenous Techniques
Architects	75%
Engineers	40%
Artisans	100%
Contractors & Builders	30%
Sustainability Consultants	80%
Homeowners	25%
Policymakers	50%
Students	70%

- Regionally Rooted Techniques Offer Climate-Responsive Solutions

Fieldwork and case study analysis confirmed the strong ecological rationale behind regionally specific construction traditions. For example, Kath-Kuni timber-stone masonry in Himachal Pradesh excels in thermal insulation and seismic resilience; rammed earth and lime constructions in Kerala and Auroville respond to high humidity; and bamboo-thatch housing in the North-East provides lightweight, seismic-safe shelter with minimal embodied emissions. These techniques emerged from centuries of trial and adaptation to environmental pressures; qualities largely absent in homogenized modern construction.

Table 2: Representative Documentation of Indigenous Techniques by Region

Region	Indigenous Techniques	Primary Materials
North	Kath-Kuni, dry stone masonry	Wood, stone, slate
South	Rammed earth, lime plaster	Earth, lime, laterite
North-East	Bamboo frameworks, thatched roofing	Bamboo, thatch
Central	Cob, adobe	Clay, sand, straw
West	Thick stone walls, lime reinforcement	Stone, lime, mud

However, systemic integration demands a holistic push: through policy incentives, academic reform, institutional validation, and market rebranding.

These findings affirm that indigenous techniques are not antiquated, but highly climate-responsive models that require structured mapping, validation, and policy support for wider adoption.

- Empirical Evidence Confirms Lower Environmental Impact

The LCA revealed significantly lower embodied carbon and energy use for indigenous materials compared to conventional construction inputs. CSEBs and bamboo showed 60-80% reductions in embodied emissions relative to cement and steel. The integration of site-sourced materials and passive cooling further reduced environmental impact across the life cycle. These findings directly support India's Nationally Determined Contributions under the Paris Agreement and SDG 11 on sustainable cities.

Table 3: Summary of Life Cycle Assessment Results for Selected Materials

Material	Embodied Carbon (kg CO_2e/ton)	Embodied Energy (MJ/kg)
Ordinary Portland Cement	900	4.60
CSEB	150-200	0.81
Lime Plaster	250	0.97
Bamboo (treated structural use)	60-80	0.45
Fly Ash Bricks	200-250	1.10

These results highlight the environmental superiority of indigenous materials, yet lack of Environmental Product Declarations (EPDs) and standardized LCA data in Indian contexts continues to deter adoption.

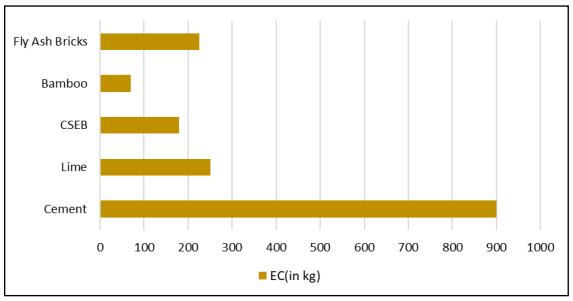


Figure 1: Comparative Embodied Carbon (EC) of Indigenous and Conventional Materials (per tonne)

- Systemic Barriers Obstruct Feasibility and Scale

Despite environmental and cultural advantages, the study found multiple institutional and economic barriers preventing integration. Engineers and contractors cited structural and regulatory uncertainties; homeowners reported a desire for "modern-looking" homes; and policymakers highlighted weak implementation of codes that could support traditional methods. This underscores the need to reposition indigenous construction as aspirational rather than alternative. Stakeholders pointed to hybrid models such as Banasura Hill Resort's integration of rammed earth with steel connectors as successful case studies demonstrating that vernacular practices can meet modern performance and aesthetic expectations.

- Cultural Knowledge Loss and Livelihood Displacement

The marginalization of artisans emerged as a critical concern. Traditional skills are disappearing as generational transmission breaks down and younger workers migrate toward other industries. Yet artisans demonstrated both, willingness and capability to contribute if institutional support, skill hubs, and dignified pay are provided. Revitalizing these crafts can simultaneously advance sustainability and preserve cultural heritage.

- Policy and Curriculum Reform is Urgent

The research found that while frameworks like ECBC, GRIHA, and IGBC mention material sustainability, they fail to promote indigenous techniques due to absence of benchmarks, testing protocols, and data integration. Similarly, vernacular architecture remains peripheral in academic curricula often taught as electives, disconnected from core design pedagogy. Students expressed a desire for immersive field-based learning with local artisans, citing it as essential to understanding sustainable construction in practice.

- Reframing Indigenous Construction as a Future-Ready Solution

Overall, the findings challenge dominant assumptions that equate modernity with cement, steel, and glass. Instead, they position indigenous construction as a resilient, low-carbon, socially embedded, and technically viable alternative especially relevant in the face of climate change and resource scarcity.

Policy and Practice Implications

The research underscores that while indigenous construction practices in India are ecologically sound and culturally rooted, they continue to be sidelined in mainstream architectural and regulatory systems. For these techniques to be meaningfully integrated into contemporary practice, actionable steps are needed not just conceptual advocacy. Three clear and feasible interventions emerge from the research findings.

1. Performance-Based Recognition in Building Codes and Certification Systems

Policymakers and regulators must move beyond material-based prescriptions to performance-based recognition of indigenous construction systems. Currently, codes such as the Energy Conservation Building Code (ECBC) and the National Building Code (NBC) offer limited guidance on regionally specific, climate-responsive practices. Based on LCA evidence generated in this study, materials like CSEB, lime plaster, and bamboo consistently outperform conventional materials in embodied emissions and energy efficiency. BIS, GRIHA, and IGBC should develop alternate certification pathways that allow for LCA-based or field-tested validation of traditional techniques, especially for rural and semi-urban contexts. This would not only expand the eligibility of indigenous systems for formal approvals but also lower entry barriers for small-scale developers and artisans.

2. Inclusion of Vernacular Methods in Public Housing and Procurement Policies

Schemes such as PMAY-G and Smart Cities should introduce pilot components that explicitly promote region-specific indigenous materials and construction methods. This research reveals that many indigenous materials are available locally and can reduce procurement costs when coupled with decentralized material sourcing and skill-based artisan labor. Government procurement frameworks can include preferential clauses for using certified low-carbon materials from indigenous sources. Additionally, artisan cooperatives supported through initiatives like the Rural Skills Mission or Van Dhan Yojana can be linked with public housing tenders to ensure quality delivery and livelihood generation simultaneously.

3. Curriculum and Capacity-Building Integration Across Institutions

The absence of indigenous techniques from architectural education has created a disconnect between theory and practice. As student interviews revealed, even those interested in sustainable design find little institutional support or exposure. The Council of Architecture (COA) and allied institutions can mandate the inclusion of vernacular design studios, field-based workshops, and live construction projects within B.Arch and M.Arch curricula. This study suggests that when students and practitioners engage directly with artisans and site contexts, it builds both appreciation and technical confidence. Alongside curriculum changes, continuing education programs for practicing architects, engineers, and contractors can offer modular training on integrating indigenous practices into hybrid, code-compliant designs. In essence, this research argues that India does not need to look outside for sustainable building solutions, it simply needs to recognize, validate, and modernize what already exists. By strengthening policies, reforming certifications, and investing in education, indigenous techniques can move from the margins of nostalgia to the mainstream of resilient, low-carbon architecture.

Conclusion

This research has demonstrated that indigenous building materials and techniques long marginalized within India's modern construction discourse offer a viable, climate-resilient, and culturally grounded alternative to conventional practices. By combining stakeholder insights, regional case studies, and Life Cycle Assessment (LCA) analysis, the study reaffirmed that these vernacular systems are not relics of the past but scientifically validated and environmentally superior design strategies. The findings emphasize that materials like bamboo, rammed earth, lime, and mud blocks can significantly reduce embodied carbon by as much as 80% in some comparisons while also supporting sustainable livelihoods and circular economies in rural and peri-urban contexts.

Importantly, the research positioned these techniques not as niche exceptions but as scalable, context-sensitive solutions that align with India's commitments under SDGs 11, 12, and 13 and the Paris Agreement. However, key barriers remain particularly the absence of codified standards, weak policy integration, and declining artisan skill transmission. These limitations highlight an urgent need for future work that not only documents but actively embeds indigenous practices into regulatory frameworks, architectural education, and government-led housing schemes. Ultimately, this study calls for a shift in how sustainability is conceived in India from importing green technologies to reimagining progress through local wisdom. Indigenous architecture holds the potential to regenerate both ecosystems and economies. If mobilized through appropriate policy, certification, and design innovation, it can redefine India's development pathway anchored not in displacement, but in rootedness, resilience, and renewal.

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5. Understanding the Income-Pollution-Gender Dynamics in the Indian Context: An Application of the Gender-Environmental Kuznets Curve

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Executive Summary

The Environmental Kuznets Curve (EKC) hypothesis, originally based on Simon Kuznets' income inequality curve, was proposed by Grossman and Krueger in 1995, suggesting an inverted U-shaped relationship between economic growth and environmental degradation. However, this framework often overlooks critical underlying factors, particularly socio-demographic dimensions such as gender, which significantly influence this income-pollution relationship. Moreover, existing EKC literature is heavily skewed toward developed countries, offering limited insights for developing contexts. The study "Exploring the Gender Dimension of the Environmental Kuznets Curve (EKC): Evidence from Indian States" addresses this research gap by introducing Gender as an interaction variable in the basic EKC model. The main objective is to examine whether the Environmental Kuznets Curve (EKC) hypothesis holds in the Indian context and how Gender influences the EKC relationship.

The study suggests the existence of a U-shaped EKC in the Indian context, implying that pollution increases at an increasing rate as income increases. The two gender-related variables affect the EKC trajectory differently: a higher Female Labour Force Participation Rate has a mitigating effect on pollution with income increases, whereas a higher Gender Parity Index in Higher Education has an amplifying effect on pollution. Significant inter-state disparities further indicate the complexity of these dynamics. The message is clear: Income growth alone cannot ensure better environmental outcomes over time, unless it is accompanied by appropriate policy measures. For India, the EKC turning point— beyond which environmental quality improves with income growth— cannot be attained merely on account of economic growth, but requires active implementation of targeted, state- or region-specific policies that promote women's meaningful economic participation in all major economic sectors, integrate environmental sustainability into higher education, and ensure its affordability.

Context & Problem Statement

The classic or standard EKC is an inverted U-shaped income-pollution relationship, implying that as income increases at low income levels, environmental degradation increases with income, which stagnates at a certain point of income. This income turning point marks the beginning of a new phase where further increase in income or economic growth is associated with improving environmental quality owing to technological efficiency and improvements, which were absent during the initial phase of economic growth when industrialization began. The theories of Ecofeminism and Environmental Justice provide the basis for the extension of this model and support the inclusion of socio-demographic dimensions in the EKC framework.

The concept of Ecofeminism describes a positive relationship between gender equality and environmental quality, and Environmental Justice suggests that environmental deterioration or pollution has differential or more severe impacts on people belonging to marginalized social groups, categorized by gender, race, caste, religion, etc. Therefore, the irony is that women's empowerment is associated with improved environmental quality, but when environmental quality deteriorates, women disproportionately bear the brunt of pollution. Hence, the study is very relevant in today's times, especially in the context of rapidly developing economies such as India, which are marked by deep structural inequalities and inter-state disparities. India needs a sustainable and inclusive development model where income growth is accompanied by an improvement in human development indicators. Several Sustainable Development Goals (SDGs), such as SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 5 (Gender Equality), highlight the importance of this study. Hence, studying the income-pollution-gender dynamics in the Indian context becomes crucial, and the EKC framework has the potential to suggest significant policy implications in this regard.

This study is novel in two aspects. One, it explores the moderating effect of Gender on the EKC relationship, that too, in the Indian context. Second, it employs a comprehensive state-level panel data of all 36 Indian states / UTs for a period of ten years from 2012 to 2021. To analyze this income-pollution-gender relationship, the study uses three environmental degradation indicators or air pollutants: Sulphur Dioxide (SO2), Nitrogen Dioxide (NO2), and Particulate Matter 10 (PM10), and two gender-related indicators: Female Labour Force Participation Rate (for female employment levels) and Gender Parity Index for Higher Education (for female educational levels). Specifically, this research has attempted to answer the following questions:

- Does the EKC relationship for SO_2, NO_2, and PM10 in India follow the standard inverted U -shaped pattern?
- For each of these pollutants, what are the income turning points?
- What impact do gender-related metrics like the Gender Parity Index for Higher Education and the Female Labour Force Participation Rate have on the EKC relationship?
- Does this income-pollution-gender relationship differ between states?

Literature Review

As the literature suggests, the theory of the Environmental Kuznets Curve (EKC) holds for most countries, but the shape of the EKC differs greatly. Mukherjee & Kathuria (2006) have presented evidence for a slanting S-shaped (cubic) EKC relationship in the Indian context. According to Zhang et al. (2023) and Caporin et al. (2024), a U-shaped EKC pattern is likely to be more prevalent for regions that are less economically developed. Hauff & Mistri (2015) imply that a quadratic model may be the best fit, especially for the Indian context. The different shapes of the EKC relationship in the Indian context are often attributed to the heterogeneity of Indian States and Union Territories on various grounds such as climatic and geographical conditions, political and historical background, socio-demographic indicators, etc. (Mukherjee & Kathuria, 2006; Hauff & Mistri, 2015; Sinha, 2016; Sinha & Bhattacharya, 2016; Rudra & Chattopadhyay, 2018). Socio-demographic factors and policy implementation play a key role in determining the shape and turning point of the EKC in any context. Torras & Boyce (1998) mention that socio-demographic factors strongly affect the environmental quality in less developed regions.

The theories of Environmental Justice and Ecofeminism, as already discussed above, highlight the relationship shared by Gender and Environment. Studies based on the relationship between Gender and Economic Development state that there is an S-shaped relation between gender inequality

and economic growth: female labor force participation rates are higher during the initial agrarian phase, decline during industrialization, and rise again in the third phase because female educational levels do not drop during the second phase unlike the employment levels (Goldin, 1995; Eastin & Prakash, 2013). This was also observed during our analysis, as the gender parity in higher education shows continuous improvement over the time period 2012 - 2021, whereas the female employment levels keep fluctuating.

Aligning with the theory of Ecofeminism, Cohen (2015) proposed that females are less employed in polluting industries than their male counterparts. However, the findings obtained from the study do not fully align with this theory, as gender parity in higher education leads to increased emissions as income increases. This finding is supported by some studies, such as Chikh-Amnache et al. (2023), which suggest that improvement in certain gender-related indicators may lead to increased emissions, as it would mean spending more resources to achieve gender equity.

In most EKC studies that incorporate a gender dimension, these factors are treated merely as control variables rather than as key independent variables. An important exception is McGee et al. (2020), where gender-related variables are used in interaction with income variables to see how gender moderates the income-environment relationship. Drawing on this approach, the present study advances a Gender-EKC framework by employing a robust empirical methodology.

Research Methodology

This empirical analysis aims to investigate income-pollution-gender dynamics in the Indian context by using a Gender-EKC framework. The study is entirely based on secondary data, involving an Unbalanced Panel Data Analysis covering 36 Indian States / UTs over 2012 - 2021. The basic EKC model used in this study is a log-log quadratic model with interaction variables (interaction of gender-related and income variables). All the key independent variables (income and gender interaction variables) are mean-centred, and only the quadratic transformation of the income variable (and not the cubic) has been considered in order to counter the problem of multicollinearity. The log-transformed per capita form of the dependent variables enabled interpretation in terms of elasticity, reduced variance, and standard errors, and eliminated the need to control for Population or Population Density in the EKC model. The three dependent variables representing environmental degradation or pollution are: SO2, NO2, and PM10. The key independent and control variables remain the same for each of these dependent variables. The variables used to predict pollution levels are: Net State Domestic Product (NSDP), Female Labour Force Participation Rate (FLFPR), and Gender Parity Index for Higher Education (GPI_HE), Share of Secondary Sector in Net State Value Added (SEC_SHARE), and Tree Cover Loss (TCL).

The Gender-EKC model used:

$$log\ (Per\ Capita\ Emissions\ it) = \beta 0 + \beta 1\ log\ (NSDPit) + \beta 2\ (log\ (NSDPit))2 + \beta 3\ Interaction_FLFPRit + \beta 4\ Interaction_GPI_HEit + \beta 5\ SEC_SHAREit + \beta 6\ TCLit + \gamma t + \square\ i + \varepsilon it$$

Where:

Per Capita Emissions it = the level of SO2 / NO2 / PM10 emissions in state i at time t,

NSDPit = Per capita Net State Domestic Product (NSDP) at constant prices,

Interaction_FLFPRit = log(NSDPit) * FLFPRit,

Interaction_GPI_HEit = log(NSDPit) * GPI_HEit,

SEC_SHAREit = Share of Secondary Sector in Net State Value Added (NSVA),

TCLit = Tree Cover Loss (in Hectares),

γt = Time Effects (controlling for all time variant factors; for example, national-level policy shocks),

α_i = Unobserved heterogeneity across states (Random Effects),

εit = Idiosyncratic error term.

For empirical estimation, Random Effects Panel Regression Analysis has been used with time effects. Since this analysis is done in the Indian context,

where the heterogeneity across cross-sectional units (States / UTs) is quite important to account for, the Fixed Effects model exhibits a disadvantage here (Torras & Boyce, 1998, pp. 152-153). Using a Random Effects model becomes preferable as we have an unbalanced panel data (Grossman & Krueger, 1995, p. 362), the Hausman Test justifies this (the exogeneity assumption holds, i.e., the state-specific effects are uncorrelated with the explanatory variables), and it gives more efficient estimates. For robustness of results, clustered standard errors and cluster-wise or region-wise regressions have also been performed, where the Hausman tests were run separately for different regions.

Findings: Gender-EKC Framework:

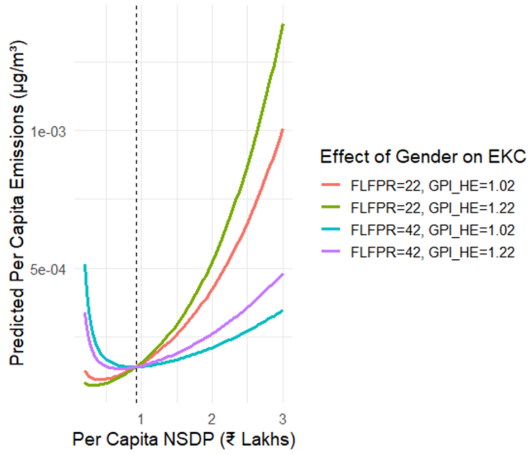
The key findings with regard to the income-pollution relationship and the moderating effect of the two gender-related variables (Gender Parity Index for Higher Education and Female Labour Force Participation Rates) on this relationship remain consistent across all three air pollutants—SO2, NO2, and PM10. This consistency ensures robustness of the study's findings on income-pollution-gender dynamics in India.

A U-shaped Income-Pollution Relationship:

For the air pollutant SO2, the estimated coefficients attached to both the income variables (linear and squared income variables) are positive and significant, implying a U-shaped quadratic EKC relationship. This means that pollution levels increase with income at an increasing rate since it is a monotonically increasing, convex curve. For the air pollutants NO2 and PM10, as well, there is a positive and significant relationship between income and pollution. There is no EKC in the classic sense (a classic or standard EKC is an inverted U-shaped curve, which is not the case here). Both the linear and quadratic terms are pushing the pollution levels upwards as income increases. The results state that at a level of income 1 unit above the mean income value, a 1% increase in per capita NSDP is associated with an approximate 2.45% increase in per capita NO2 emissions, keeping gender-related variables at their mean values and other variables constant.

Increasing Female Labour Force Participation Rates and the Income-Pollution Relationship:

Female Labour Force Participation Rate has a negative moderating effect on the income-pollution or EKC relationship. The estimated coefficient for the interaction variable associated with the female labour force participation rate is negative and highly significant, implying that when female labor force participation rates are higher (above average levels), economic growth has a mitigating



effect on pollution levels. According to the results obtained, a 1 percentage point increase in female labour force participation rate (above the average level), at a level of income 1 unit above the mean income value, is associated with a 4.8% decrease in per capita PM10 emissions, ceteris paribus.

Figure 1: Interaction Effects of Gender-related Indicators on the Income-Pollution (EKC) Trajectory

Source: Author's own analysis.

Increasing Gender Parity in Higher Education and the Income-Pollution Relationship:

Gender Parity Index for Higher Education has a positive moderating effect on the EKC relationship. A higher gender parity in higher education (more than average levels) is associated with increasing pollution levels as income increases—indicating an amplifying effect. The analysis suggests that a 0.1 unit increase in the gender parity

higher education has been continuously improving for all Indian states, but this improvement has turned out to be an expression of consumption expansion as income increases, and unfortunately, attaining higher education doesn't indicate increased environmental consciousness.

Figure 1 below demonstrates the impact of the gender-related variables on the EKC trajectory. It must be noted that the figure presented doesn't represent a standard income-pollution or EKC relationship, but an EKC model which includes gender interaction variables (interaction of gender with income). The impact of gender on EKC is shown using a high and a low value for each of the two gender-related variables. In the figure, the dashed vertical line represents the mean income value where the gender-related variables have no moderating effect on the EKC relationship.

As can be observed from the figure, keeping the Gender Parity Index for Higher Education (GPI_HE) fixed, an increase in Female Labour Force Participation Rate (FLFPR) flattens the slope of the EKC curve, implying that with an increase in Female Labour Force Participation Rate above the mean income level, pollution levels rise less rapidly as income increases.

Similarly, keeping the Female Labour Force Participation Rate (FLFPR) fixed, an improvement in the Gender Parity Index for Higher Education above the mean income value makes the slope of the EKC steeper, meaning that pollution increases more rapidly as income increases when gender parity in higher education further improves.

No Income Turning Points:

There is no income turning point or inflection point for this curve since it's monotonically increasing. At mean income values, there would be no moderating effect of the gender-related variables on the income-pollution relationship in this model. Non-existence of an income turning point indicates that in the case of India, higher economic growth cannot lead to an improvement in environmental quality (or, air quality here), at least in the near future. This may be primarily due to the reason that economic expansion in the Indian context is not accompanied by technological innovation or a shift towards cleaner technologies.

Inter-state Disparities:

AS a way of exploring inter-state variations in the gender-income-pollution nexus and for ensuring robustness of results, cluster-wise regressions for BIMARU+ (Bihar, Madhya Pradesh, Rajasthan, Uttar Pradesh, Odisha, West Bengal, Jharkhand, Chhattisgarh) and North-Eastern states (Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura) have also been performed. These two groups of states have been selected in particular for two main reasons. First, these groups comprise the same number of states, which keeps the number of observations uniform. Second, one group of states (North-eastern) performs better than the other (BIMARU+) for all pollution and gender-related indicators considered in this model.

For BIMARU+ states, the EKC hypothesis fails due to insignificant estimated coefficients. However, when the income variable is interacted with gender-related variables, the estimated coefficients become highly significant, indicating the moderating effect of gender on the income-pollution relationship in these states. This finding is in line with the study by Torras & Boyce (1998), suggesting that in less developed regions, the effect of socio-demographic characteristics on the environment is comparatively stronger. Here, the Female Labour Force Participation Rate has a negative moderating effect: decreasing pollution levels as income increases, whereas the Gender Parity Index for Higher Education has a positive moderating effect: increasing pollution levels as income increases.

For North-eastern states, a significant income-pollution relationship or a U-shaped EKC exists, indicating that per capita emission levels increase at an increasing rate as income increases. Here, the negative moderating effect of Female Labour Force Participation Rate remains, implying that higher FLFPR values (more than the average value) have a decreasing effect on pollution as income increases. But the interaction variable for Gender Parity Index in Higher Education loses its significance, which is a good sign, implying that in these states,

higher gender parity in higher education is not associated with increasing emissions as income levels increase.

Hence, it can be concluded that for both less developed and relatively more developed states, higher female labour force participation rates are critical in ensuring that pollution levels decrease as incomes increase. It means that income growth alone doesn't ensure pollution reduction. Socio-demographic factors such as gender may influence the EKC relationship significantly and that to reach a turning point on the EKC (the point beyond which pollution decreases as income increases), an inclusive growth model and an appropriate policy framework are essential (Sinha & Bhattacharya, 2016; Sinha, 2016; Zhang et al., 2023; Eastin & Prakash, 2013; Bilgili, Khan, & Awan, 2022).

Policy and Practice Implications:

The Indian EKC doesn't seem to be nearing an income turning point as it's a steep, upward-sloping curve with no inflection points. The results suggest that India might be at the first stage of a standard EKC where low levels of income prevail (Caporin et al., 2024). It also suggests a disruption of the idea of structural transformation of the economy. There is an indication of a lack of use of clean and green technologies (which come with higher income levels). Also, since the SO2, NO2, and PM10 emission levels and income are taken in per capita form, India's high population growth is an important contributing factor in this regard.

Framing gender-sensitive environmental policies is very important. In the Indian context, the female workers are largely concentrated in agriculture and informal sectors, which are characterized by disguised unemployment and low wages. So, there is a need to promote greater female participation in other economic sectors that are traditionally male-dominated and to adopt cleaner technologies such as renewable energy instead of relying on fossil fuel combustion.

This would help reap the environmental benefits that higher female labour force participation offers. The amplifying effects of higher gender parity in education suggest that the setup of higher education systems in India needs to be associated with increased environmental education and awareness to ensure that at least highly educated people are more environmentally conscious. Hence, investment in green education infrastructure is required to decouple gender parity in education from environmental degradation. In the Indian context, gender parity in higher education comes out to be a proxy for middle-class consumption expansion rather than environmental consciousness. Income levels and Gender Parity in Higher Education are found to be highly correlated, indicating more access to higher education as income increases. Hence, efforts should be made towards an inclusive development by making higher education affordable for people of all income levels. Given these trends, it is important to emphasise that the positive environmental impact of gender equality stems more from women's actual participation in the labour force than from higher educational attainment alone—particularly in the Indian context, where entrenched social norms and gendered divisions of labour often limit the translation of women's education into meaningful employment. High income inequality, gender inequality, and other kinds of structural inequalities in the Indian context are a prime reason behind this observed trend. Also, the significance of time effects in the model states that national-level policy implementation plays an effective role in managing pollution levels. Income growth alone does not help reduce pollution levels.

Gender-focused measures, such as improving Female Labour Force Participation Rates through skill development in green sectors, may have disproportionately favourable environmental consequences in BIMARU+ states. To improve environmental quality as income levels rise, environmental governance and regional planning should be integrated in the North-Eastern states. It is doubtful

that uniform policy recommendations will be effective; instead, local socioeconomic conditions must be taken into account when developing pollution and climate control plans.

Conclusion

The introduction of gender interaction terms in the EKC framework has given some important insights. The U-shaped EKC relationship implies that pollution levels increase at an increasing rate as income increases. As income levels increase, a higher Female Labour Force Participation Rate is associated with a mitigating effect on pollution levels, supporting ecofeminist claims that supporting women in the workforce can improve environmental quality. On the other hand, a higher Gender Parity Index in Higher Education is found to be associated with an amplifying effect on pollution levels as income increases, which may indicate a mismatch between education and employment levels or towards the amount of resources required to increase women's access to higher education. Additionally, the analysis shows significant inter-state differences in the dynamics of income, pollution, and gender, especially between the BIMARU+ and North-Eastern states. In contrast to the North-Eastern states, which show a strong and positive U-shaped EKC link, the BIMARU+ states do not support the EKC hypothesis. In these less developed states (BIMARU+), however, the income-pollution association becomes statistically significant when gender is included as an interaction variable. This suggests that environmental gains are not always a direct result of economic growth, particularly in areas with significant gender inequality.

For the objective of future research in this direction, this model may also be applied to a district or city-level data, or some unconventional indicators for gender and environmental degradation may be taken up— for example, taking environment-related diseases as a dependent variable (relevant in the area of health economics), or including interaction variables for some other socio-demographic indicators in place of gender.

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4. SUSTAINABLE DEVELOPMENT THROUGH ENERGY TRANSITION & DECARBONISATION PATHWAYS

Addressing energy transitions, decentralized systems, and low-carbon technologies.

POSITION PAPERS

Resilient Healthcare through Energy Access: A Decentralised Pathway for Sub-Saharan Africa
Apoorva Mishra

Pathways for Decarbonization: Strategies for Achieving Net-Zero Emissions in Energy-Intensive Industries
Mynam Venkata Harshita

Rewiring Sustainability in Commercial Transport: An LCA-Based Comparison of TATA ACE ICE and EV Model
Priyank Srivastava

Harnessing the Sun Responsibly: The Impact of Solar Technology on Agriculture and Public Health
Nisha Manghwani

Integrating Agrivoltaics in India for Carbon Sequestration and Carbon Credit Optimization
Srinanda Mondal

Consumer and Producer Perspectives on Circular Economy Transition in Indian Textile Industry
Pooja Chaudhary

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Chapter 2:
Resilient Healthcare through Energy Access: A Decentralised Pathway for Sub-Saharan Africa

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Executive Summary

The provision of quality healthcare in Sub-Saharan Africa (SSA) is critically undermined by inadequate access to reliable electricity. According to the World Health Organisation (WHO) (2023), nearly 60% of health facilities in the region lack dependable power, 15% are completely unelectrified, while 45% function with only intermittent or unstable electricity. This severely compromises essential medical services such as vaccine storage, maternal and emergency care, and diagnostic procedures. The COVID-19 pandemic further exposed these vulnerabilities, particularly in cold chain logistics and emergency responsiveness.

This thesis explores Decentralised Renewable Energy (DRE) technologies, primarily solar mini-grids and hybrid systems, as sustainable and context-appropriate solutions to address energy deficits in healthcare infrastructure. Evidence from case studies in Nigeria and Uganda reveals that solar mini grids can reduce carbon emissions by over 50%, deliver up to 95% electricity uptime, and enhance rural healthcare accessibility by approximately 35% (Moner-Girona et al., 2021).

Positioned at the intersection of public health and energy security, this research examines the viability of decentralised energy models for healthcare electrification. It draws on data from leading global institutions such as WHO, Sustainable Energy for All (SEforALL), and IRENA to analyse operational success stories, implementation barriers, and critical policy gaps. The findings demonstrate that solar-based systems not only enhance energy reliability but also reduce dependence on costly, polluting diesel generators. However, widespread deployment is impeded by fragmented policies, limited financing, and inadequate maintenance infrastructure. These systemic challenges necessitate urgent and integrated action.

Context and Problem Statement

Electrifying healthcare facilities in Sub-Saharan Africa should be recognised as a fundamental component of public health strategy, rather than a secondary development objective. The deployment of decentralised renewable energy systems such as solar mini grids must be supported through coherent policy frameworks, sustained financial investment, and local capacity development. Achieving Sustainable Development Goals (SDG 3: Good Health and Well-being and SDG 7: Affordable and Clean Energy) depends on ensuring that reliable electricity is an integral element of healthcare infrastructure. Without it, the delivery of effective and equitable healthcare cannot be realised.

Literature Review

Sub-Saharan Africa's healthcare systems face a chronic infrastructure gap, with energy poverty being among the most pressing and under-addressed challenges. Electricity is essential for powering lifesaving equipment, ensuring 24/7 care, maintaining vaccine cold chains, and supporting digital health systems. Yet over 60% of healthcare facilities in SSA operate without reliable power.

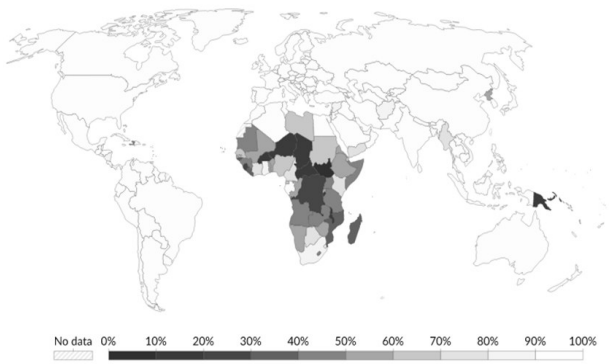


Figure 1: Share of the population with access to electricity, 2022 (World Bank, 2022). Having access to electricity is defined in international statistics as having energy sources that can provide basic lighting, and charge a phone, or power a radio for 4 hours per day.

A WHO report (2023) reveals that 15% of these facilities are entirely un-electrified, mostly in rural and peri-urban areas. Power outages or the absence of electricity severely limits healthcare delivery. Nighttime operations, maternal deliveries, and emergency care become risk-laden or impossible. Without consistent power, healthcare professionals cannot operate basic diagnostic equipment or preserve heat-sensitive medicines, which results in higher mortality and morbidity rates. The problem is further exacerbated by climate change, increasing disease burdens, and economic instability.



Figure 2.1: SSA data for Healthcare electricity (Source: SEforALL)

Although initiatives like WHO's *Energy for Health*, SEforALL's *Powering Healthcare*, and donor-driven electrification pilots exist, implementation remains sporadic. Projects often fail due to a lack of long-term maintenance planning, insufficient training for health workers, and fragmented institutional responsibility.

Additionally, energy interventions are typically donor-driven and focus solely on infrastructure, overlooking critical elements like operational training, maintenance funding, and local community engagement. In many cases, even when solar systems are installed, they are left unused due to minor technical issues and the absence of trained staff.

The core gap is not technological but systemic: insufficient coordination between health and energy sectors, lack of coherent policies, and poor integration of electrification into national health plans. This thesis seeks to address these systemic gaps by proposing context-specific, sustainable, and scalable electrification strategies tailored to SSA's healthcare sector.

Energy access and healthcare are increasingly recognised as interlinked development priorities. Literature by Adair-Rohani et al. (2013) and WHO (2023) highlights that healthcare facilities lacking electricity are significantly less effective in providing essential services such as childbirth, vaccinations, and surgery. The literature makes a compelling case for energy as a social determinant of health. SEforALL's *Powering Healthcare* report (2021) identifies DRE solutions, particularly solar

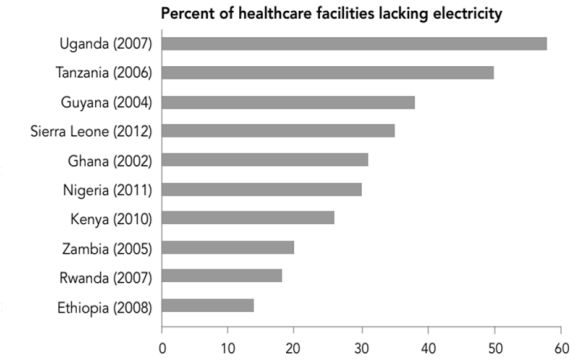


Figure 2.2: High Electricity deficits for healthcare facilities (Adair-Rohani et al., 2013)

PV and hybrid mini grids, as key to achieving universal energy access in healthcare facilities. These technologies offer reliability, cost-effectiveness, and climate resilience, particularly in off-grid and under-electrified areas.

Bhattacharyya (2013) and Cross & Murray (2018) explore the practical and institutional challenges of implementing decentralised energy systems. They emphasise the need for local capacity building and community ownership for long-term sustainability. Other scholars critique the "infrastructure-only"

approach, pointing out that electrification must be integrated into health system planning and workforce development.

Despite a growing body of evidence, the literature also shows significant gaps. There is limited work on gendered impacts of energy-poor health systems or on mechanisms for integrating energy access into public health policy. Moreover, many studies treat electrification as a stand-alone technical intervention rather than as part of a holistic healthcare delivery model. This thesis builds on and contributes to this body of work by focusing on policy frameworks, stakeholder engagement, and sustainability planning. It advances the argument that electrification must be embedded within health system strengthening efforts and aligned with national development goals.

Research Focus

Research Questions

1. How does a lack of reliable electricity affect healthcare delivery in SSA?
2. What decentralised renewable energy models are most effective for rural and semi-urban healthcare electrification?
3. What policy frameworks are required to scale these models?

Objectives

1. Assess the current energy access status in SSA's healthcare sector
2. Evaluate solar-based decentralised energy models for viability and sustainability
3. Identify policy gaps and propose actionable recommendations

Methodology

This study employs a mixed-methods research design to comprehensively investigate the current status, challenges, and opportunities in electrifying healthcare facilities in SSA. By integrating quantitative data with qualitative insights, the methodology provides both a macro-level overview and a detailed understanding of localised implementation, making it well-suited for analysing the multidimensional links between energy access and healthcare delivery.

Quantitative Component: Measuring Energy Gaps and Health Outcomes

The quantitative aspect of the study focuses on assessing the extent and reliability of electricity access in SSA's healthcare sector and evaluating the performance and sustainability of DRE systems. Secondary data will be sourced from established institutions such as WHO (SEforALL), the International Energy Agency (IEA), the World Bank, and national ministries of health and energy.

Key indicators to be analysed include the percentage of healthcare facilities connected to the national grid, those relying on diesel generators, and those entirely un-electrified. Additional metrics include outage frequency and duration, disruptions in service delivery, and critical health outcomes such as maternal mortality, emergency response efficiency, and vaccine storage failures. Descriptive statistics and time-series analysis will be used to identify trends and patterns. Furthermore, Geographic Information System (GIS) tools like QGIS and ArcGIS will support spatial mapping of electrified versus non-electrified facilities, revealing regional disparities and clusters of energy-deficient health infrastructure.

Qualitative Component: Understanding Impact and Implementation

The qualitative component seeks to explore how energy access affects healthcare delivery, identify successful DRE implementation models, and examine policy and institutional barriers. Case studies will be conducted in Nigeria and Uganda, selected for their contrasting energy contexts and ongoing healthcare electrification efforts. The focus will be on rural and semi-urban facilities that have adopted solar mini grids within the last three to five years.

Data will be gathered through semi-structured interviews with policymakers, energy service providers, healthcare workers especially those in maternal care and relevant NGO and donor representatives. Focus group discussions with patients and local community members will offer additional perspectives on perceived changes in service quality and accessibility. A SWOT analysis will be applied to each case

study to evaluate factors such as policy coherence, financial sustainability, maintenance practices, and stakeholder involvement.

Triangulation and Integration of Methods

To enhance the validity and richness of the findings, the study integrates data from both quantitative and qualitative sources. This triangulated approach allows for cross-validation of results and a deeper understanding of context-specific innovations and implementation challenges.

Matrix frameworks will be used to compare patterns across countries, facility types, and stakeholder groups, while narrative synthesis will help merge statistical data with qualitative observations, highlighting common themes and divergences.

Sampling Strategy

A purposive sampling strategy will be used to select healthcare facilities and stakeholders. Facilities must have implemented decentralised electrification within the past three to five years. The sample will include both primary healthcare centres (PHCs) and district hospitals, ensuring diversity in service level and geographical context.

Special attention will be given to gender representation and inclusion of stakeholders across the energy and health sectors. This comprehensive approach aims to generate actionable insights and inform a practical policy roadmap for healthcare electrification in SSA.

Key Findings and Argument

This study reveals a series of interrelated findings that collectively demonstrate the critical role of energy access in strengthening healthcare delivery in Sub-Saharan Africa. Through a combination of quantitative data analysis and qualitative case studies, five major themes emerged, each highlighting distinct but interconnected aspects of the energy-healthcare nexus. Together, these findings substantiate the argument that decentralized renewable energy solutions, particularly solar mini grids, are not only technically viable but also essential for delivering equitable and resilient healthcare in the region.

Theme 1: Energy Access Directly Correlates with Health Outcomes: Facilities with uninterrupted solar power reported improved maternal health services, better vaccine storage, and higher patient satisfaction. In Nigeria, a pilot solar mini-grid project led to a 60% increase in nighttime emergency services within the first six months.

Theme 2: Solar Mini-Grids are technically and economically feasible: Solar mini grids combined with battery storage and backup generators provided >95% uptime. Lifecycle costs were 30–40% lower than diesel-based systems. Environmental impact was also significantly reduced, supporting SDG 13.

Theme 3: Institutional Fragmentation is a Key Barrier: Policies regarding energy and health often operate in silos. Ministries lack coordination, leading to poor resource allocation and project duplication. In Uganda, delays in electrification were linked to unclear jurisdiction between national health and rural electrification agencies.

Theme 4: Long-Term Maintenance and Training Are Overlooked: Many solar systems failed within 2–3 years due to the absence of local technicians or spare parts. Training health workers on system usage was rare, despite its criticality for operational sustainability.

Theme 5: Gendered Impact of Electrification: Female health workers reported feeling safer during nighttime duties in electrified clinics. Mothers preferred delivering in facilities with lights and working equipment, contributing to increased institutional births.

Conclusion of Argument:

Electrification must be reframed not as an infrastructure project, but as a core health intervention. Decentralised solutions, especially solar mini grids, are scalable, sustainable, and contextually appropriate for SSA. However, success hinges on integrated policies, community involvement, and sustainable financing.

Policy & Practice Implications

Integrate Electrification into National Health Planning: Healthcare electrification must be formally embedded in national health sector plans. Ministries of Health and Energy should establish joint task forces to coordinate implementation, monitor outcomes, and allocate budgets collaboratively.

Promote Scalable Financing Models: Introduce results-based financing and public-private partnership models to attract investment. Donor agencies should fund not just capital expenditure but also maintenance, training, and local capacity building.

Establish Maintenance and Training Ecosystems: Every healthcare electrification project should include long-term O&M contracts with local technicians. Training health staff in basic troubleshooting and energy management is crucial for system sustainability.

Localise Energy Planning and Encourage Innovation: Leverage community-based organisations and local governments to co-design energy solutions. Innovations such as energy-as-a-service (EaaS) models, pay-as-you-go solar, and blockchain -based energy tracking should be piloted and scaled. These recommendations align with SDG 3 and SDG 7 while contributing to SDG 13 (climate action) and SDG 5 (gender equality), making them both practical and ethically grounded.

Conclusion

This study reaffirms that access to reliable electricity is an indispensable component of effective and equitable healthcare delivery in Sub-Saharan Africa. Across the region, persistent power deficits continue to compromise health outcomes, hinder service delivery, and strain healthcare systems, particularly in rural and underserved areas.

The research demonstrates that decentralised renewable energy solutions, most notably solar mini grids, can play a transformative role in addressing these challenges. When implemented with appropriate technical design, long-term maintenance strategies, and inclusive policy frameworks, these systems substantially enhance the reliability of essential services such as maternal care, emergency response, and vaccine storage.

By reconceptualising energy access as a public health imperative rather than a standalone infrastructure goal, this paper advocates for a paradigm shift in healthcare and energy policy planning. Cross-sectoral collaboration among national governments, international donors, energy providers, and local communities is vital to scaling up sustainable and resilient electrification initiatives. Moreover, integrating energy access into the core of health system strengthening efforts will contribute meaningfully to the achievement of Sustainable Development Goals 3 (Good Health and Well-being) and 7 (Affordable and Clean Energy).

Future research should build on these findings by exploring diverse implementation models, innovative financing mechanisms, and community-driven maintenance frameworks. Only through such a holistic, inclusive, and sustainable approach can healthcare facilities in Sub-Saharan Africa become resilient to both public health crises and broader environmental and economic disruptions.

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7. Pathways for Decarbonization: Strategies for Achieving Net-Zero Emissions in Energy-Intensive Industries

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Executive Summary

In order to prevent escalating climate change, reducing emissions from different industrial sectors is necessary. The emissions of greenhouse gases from various sectors have led to long-term increase in the earth's global temperature. This global warming has disastrous effects, such as frequent cloudbursts, cyclones, floods, and droughts especially in topographically sensitive zones. Implementing decarbonization pathways in the different sectors particularly in transportation, residential, and commercial, is indispensable to achieve climate mitigation and the net zero strategies [1]. Among these sectors, industries contribute one-third of total greenhouse gas emissions. Several industrial processes such as iron & steel making, cement manufacturing, production of fertilizers, and petrochemicals emit many greenhouse gases. In industries, an enormous amount of energy is required across various industrial processes. Coal is the primary fossil fuel that contributes significantly to greenhouse emissions.

Critical factors that affect industrial emissions are (i) the presence of large no. of small-scale industries, (ii) unplanned industrial growth, (iii) lack of policy to control emissions, (iv) use of outdated technology, and (v) lack of policy to control the emissions. Decarbonizing the industrial sector is essential because it is fundamental for developing low-carbon technologies such as energy-efficient buildings, renewable electricity, and generation. Identify the applicable funding agency here. Different technology, operational choices, and product design choices can reduce greenhouse emissions and energy consumption faster. The use of circular economy interventions, i.e., product longevity, reusability, ease of refurbishment, and recyclability, can reduce emissions in industrial sectors. Increasing energy demand has created a burden on fossil fuel consumption, leading to a drastic increase in the rate of carbon emissions [2]. The GHG emissions are rising at an intense pace. In developing countries, industries are the primary source of emissions, with coal as its primary fossil fuel. It is responsible for around 50 % of all GHG emissions, followed by manufacturing and construction (22%), transportation (11%), and industries (5%). Several technologies, decisions in product design, and operational strategies may quickly and affordably reduce energy use and GHG emissions across many businesses [3]. While still offering the same or better services, methods like lightweighting and design for longevity/reuse offer strategies to reduce material use. The image includes more than just technologies. By enacting the appropriate rules, investments in cleaner industrial processes can become more viable, and emission reductions can be accelerated significantly. The proper authorities can disseminate ideas through global supply chains, boosting businesses in nations without robust domestic regulations [4]. Cement production, oil refineries, and iron and steel production contribute to around 7%, 6%, and 5% of the 20–30% of emissions from industrial sources.

This position paper argues that current governance mechanisms are inadequate to address the specific wastewater challenges faced by India's small towns. It recommends urgent investment in decentralised wastewater treatment units (DWWTs), the establishment of town-level river health governance bodies, and the institutionalisation of water quality modelling in local planning frameworks.

Context & Problem Statement

Decarbonizing of the industry is one of the key issues in the modern, developing world. Although it can be challenging to comprehend, it dramatically impacts life and business operations. From a sustainability perspective, knowing the potential weaknesses will help businesses decide how to effectively engage in industrial CO2 removal. Industries contribute significantly to total emissions. Several industrial processes such as cement production, iron and steel making, and chemicals release a huge quantity of greenhouse gasses [5]. Several techniques are used to decarbonize industries across the supply and demand sides as shown in Fig 1.

A. Demand side technologies

Demand side techniques include extended product life, increased product usage driven by changes in demand, material substitution, and efficiency through circular economy initiatives.

1) Circular Economy: The concept of a ”Circular Economy” (CE) has emerged. Products at the end of their proper life cycle are considered resources in a CE. CE is not just one thing (like ”recycling”) but rather a series of solutions that maximize the value of every product, component, and material by using them as effectively as possible [6]. The first purchaser to keep using the product for as long as possible, to pass it on to other people, and take care of it so that it lasts as long as possible before needing replacement or repair [7]. In cases where this is not an option, transferring ownership to a new buyer is the next best thing. Refurbishing or remanufacturing the product is a good third choice. (Remanufacturing is dismantling a product to reuse its components.) Reusing the features that make up the product is the fourth best choice.

2) Material Substitution: One of the key strategies for reducing industrial GHG emissions can be found in substituting lower embodied carbon materials for higher incorporated carbon materials in products. The primary source of GHG emissions is the product category of building materials, mainly concrete and steel [8]. These emissions account for over 10% of all world emissions in total. Very few alternative materials are available in amounts adequate to appreciably reduce consumption due to their vast scale 4 Gt/year of cement production and 1.8 Gt/year of steel manufacturing [9]. Two frequently discussed prospects for substitution at scale in the construction industry are the use of timber-based products and the partial replacement of cement with supplemental cementitious materials [10].

3) Longevity, intensity, and material efficiency: For substitution, it is most frequently considered when steel may be substituted with aluminium, carbon fibre, or other solid and lightweight materials, boosting the vehicles’ fuel efficiency. Compared to the heavier materials they replace, these materials frequently have higher embodied emissions per vehicle. Fortunately, the energy and greenhouse gas emissions saved by a light car during its lifetime typically outweigh the additional energy and emissions incurred in producing its unique materials. Understanding the trade-offs and demonstrating where material replacement makes sense can be made via life cycle assessments (covering manufacturing, usage, disposal, and recycling ability. By increasing the efficiency of the materials, emissions can be reduced, and materials can be used for longer periods of time

B. Supply side technologies

1) Hydrogen: Using hydrogen as a fuel is one of the essential techniques practiced in industrial processes such as producing fertilizers, metal treatment, refining petroleum, and as catalysts in producing ammonia. Hydrogen is produced primarily through steam reforming, coal gasification, and electrolysis. It is formed as a byproduct of different industrial processes such as the Direct reduction of steel & iron making and the production of NaOH (Sodium Hydroxide) and Chlorine (Cl) in chlorine.

Around 30Mt of hydrogen is produced yearly as a by-product in industrial processes. Most H2 produced is used across several industries, such as ammonia, methanol, refineries of oil, and other sectors 43%, 34%, 17%, and 6%, respectively. Around 0.01% of H2 is used in fuel-cell electric vehicles.

2) Electrification: The industrial process requires a significant amount of fuel to produce heat. It is primarily used for processing heat, fueling the boiler, and other end-use uses. Electrification plays a crucial role in the decarbonization of industrial sectors. Different materials respond differently to electromagnetic energy. Compared to conventional, fuelbased process heating operations, there may occasionally be a transformation pathway that yields the necessary output product with less overall heat input. However, Technologies based on electricity have higher efficiency and lower thermal requirements than traditional methods of operation. Electric arc furnaces, resistive heating, and laser sintering are examples of specific uses where thermal heat can be replaced by electricity [5].

3) Energy efficiency: Improvements in energy efficiency can reduce water use, greenhouse gas (GHG) emissions, and other pollutants. It can be achieved through enhancement in the design of materials, efficient heat recovery and steam systems, and implementation of energy-efficient design for industrial sectors. Efficiency improvements are categorized based on their performance and effect on energy, mass, and information. It can also considerably improve efficiency by optimizing production processes and implementing the best available technologies. However, implementing efficiency measures leads to several benefits. It includes lowering the energy cost, creating a reliable supply of power, and reduction in greenhouse emissions IEA.

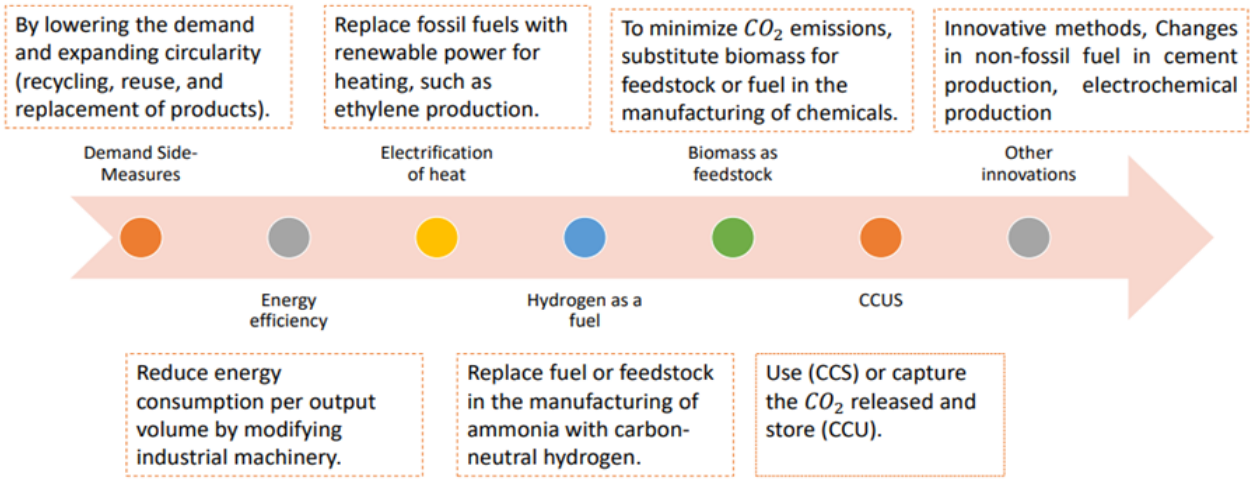


Fig. 1. Decarbonization option

3. Position Statement

Energy-intensive industries can achieve net-zero emissions through a strategic combination of emerging technologies (like green hydrogen, CCS, and electrification), enabling policy frameworks, and a socio-economically just transition especially in emerging economies like India where economic spurt and sustainable practices must be balanced. methods of operation. Electric arc furnaces, resistive

Key Arguments & Supporting Evidence

A. Cement Industry

Cement is one of the most used materials worldwide for several purposes. Cement production is one of the industrial sectors' that contributes significantly to greenhouse gases. Energy use and calcination reactions are the two primary processes that emits GHG during cement manufacture. When thermal fuels, most frequently coal, are used to heat a precalciner, and rotary kiln results in emissions of greenhouse gasses. The precalciner, where limestone CaCO3 is broken down into lime (CaO) and carbon dioxide, is the other primary source of direct GHG emissions. Cement has several applications across the world.

Primary applications include binder in concrete, which is used as a primary material for construction, such as roads, housing, schools, ports, and dams. Several decorative applications include patios, floors, driveways, pool decks, tables, and sculptures. In cement production, major sources of GHG emissions are the production of clinkers. In present scenarios, Several techniques are used to reduce greenhouse gasses. They are substitutions of alternative clinkers, electrification, CCUS, and fuel switching.

B. Iron & steel

Iron and steel are used widely for several applications, such as railways, roads, buildings, and other infrastructures. It is produced through chemical reactions inside the blast furnace. The raw materials in blast furnaces are heated at a high temperature (2200°C) which leads to the formation of molten Iron and liquid slag, as shown in fig . The molten Iron, also called pig iron, consists of a high concentration of carbon. It consists of various impurities, i.e., sulphur, carbon, silicon, manganese, and phosphorus. These impurities are removed through oxidation, and the temperature inside the blast furnace is controlled by the amount of scrap steel and iron ore. In the next step, steel is separated from the blast furnace, and the slag is recycled. The production of cement contributes significantly to greenhouse emissions. Industries are opting for electric arc furnaces to mitigate these emissions despite Basic oxygen furnaces for producing Iron & steel.

C. Chemical

The primary source of GHG emissions in the chemicals sector is the combustion of fossil fuels; hence the development of methods to lower these emissions should be prioritized. Effective strategies could be improved for usage in the industry [4]. For instance, to break down naphtha for further processing, steam crackers need to achieve a temperature of 850 °C. GHG emissions might be cut by up to 90% if this energy could be generated using electricity with no emissions. Six major chemical producers (BASF, Borealis, BP, LyondellBasell, Sabic, and Total) have collaborated to research the development of the first electrical steam crackers or naphtha crackers. New catalysts can lower the energy needed to initiate various chemical reactions. For instance, modern catalyst systems enable the dry reforming of methane CH4 into dimethyl ether (CH3OCH3), which can then be converted into a variety of olefins, including ethylene (C2H4), the most abundant organic chemical in the world. A more comprehensive choice of energy-efficient solutions, including ones with negative lifetime costs, are available to manufacture chemicals.

D. Ammonia

Ammonia is one of the products used in the chemical industry to produce fertilizers such as ammonium carbonate and Urea [10]. Ammonia is used as a fuel and energy carrier for several industrial purposes. These multiple applications of Ammonia have led to an increase in demand, which further leads to increased CO2 emissions. Among several industrial processes, ammonia production contributes to air pollutants such as CO2, SO2, and NOx emissions. Reducing emissions and saving energy can be achieved by improving energy efficiency, transition path, and emission characteristics. Nowadays, natural gas is preferred in the gas formation process. In addition to achieving the deep decarbonization target, using a cleaner electrolysis-based ammonia process and adopting CCUS techniques can reduce this emission by 98% in these industries cite.

E. Paper & Pulp

Paper is one of the essential products with several applications, such as printing, painting, graphics, signage, design, packaging, decorating, writing, and cleaning. It is produced through a physical and chemical process that involves soaking cellulose fibers from wood, rags, grass, or other vegetable sources. Water is drained through a fine mesh, so the fibers are evenly dispersed, press the material and let it dry. The pulp is the primary component in producing paper, which is created by dissolving the fibrous section of plants, primarily trees or recycled paper. The most typical source of fiber for papermaking and the foundation for many paper and wood goods is wood fiber or pulp derived from trees. Paper and pulp industries contribute significantly to greenhouse gasses. Different techniques, such as waste paper recovery and paper and cardboard recycling, can reduce these emissions.

5. Policy Recommendations

1) Carbon Pricing: Carbon pricing, which requires emitters to pay a fee per tonne of CO2 (or, better yet, per tonne of GHGs, measured in CO2-equivalent) they emit, is one of the most well-known emissions-reduction strategies. Carbon pricing enables regulators to limit GHG emissions from the industry sector cost-effectively without the need to develop expertise in manufacturing processes, as might be necessary to set emissions standards for specific types of equipment or per unit of a commodity. Emitters are free to choose the least expensive way to reduce emissions or to pay the carbon price in cases where emissions reduction is expensive [5].

2) Emission Standards: The government makes these standards to reduce air pollution from factories and other industrial facilities. Standards are binding requirements that specify maximum allowable levels of contaminants from a specific source. Energy efficiency regulations for appliances, equipment, and vehicles are among the most potential governmental initiatives for reducing energy use in the present scenario. Motors account for two-thirds of industrial electricity consumption; electric motor standards have significantly lowered electricity consumption during operation.

3) Low-carbon materials and product labelling: The uses of low-carbon materials and goods play a crucial role in decarbonizing industrial sectors. There is a need to encourage the markets for low-carbon goods. Similar to current labelling programs for energy-efficient appliances, lighting, windows, and other products, labels for some finished products may be directed at consumers. However, they would disclose manufacturing-related GHG emissions rather than the product's energy efficiency.

4) Recycle requirements or incentives: Recycling of materials in several industries can decrease emissions in these sectors. For some commodities, like steel and aluminum, the inherent value of the waste materials may be high enough to make recycling worthwhile financially and logistically. Even these materials, meanwhile, are frequently not recycled. For instance, only 33% of steel and 19% of aluminum in municipal solid waste (MSW) are recycled .

5) Building Codes: Buildings are essential to human wellbeing, and their construction accounts for a sizable portion of economic activity. (For instance, 8% of the US GDP). The production of materials, primarily structural materials like steel and concrete, accounts for over 20% of global energy and process-related GHG emissions. Construction, therefore, has a significant environmental impact.

Conclusion

Decarbonizing industrial sectors presents several challenges:

- Many industrial processes require high-temperature heat (>500°C), which is difficult to generate using renewables.
- Processes are deeply integrated, making modifications complex.
- Industries have long lifespans and high capital costs, limiting flexibility.
- Reducing feedstock emissions often requires switching to cleaner alternatives like hydrogen or biomass.

This paper reviews demand- and supply-side technologies that support industrial decarbonization. Key sectors cement, steel, and chemicals account for over 80% of projected CO_2 reductions between 2015 and 2050. Tackling overcapacity and deploying energy-saving, emission-reducing technologies in these sectors is critical. In others (e.g., textiles, mining, agriculture), electrification—expected to reach 80% by 2050 is the main strategy. Hydrogen and CCUS are also expected to play vital roles in achieving industrial carbon neutrality.

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10. Rewiring Sustainability in Commercial Transport: An LCA-Based Comparison of TATA ACE ICE and EV Model

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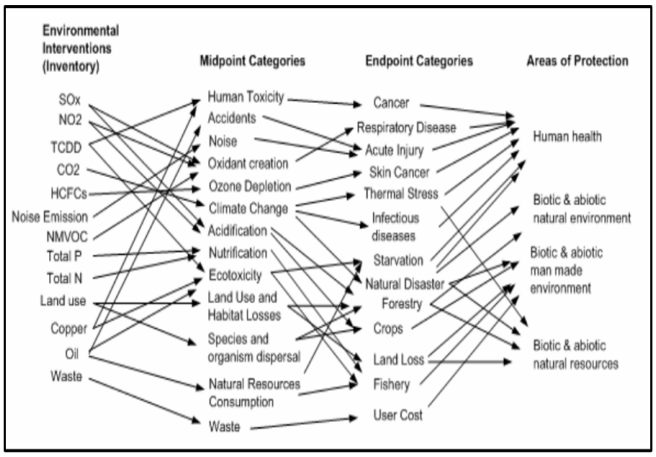
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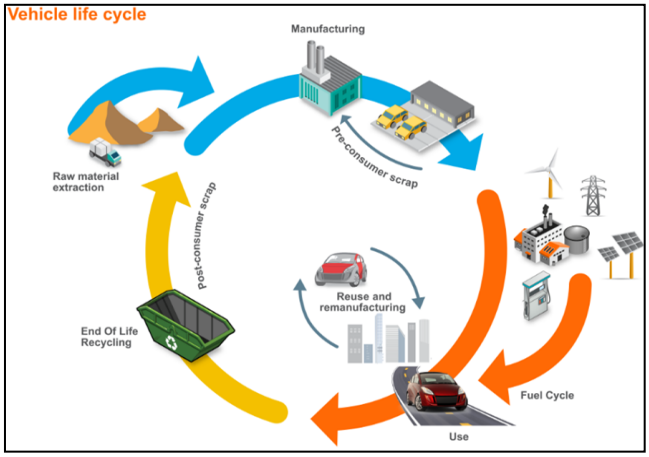
Executive Summary

This position paper presents key insights from a Life Cycle Assessment (LCA) comparing the environmental performance of Tata Motors' most popular commercial mini truck Tata Ace in its Internal Combustion Engine (ICE) and Electric Vehicle (EV) variants. Utilizing SimaPro software and the ReCiPe Midpoint 2016 methodology, the study evaluates cradle-to-grave environmental impacts, including Global Warming Potential (GWP), resource depletion, toxicity, and fossil fuel consumption.

The Tata Ace EV demonstrates a 41% lower GWP than its ICE counterpart, driven by zero tailpipe emissions during the use phase. However, the EV's advantages are partially offset by increased toxicity and resource depletion, especially from battery production and raw material extraction of lithium and copper. When the electricity mix is shifted to 100% renewables, the EV's environmental performance significantly improves across categories This paper argues that while EVs are aligned with national decarbonisation goals, strategic interventions are needed to mitigate upstream and end-of-life environmental burdens. Recommendations include improving battery recycling, adopting circular economy strategies, integrating cleaner energy in manufacturing, and regionalising EV supply chains.

The position is clear: the Tata Ace EV represents a significant leap forward in sustainable mobility for India's commercial vehicle sector—but only if the environmental trade-offs are proactively managed. Policymakers and manufacturers must act jointly to accelerate India's low-carbon transition while ensuring resource efficiency and ecological safety. The insights from this LCA offer a roadmap to shape future-ready commercial vehicle development rooted in sustainability and resilience.





Context and Problem Statement

India's commercial vehicle sector is undergoing a significant transformation, driven by the twin forces of policy reform and environmental urgency. Government schemes like the Faster Adoption and Manufacturing of Electric Vehicles (FAME II), the National Electric Mobility Mission Plan (NEMMP), and India's commitment to achieving Net-Zero emissions by 2070 are pushing automakers and fleet operators toward electrification. At the heart of this shift lies a fundamental question: Are electric vehicles (EVs) truly more sustainable than conventional Internal Combustion Engine (ICE) vehicles when viewed across their entire lifecycle?

The Tata Ace, one of the country's most sold and widely used commercial mini trucks, provides a representative case to explore this question. It serves thousands of micro-entrepreneurs, small traders, and last-mile delivery operators across India. With diesel still dominating the light commercial vehicle (LCV) market, the introduction of the Tata Ace EV is seen as a step toward greener logistics. But behind the promise of zero tailpipe emissions lies a more complex reality.

Most discussions around EVs are narrowly focused on the use phase, highlighting reduced local air pollution and zero operational emissions. However, these benefits can be misleading if not contextualized within the entire life cycle of the vehicle—from raw material sourcing, battery manufacturing, and grid electricity mix to end-of-life battery disposal and recycling. The environmental impact of extracting lithium, cobalt, and copper; the carbon footprint of battery production; and the challenges of battery end-of-life treatment pose serious concerns that must be evaluated.

Moreover, India's electricity grid remains predominantly is coal-based. Charging an EV on this grid could offset many of the environmental benefits unless renewable energy integration is prioritized. In such a scenario, a cradle-to-grave Life Cycle Assessment (LCA) becomes essential to understand the full spectrum of environmental trade-offs.

This paper responds to that need. By conducting a comparative LCA of the Tata Ace ICE and EV variants, it seeks to quantify emissions, resource consumption, and toxicity impacts across each life cycle stage. The aim is not just to validate the benefits of EVs but to uncover the hidden costs and systemic inefficiencies that may otherwise be overlooked.

In doing so, this paper contributes to the evolving discourse on sustainable transportation in India. It provides a nuanced view that can inform policy, shape manufacturing strategies, and guide investment in cleaner, more circular technologies for the commercial vehicle segment

Literature Review

In recent years, the comparative sustainability of Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles has become a critical subject of research, particularly through the lens of Life Cycle Assessment (LCA). Unlike tailpipe emission comparisons, LCAs allow a more complete evaluation by including upstream and downstream impacts from raw material extraction and manufacturing to usage and end-of-life processing.

Hawkins et al. (2013) emphasized that while EVs significantly reduce operational emissions, their overall environmental advantage is tempered by the carbon-intensive processes involved in battery manufacturing and raw material sourcing. Similarly, Ellingsen et al. (2016) highlighted that environmental outcomes for EVs are highly sensitive to electricity grid mix and battery disposal strategies, making localized studies essential.

In the Indian context, Jain and Sharma (2018) pointed out that the benefits of EVs are significantly diluted by India's coal-heavy electricity grid. They argued that unless cleaner energy sources are adopted, the net GHG reduction from EVs remains marginal.

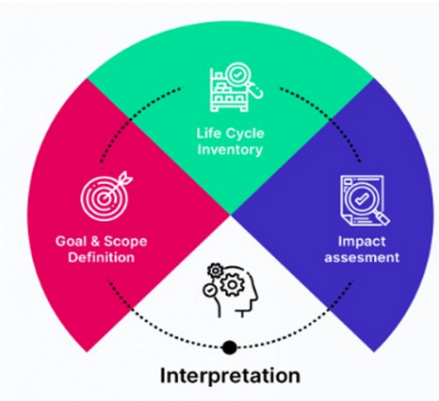
Raghavan et al. (2017) advanced this understanding through scenario-based modeling, demonstrating that with higher renewable energy penetration, EVs show clear environmental advantages over ICE vehicles.

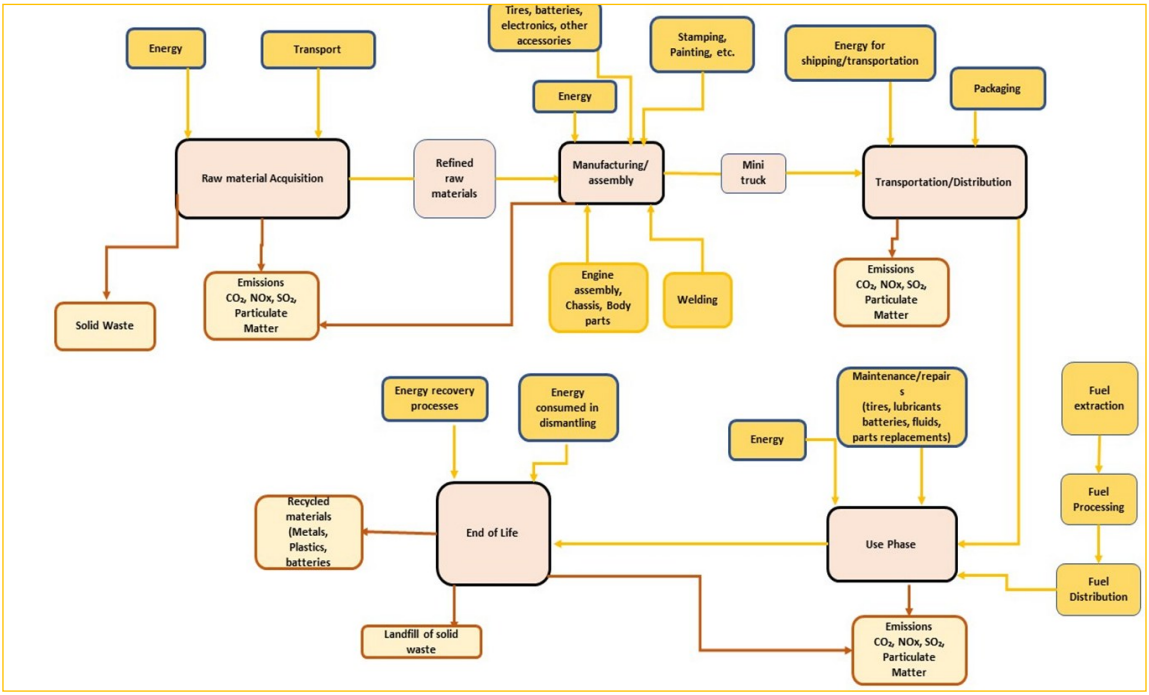
Kumar et al. (2019) focused specifically on commercial EVs and noted that while operational emissions are notably lower, the environmental burden shifts to upstream activities, particularly mining and manufacturing.

Their work underlined the need for policy frameworks that go beyond end-use emissions and encourage sustainable sourcing, manufacturing, and recycling practices. More recently, Singh et al. (2020) and Sharma, Gupta, and Bansal (2021) stressed the role of circular economy practices in improving the lifecycle performance of EVs. These include design for disassembly, battery second-life use, and advanced material recovery techniques all of which can substantially mitigate the resource depletion and toxicity impacts of EVs.

Despite these advancements, literature remains limited when it comes to LCA studies on light commercial mini trucks, especially in the Indian context. Given the Tata Ace's widespread usage and relevance to last-mile connectivity, an LCA focused on its ICE and EV variants fills a crucial gap. It brings specificity to a category often generalized under passenger or heavy-duty vehicle research and adds practical value for policymakers, industry leaders, and sustainability professionals. This paper builds upon the global LCA discourse and adapts it to the Indian commercial vehicle landscape delivering both contextual relevance and actionable insights.

This study aims to evaluate and compare the environmental performance of the Tata Ace ICE and EV variants using a cradle-to-grave Life Cycle Assessment (LCA) approach. The goal is to move beyond superficial emissions comparisons and instead provide a comprehensive, evidence-based assessment of environmental trade-offs associated with transitioning from diesel-powered to electric mini trucks in India's light commercial vehicle (LCV) segment.





The functional unit for this assessment is one Tata Ace vehicle (either ICE or EV) operating over a lifespan of 150,000 kilometers. The system boundary includes all major life cycle stages: raw material extraction, manufacturing, transportation, use phase, and end-of-life treatment, including disposal and recycling. This ensures a holistic perspective, capturing direct and indirect environmental burdens.

Environmental impact categories assessed include:

- Global Warming Potential (GWP)
- Fine Particulate Matter (PM2.5) Formation
- Fossil and Mineral Resource Depletion
- Water Consumption
- Human and Ecotoxicity

The analysis is performed using SimaPro 9.0 software, based on the ReCiPe Midpoint 2016 methodology. Primary data is collected from Tata Motors' Pantnagar plant, with supplementary data sourced from the Ecoinvent database and peer-reviewed academic literature.

To deepen the analysis, the study integrates four analytical layers:

- **Comparative Analysis –** Directly compares environmental impacts across both vehicle variants for each impact category.
- **Hotspot Analysis –** Identifies which life cycle stages contribute most to overall impact (e.g., use phase for ICE; battery production for EV).
- **Trade-Off Analysis –** Evaluates areas where environmental gains (e.g., reduced GHG emissions in EVs) come at the cost of increased burdens elsewhere (e.g., higher resource depletion and toxicity).
- **Scenario Analysis –** Models the EV under three electricity grid scenarios:
  - Business-as-usual (70% fossil-based grid)
  - 50% Renewable Energy
  - 100% Renewable Energy

These scenarios help assess the sensitivity of EV performance to India's evolving energy mix and inform future policy direction.

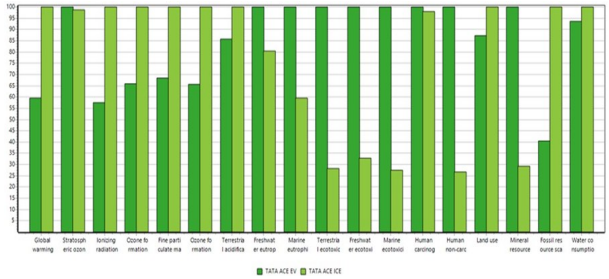
The combination of real-world data, standardized LCA tools, and scenario modeling ensures that the findings are not just academically robust but also practically relevant. By focusing on the Tata Ace—an icon of India's small-scale logistics economy—this study provides insights that are directly applicable to the country's mobility and sustainability transition.

Key Findings and Arguments

The Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants reveals a complex sustainability landscape that cannot be judged solely by tailpipe emissions. This section presents the four core analytical dimensions—comparative analysis, hotspot analysis, trade-off analysis, and scenario analysis—to deliver a complete picture of environmental performance.

1. Comparative Analysis

The Tata Ace EV outperforms the ICE variant in terms of Global Warming Potential (GWP), emitting approximately 28,712 kg CO_2 eq over its lifecycle, compared to the ICE's 48,166 kg CO_2 eq—showing a 41% reduction. The EV's advantage lies in its zero tailpipe emissions during the use phase.



However, when toxicity-related impacts are considered, the picture changes. The EV exhibits significantly higher terrestrial and freshwater ecotoxicity—almost 3.5 times more than the ICE model—mainly due to battery production and material processing. Additionally, the EV scores poorly in mineral resource scarcity, driven by the demand for lithium, cobalt, and copper used in battery and motor components.

2. Hotspot Analysis

Hotspot analysis pinpoints the life cycle stages that contribute most to each environmental category:

ICE Variant: The use phase is the largest contributor to GWP, particulate matter, and acidification impacts, primarily due to diesel combustion. Manufacturing is also a EV Variant: The environmental burden shifts upstream. Material acquisition (especially battery materials) and manufacturing are the dominant contributors to GWP, toxicity, and resource depletion. The EV's use phase is significantly cleaner, but indirect emissions from electricity production must be accounted for.

End-of-Life Phase: Although relatively minor in overall impact, EVs pose challenges due to battery recycling, which introduces additional toxicity and energy demand major contributor due to steel and aluminum use.

3. Trade-Off Analysis

The shift from ICE to EV is not an environmental panacea; it involves trade-offs:

- GHG vs. Resource Depletion: While the EV cuts GHG emissions, it increases demand for non-renewable resources. For instance, the mineral resource scarcity of the EV is 434.55 kg Cu eq compared to the ICE's 126.62 kg Cu eq.
- Air Quality vs. Toxicity: The EV variant significantly reduces particulate emissions (82.43 kg PM2.5 eq vs. 120.22 kg PM2.5 eq for ICE), but introduces higher risks in terms of human and ecological toxicity, which are often overlooked in policy frameworks.
- Operational Gains vs. Manufacturing Burden: The use-phase benefits of EVs are undermined by emissions and resource use in battery manufacturing, transport (especially international battery imports), and raw material extraction.
- These trade-offs reinforce the need for innovations in battery chemistry, lightweight materials, and closed-loop recycling systems.

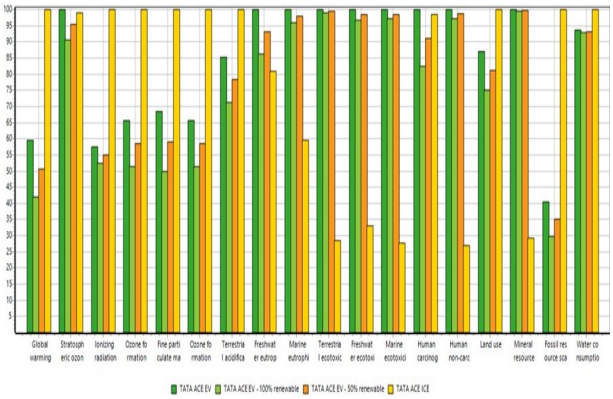
4. Scenario Analysis

- To assess how India's electricity grid influences EV sustainability, the study modeled three scenarios:
- Business-as-usual (70% fossil-based grid): EV emits 28,712 kg CO_2 eq—better than ICE but not dramatically.
- 50% Renewable Grid: EV emissions reduce to ~24,450 kg CO_2 eq, with noticeable improvements in GWP and air quality indicators.
- 100% Renewable Grid: EV emissions drop to ~20,235 kg CO_2 eq—a 58% reduction from ICE baseline and nearly 30% better than the business-as-usual EV.

While toxicity impacts remain, they also marginally improve due to cleaner electricity in manufacturing and charging.

Synthesis

Taken together, the data suggests that while the Tata



Ace EV aligns with India's climate goals, its sustainability benefits are conditional—not guaranteed. The vehicle's overall environmental profile is influenced more by how it is made, powered, and disposed of, rather than simply by the fact that it's electric.

This reinforces a crucial argument: for EVs to become truly sustainable, interventions are needed across the entire value chain—from sourcing of minerals to design for disassembly, and from grid decarbonization to robust battery take-back systems.

The Tata Ace EV can serve as a catalyst for transforming India's small commercial vehicle market—but only if the systemic trade-offs are acknowledged and addressed through coordinated industrial, technological, and policy measures.

Policy and Practice Implications

The comparative Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants reveals that while EVs offer significant environmental benefits in terms of greenhouse gas emissions, these advantages are tempered by challenges related to resource depletion, toxicity, and energy sourcing. To truly realize the promise of sustainable electric mobility in India's commercial vehicle sector, multi-stakeholder actions are required. The following are the key policy and practice implications derived from this study:

1. Innovation in Battery Design and Circularity

The high environmental burden of battery manufacturing highlights the urgent need for innovation in battery design. Policymakers must incentivize research in next-generation battery chemistries—such as solid-state and sodium-ion technologies—that are less resource-intensive. Additionally, automakers should adopt circular economy principles such as modular battery packs and second-life applications to improve recyclability and reduce raw material dependence.

2. Renewable Energy Integration in Manufacturing and Charging

The scenario analysis clearly shows that the environmental performance of EVs improves substantially with cleaner energy. It is therefore imperative that both government and industry push for higher renewable energy adoption at manufacturing sites and EV charging stations. Tata Motors and other OEMs can set an example by shifting their plant operations to solar and wind-based energy sources.

3. Localized Supply Chains and Sustainable Procurement

Transport emissions and material sourcing impacts can be reduced by localizing supply chains. Tata Motors should consider sourcing battery components and metals domestically where possible, reducing the need for carbon-intensive imports. Further, suppliers should be evaluated on sustainability parameters including ethical mining practices and environmental compliance.

4. Lifecycle-Based Policy Incentives

Current EV incentives are largely based on upfront purchase price and use-phase emissions. A shift toward lifecycle-based incentive structures—where vehicles with lower cradle-to-grave impacts receive higher support—will encourage more responsible product design and sourcing. Policy frameworks such as FAME III should integrate lifecycle metrics for subsidy disbursement.

5. Battery Recycling Ecosystem Development

India currently lacks a formal, scalable battery recycling system. The government must accelerate the implementation of Extended Producer Responsibility (EPR) rules, and support the development of advanced recycling infrastructure. Collaborations between OEMs, startups, and public agencies can enable closed-loop systems that recover valuable materials and reduce environmental harm.

By addressing these critical areas, India can move beyond incremental improvements and toward transformative change in the commercial EV segment. The Tata Ace EV, as a high-volume, widely recognized vehicle, has the potential to serve as a scalable model for sustainable last-mile logistics if supported by bold and holistic action from both policymakers and industry.

Conclusion

The comparative Life Cycle Assessment (LCA) of the Tata Ace ICE and EV variants presents a nuanced, evidence-backed understanding of what sustainable mobility truly entails in the Indian context. While the EV model clearly reduces operational emissions and aligns with India's climate objectives, the environmental costs associated with upstream battery production, material sourcing, and end-of-life recycling cannot be overlooked.

This study's multi-dimensional framework spanning comparative metrics, hotspot analysis, trade-offs, and future energy grid scenarios demonstrates that environmental performance is not just about what a vehicle emits on the road, but also about how it is manufactured, powered, and disposed of. For instance, the EV's Global Warming Potential drops significantly under a 100% renewable energy scenario, yet its toxicity and resource depletion impacts remain areas of concern unless addressed through system-level innovations.

The key takeaway is this: EVs like the Tata Ace represent a critical opportunity to decarbonize India's small commercial vehicle fleet, but this transition must be managed thoughtfully. Sustainability cannot be treated as a checkbox. It requires collaboration across policy, technology, supply chain, and public awareness.

To unlock the full potential of the Tata Ace EV, India must invest in cleaner manufacturing, renewable energy infrastructure, localised supply chains, and a robust battery recycling ecosystem. This paper makes the case for a lifecycle-thinking approach one that ensures the country's low-carbon ambitions are not achieved at the cost of new ecological burdens.

With strategic interventions, the Tata Ace EV can become not just a zero-emission vehicle but a symbol of holistic, responsible, and future-ready mobility.

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Harnessing the Sun Responsibly: The Impact of Solar Technology on Agriculture and Public Health

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Executive Summary

This paper explores the multifaceted impact of solar technology on three critical pillars of rural development in India: agriculture, public health, and environment. With solar energy now a core component of climate change mitigation efforts, particularly through initiatives like the PM-KUSUM scheme, its application in rural areas has grown exponentially. The key objective of this paper is to assess how solar electrification—mainly through solar-powered irrigation, mini-grids, and rooftop systems—affects agricultural productivity, health infrastructure, environment and livelihoods.

Main findings indicate that solar technology reduces operational costs and air pollution, thereby enhancing both agricultural output and respiratory health. However, the benefits are often tempered by unintended consequences such as groundwater depletion, soil degradation, and uneven access due to policy and infrastructural gaps. Economically, while solar adoption boosts farm income and rural enterprise, its positive effects are not evenly distributed across socio-economic groups. The implications of these findings call for a holistic and integrated policy approach. Solar technology, while beneficial, must be deployed in a manner that anticipates ecological trade-offs, enhances policy coherence, and ensures equitable access. This paper argues for the adoption of cross-sectoral planning frameworks such as the Water-Energy-Food Nexus and highlights the need for regulatory reforms that link solar energy deployment with water and land-use governance.

Position Statement: Solar technology holds transformative potential for sustainable development in India, but its success depends on addressing ecological, social, and governance challenges through integrated and inclusive policy mechanisms.

Context and Problem Statement

India's transition drive towards clean energy has made solar technology central to its development agenda, particularly in rural areas. The country's National Solar Mission and schemes like PM-KUSUM aim to decentralize energy access, reduce greenhouse gas emissions, and empower rural livelihoods. However, the rapid and often unregulated expansion of solar electrification raises critical questions about its long-term sustainability and socio-environmental implications.

In agriculture, solar-powered irrigation systems (SPIS) have significantly reduced dependence on diesel and improved access to reliable water sources. This has led to improved productivity and crop diversification. However, studies have shown that the zero marginal cost of operating solar pumps encourages excessive groundwater extraction, particularly in water-stressed states like Rajasthan and Gujarat. This threatens aquifer sustainability, contributes to land degradation, and undermines climate adaptation goals.

Similarly, the health sector benefits from improved lighting, refrigeration, and water pumping enabled by solar mini-grids and rooftop systems. These advances support vaccine preservation, night-time deliveries, and disease diagnostics. Nevertheless, rural clinics often lack

capacity to maintain these systems, limiting their effectiveness. Furthermore, improper disposal of solar panels and batteries introduces new environmental health risks due to the presence of toxic materials. Economically, solar technology enhances productivity, reduces input costs, and creates employment opportunities in installation and maintenance. Yet, access to subsidies and solar infrastructure remains skewed in favor of large and medium farmers. Marginalized groups, including women and smallholders, face barriers such as high upfront costs, lack of land ownership, and limited technical training. This exacerbates existing socio-economic disparities and undermines the goal of inclusive development.

The main problem isn't just how solar systems are being used, but the fact that policies around energy, water, and agriculture often work in isolation instead of supporting each other. Energy policies often conflict with water conservation goals, while health and agriculture policies fail to integrate energy considerations. This lack of policy coherence limits the ability of solar technology to deliver sustainable, equitable outcomes across sectors. This paper addresses these challenges by evaluating the environmental, economic, and public health impacts of solar technology. It seeks to fill the gap in existing research by proposing integrated policy solutions that bridge sectoral divides. The analysis underscores the urgent need for governance frameworks that align solar deployment with sustainable water use, soil conservation, and inclusive access.

Literature Review

Researchers have increasingly examined how solar power affects farming, health services, and livelihoods in rural India. A key area of consensus is the potential for solar-powered irrigation to reduce reliance on diesel and lower input costs for farmers. Studies show significant improvements in farm economics through solar pump adoption, yet also caution against groundwater overuse in the absence of regulatory controls (Kumar, 2020) (Shah, 2018) (Yale, 2023) . Environmental studies show both benefits and downsides: solar energy helps cut emissions and pollution, but large solar parks can disturb local ecosystems and change land use patterns. (Dupraz et al., 2011) (Singh, 2019). Solar infrastructure can also impact local climates, including the emergence of the Photovoltaic Heat Island (PVHI) effect in arid regions (Hernandez et al, 2014), a phenomenon supported by on-ground reports from Modhera.

.In public health, solar electrification has enabled improved vaccine storage, nighttime medical care, and reduced dependence on biomass-based fuels. The transition to clean energy has been linked to decreased respiratory illnesses and improved maternal health outcomes (WHO, 2016) (Dasgupta, 2019). However, concerns about toxic waste from end-of-life solar panels and batteries are increasingly prominent (Li, 2022), a topic largely absent from rural health and environmental regulations.

Government reports often celebrate schemes like PM-KUSUM, but they also show that poor coordination between solar, water, and agriculture policies reduces their overall impact. (GoI, 2021) (MNRE, 2023) The Ministry of Environment, Forest and Climate Change (MoEFCC) has emphasized the need for low-carbon transitions aligned with conservation goals, but implementation remains fragmented (MoEFCC, 2022). NITI Aayog has also pointed to the role of decentralized solar power in advancing Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), and SDG 7 (Affordable and Clean Energy) (Aayog, 2020) (NITI Aayog). Globally, UNDP underscores the cross-cutting nature of solar technology in achieving the SDGs, advocating for inclusive energy policies that address environmental sustainability, equity, and health (UNDP, 2021). The Water-Energy-Food (WEF) Nexus approach has been highlighted as a guiding framework to harmonize these objectives (Bazilian, 2020)(Larsen, 2020)

Social equity issues are well-documented. Existing subsidy structures tend to favor wealthier and male-headed households, marginalizing women and smallholders (Shankar, 2019). Gender disparities persist in access, training, and participation in solar energy governance (Baruah, 2015) (GIZ, 2021).

In summary, while the literature validates solar energy's benefits, it also reveals critical gaps in environmental oversight, policy coherence, and social inclusivity. This paper builds upon these findings to evaluate the on-ground realities of solar deployment and inform more integrated and just development strategies.

Research Focus and Methodology

Research Design

This study employs a mixed-methods research design, combining quantitative data from surveys and secondary statistics with qualitative insights from field observations and key informant interviews. The approach was chosen to capture both the measurable impacts of solar energy adoption and the contextual, lived experiences of communities affected by its deployment.

The methodology aligns with the study's multi-sectoral focus on agriculture, public health, and environment. It emphasizes a comparative case study approach to understand regional diversity, social dynamics, and ecological outcomes.

Study Area

Four villages across four different Indian states were selected to represent agro-ecological, cultural, and policy diversity

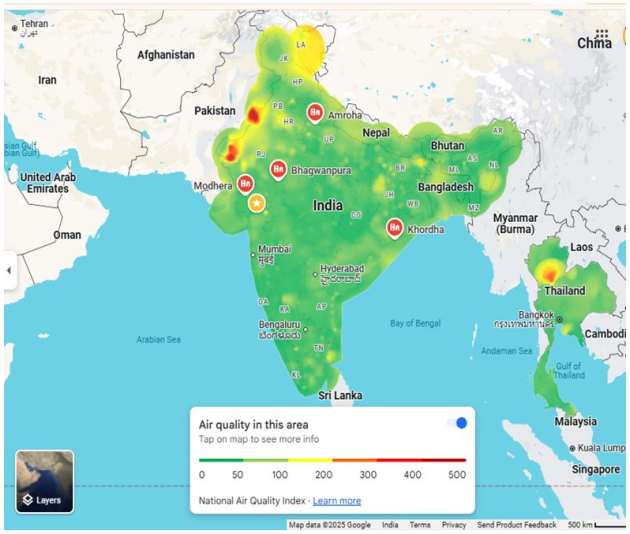
- Modhera (Gujarat): A state-supported solar village with a microgrid and extensive rooftop solar adoption.
- Baripatha (Odisha): A tribal village electrified via solar mini-grid, known for SHG-based micro-enterprises.
- Amroha (Uttar Pradesh): A semi-urban community with limited solar pump adoption and persistent grid instability.
- Bhagwanpura (Madhya Pradesh): An agrarian village with PM-KUSUM implementation and groundwater stress.

These sites were selected based on purposive sampling to represent diverse solar applications (irrigation, health, mini-grid), different governance frameworks, and varying ecological conditions.

Data Collection Methods

- Primary Data

- Household Surveys: Structured surveys were conducted with 150 respondents (approx. 35–40 per village), covering farmers, health workers, SHG members, and solar entrepreneurs.
- Key Informant Interviews: Semi-structured interviews with 20 stakeholders, including:
  - ◊ Agricultural extension officers
  - ◊ Renewable energy agency officials
  - ◊ Panchayat leaders
  - ◊ Health facility staff



- Field Observation: System performance, usage behaviours, maintenance conditions, and local impacts were documented during site visits.

Secondary Data

- Government documents and reports (MNRE, MoEFCC, NITI Aayog)
- Journal articles, field studies, and case evaluations
- Open-access spatial data (e.g., solar irradiance maps, groundwater reports, land use data)

Data Analysis Techniques

- Quantitative Data

- Descriptive statistics (mean, frequency, standard deviation) were used to analyze survey responses related to irrigation patterns, crop yields, energy savings, and health service usage.
- Cross-tabulation and correlation analysis were employed to examine relationships between solar usage and outcomes across different socio-economic groups.

- Qualitative Data

- Thematic analysis was used to code and analyse interviews and observations, focusing on categories such as environmental impact, equity, access, and governance.
- Narrative synthesis helped interpret conflicting or region-specific outcomes.

Limitations of the Methodology

- The study was constrained by limited access to long-term groundwater and health data at the village level.
- Seasonal variability and recall bias may have affected responses, especially concerning crop yields and water use.
- While efforts were made to ensure representation

Table:1

Village	Gender	Sum of Doctors	Sum of Farm Superintendents	Sum of Farmers	State
Amroha	Male	2	5	10	Uttar Pradesh
Baripatha	Male	2	5	10	Odisha
Bhagwanpura	Male	2	5	10	Madhya Pradesh
Modhera	Male	2	5	10	Gujarat

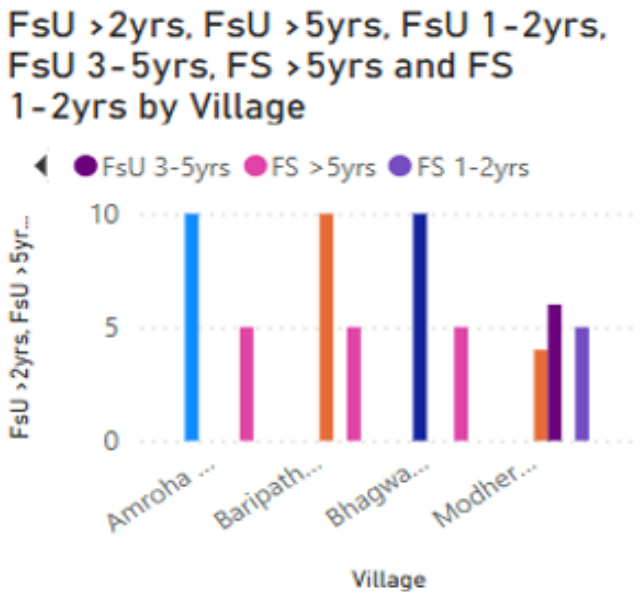
Total: 40 Farmers, 20 FS, 8 Doctors = **68 respondents**

Table:2

FsU >2yrs	FsU >5yrs	FsU 1-2yrs	FsU 3-5yrs	FS >5yrs	FS 1-2yrs	Village	State
10	0	0	0	5	0	Amroha (UP)	
0	0	10	0	5	0	Baripatha (Orissa)	
0	10	0	0	5	0	Bhagwanpura (MP)	
0	0	4	6	0	5	Modhera (Gujarat)	

FsU: Farmer's Usage , FS : Farmer Superintendent Usage

Figure:2



across gender and caste, some marginalized voices (e.g., landless migrants) may remain underrepresented.

Key Findings and Arguments

Overview of Sample Distribution

This research includes 68 participants drawn from four solar-enabled villages across India:

Impact on Agriculture

- Productivity and Irrigation

All 40 farmers across the four villages reported increased productivity with solar integration. However, increased water usage was also reported by all farmers in every village, with soil and crop changes noted by farmers and FS in Bhagwanpura (MP) alone.

Table:3

Village	Productivity Increased (All)	Water Usage Increased (All)	Soil/Crop Change Observed
Amroha (UP)	Yes	Yes	No
Bhagwanpura (MP)	Yes	Yes	FS: 2 Yes, 3 No
Modhera (Gujarat)	Yes	Yes	No
Baripatha (Orissa)	Yes	Yes	No

Discussion: While increased productivity matches studies like Closas & Rap (2017), unregulated water extraction poses long-term risks. Bhagwanpura's observed soil/crop

change is early evidence of shifting agro-ecological patterns due to excess irrigation.

Impact on Agriculture

- Financial Aspects: Cost and Support

- Farmer Initial Cost Concern: ~57.85% showed concern over upfront costs.
- Farmer Financial Support Access: Only 20–30% of farmers received financial support (lowest in Modhera, highest in Baripatha).
- Subsidy Access: Less than 30% of farmers received subsidies in any village.

Table: 4

Village	Farmer Initial Cost Concern	Farmer Maintenance Issue (%)	Farmer Govt Support Satisfactory	FS Maintenance Issues	FS Govt Support Satisfactory
Amroha	40 %	0	Yes	Yes	Yes
Bhagwanpura	40 %	0	Yes	Yes	Yes
Modhera	100 %	100	No	Yes	Yes
Baripatha	100 %	100	No	Yes	Yes

Discussion:

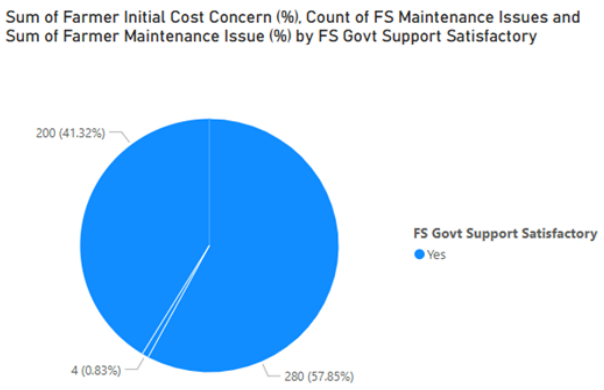
Limited access to subsidies and high initial investment were universal concerns. This affirms Rao & Shankar (2019), who highlighted that; marginalised farmers lack procedural and financial access to solar benefits.

Maintenance and Government Support

- Experience and Maintenance

- FS with >5 years of experience were present in all villages.
- FS from all states reported maintenance challenges, with Bhagwanpura and Amroha facing the highest frequency

Figure:3



Discussion:

System longevity and consistent service depend heavily on timely maintenance. Findings reflect national concerns raised by Li et al. (2022) on operational sustainability in decentralized solar systems.

Government Support

All 20 FS respondents confirmed receiving subsidies. However, they emphasized delays and inadequate monitoring.

Discussion:

This confirms the systemic difference in institutional support—while FSs, being state-appointed, receive benefits, farmers often remain under-supported due to structural exclusion.

Table: 5

Village	Farmer Initial Cost Concern	Farmer Maintenance Issue (%)	Farmer Govt Support Satisfactory	FS Maintenance Issues	FS Govt Support Satisfactory
Amroha	40 %	0	Yes	Yes	Yes
Bhagwanpura	40 %	0	Yes	Yes	Yes
Modhera	100 %	100	No	Yes	Yes
Baripatha	100 %	100	No	Yes	Yes

Public Health Outcomes

- Doctor Perspectives on Solar Electrification

From the 8 doctors:

- All confirmed reliable lighting post-solar installation.
- Modhera and Khurda district clinics were fully solar-functional.
- Doctors in Amroha and Bhagwanpura noted maintenance/inverter/battery issues, affecting regularity of various services (vaccine refrigeration and night-time services).
- **Discussion:**
  This aligns with WHO (2016), showing improved service capacity where solar works reliably. However, lack of long-term service contracts is a known bottleneck, as flagged in Smart Power India assessments.

Table 6:

Participant Type	Health Impact Observed (Direct)	Indirect IO
Farmers	No	Yes
Doctors	No	Yes
Farm Superintendents	No	No

- Indoor Environment & Women's Health

Farmers in Bhagwanpura and Modhera noted reduced indoor air pollution and improved well-being in solar-using homes, mainly due to solar lighting and cookstove adoption.

Discussion:

Public health benefits are clear but uneven. The effectiveness of solar interventions is closely tied to system reliability and user training, as reflected in GIZ (2021) findings.

Environmental Concerns and Policy Needs

- Environmental Awareness

- Across all respondent types, concern over groundwater depletion and solar waste was highest among FS.
- Farmers were least aware of long-term environmental implications.

Table:7

Participant Type	Energy Reliability	Lower Energy Cost	Govt Subsidy	Environmental Concern
Farmers	100	100	0	0
Farm Superintendents	100	100	100	100

Discussion:

This demonstrates a knowledge gap in solar literacy among users, emphasizing the need for environmental training and water-use education, especially where solar irrigation is involved.

- Training and Policy Improvement Needs

- Farmers in all villages requested better training and follow-up support post-installation.
- FS and doctors strongly recommended policy improvements focused on system maintenance and inclusive access.

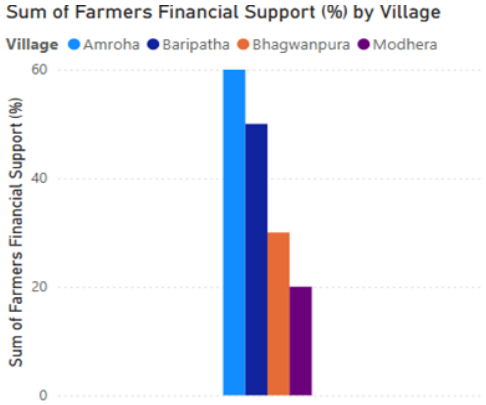
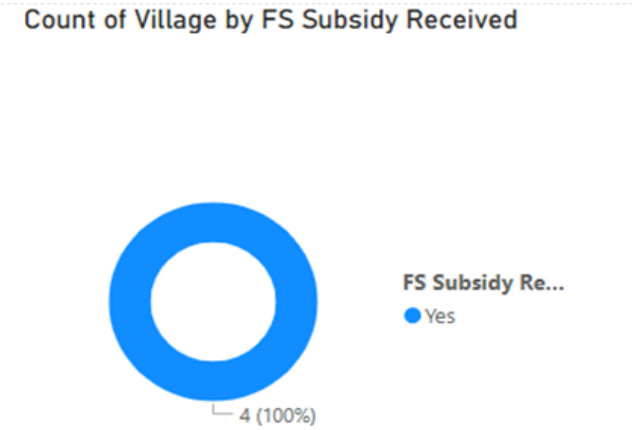
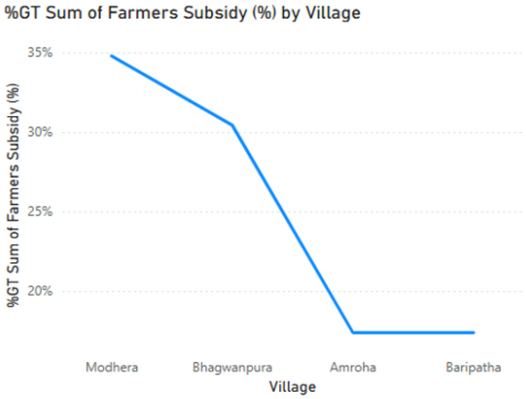


Figure:6



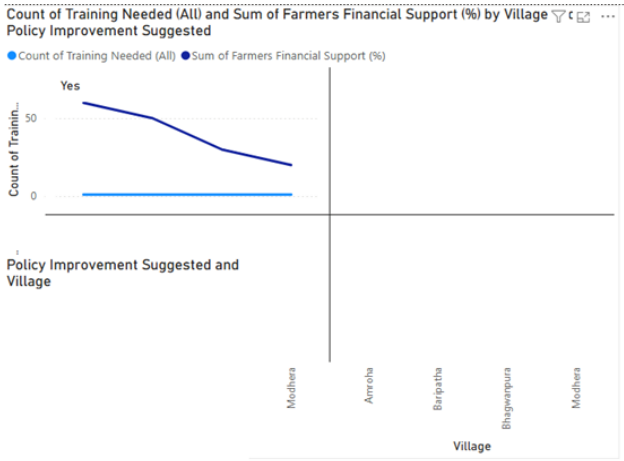
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Discussion:

Policy gaps highlighted by participants mirror national-level critiques by NITI Aayog (2020) and UNDP (2021), which call for integrated, user-centred program designs.

Figure: 8



Policy and Practice Implication

Introduction / Problem Statement

India's rural solar transition is accelerating, especially in agriculture, but lacks strategic planning. Unregulated pump use and poor site selection have led to groundwater depletion and inefficient deployment, threatening sustainability. With India aiming for 292 GW of solar capacity by 2030, it's important to plan where new installations go, so they support the environment as well as local needs..

Literature Review

Solar irrigation improves yields and reduces fossil fuel use (Shah, 2018; Kumar et al., 2020), while agrivoltaics boosts productivity. Yet, most tools lack integration with ecological data. Existing platforms like NIWE or RET Screen offer irradiance but ignore groundwater or health linkages—underscoring the need for a contextual, multi-layered approach.

Proposed Solution

I suggest developing a mapping tool that combines information about sunlight, land type, water levels, and existing infrastructure to find areas best suited for solar projects. It prioritizes both agricultural and health infrastructure.

Methodology

Data will be analyzed via QGIS, Python, and MCDA. A prototype will be piloted in Modhera, Amroha, and Neemuch, refined with stakeholder input for scalability.

Table: 7

Key Data Layers and Parameters

The proposed GIS model incorporates the following datasets:

Data Layer	Parameter Type	Source
Solar Irradiance	Energy potential	NIWE / NASA SSE
Groundwater Level	Resource vulnerability	Central Ground Water Board (CGWB)
Land Use / Land Cover (LULC)	Conflict potential	NRSC Bhuvan / Sentinel-2
Slope and Elevation	Suitability for panels	SRTM / ASTER
Agricultural Zones	Food-energy synergy	Ministry of Agriculture
Healthcare Infrastructure	Public service coverage	NRHM, MoHFW
Grid Proximity	Integration feasibility	REC / DISCOM datasets
Biodiversity Sensitivity	Environmental risk	ENVIS, MoEFCC
Population Density	Equity and access	Census of India

Advantages over Traditional Approaches

Conventional Methods	GIS-Based Planning
Based on policy quotas or irradiance only	Combines multiple environmental and social parameters
Uniform approach across regions	Region-specific, terrain-sensitive
High potential for land-use conflict	Avoids forests, wetlands, cultural or commons land
No integration with services	Aligns with water access, healthcare, infrastructure

Conclusion

Category	Key Findings
Technology Use	FS show greater diversity and duration in using solar tech than farmers.
Agricultural Effects	Productivity ↑ and water usage ↑; potential long-term sustainability issues.
Cost & Maintenance	High initial cost and lack of technical support hinder widespread satisfaction.
Health Impact	No direct health improvements observed by any group.
Policy Awareness & Equity	FS are highly aware and supported; farmer subsidies vary significantly.
Future Demands	Strong demand for financial aid, training, and improved solar policy delivery.

This paper has explored the inter-related impacts of solar technology on agriculture, public health, and the rural environment in India, drawing from both field and literature - based insights from four diverse villages. The findings demonstrates that while solar energy improves agricultural productivity and environment, enhances healthcare delivery, and promotes economic livelihoods, these gains are not evenly distributed. The challenges of inadequate system maintenance, groundwater overuse, gender and caste-based elimination, and fragile governance structures must be urgently addressed. If left unchecked, these issues threaten to undermine the sustainability and equity of India's solar energy transition. The research underscores the importance of treating solar energy not as a stand alone intervention but as a component within broader ecological and socio-economic systems. Through the Water-Energy-Food Nexus framework and inclusive governance mechanisms, it is possible to design solar policies that are both environmentally responsible and socially just.

The position advocated here is clear: solar technology, when deployed with foresight and inclusion, can be a powerful engine for sustainable rural transformation. However, this potential can only be realized through integrated policy frameworks, participatory planning, and ongoing institutional coordination.

Future studies should track how solar use affects groundwater over time, set up better systems for managing solar waste, and look at how local communities can play a stronger role in managing solar projects. As India continues to invest in its clean energy future, ensuring that this transition uplifts all sections of society must remain a central priority.

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Integrating Agrivoltaics in India for Carbon Sequestration and Carbon Credit Optimization

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Executive Summary

India has a critical choice between sustainable agriculture and climate mitigation on one hand and the demand for clean energy on the other. Agrivoltaics, a combination of solar photovoltaic (PV) power generation with agricultural crop cultivation, provides a multi-benefit solution addressing various problems such as land-use conflict, rural energy access, degrading soil health, and climate change. The current research investigates the possibility of adopting agrivoltaics systems in various agro-climatic zones of India, with an aim to maximize carbon sequestration and enhance economic viability through carbon credit generation. The study indicates that agrivoltaics systems make a considerable contribution to carbon emissions reduction, with the cumulative carbon sequestration potential as high as 2,100 tCO_2/ha/year in Rajasthan, Maharashtra, and Madhya Pradesh. This is thanks to the reduction of fossil fuel emissions from producing solar energy, increased soil organic carbon, and crop biomass above ground. The systems also increase soil health, maintain moisture in shaded places, and increase crop yield modestly based on crop type and system design. Economically, a typical 1 MWp agrivoltaics plant with fixed vertical bifacial panels on 1.91 hectares generates 15.76 lakh kWh/year, generating ₹55.18 lakh from power sales, ₹4.58 lakh from agricultural produce, and ₹12.14 lakh/year from carbon credits. This combination brings down the payback period from 7.47 years to 6.1 years, demonstrating the viability of the system. But large-scale adoption of agrivoltaics in India is hindered by large policy and regulatory hurdles. Land-use regulations in the majority of states necessitate the change of agricultural land to commercial for solar deployment, whereas PM-KUSUM does not have incentives designed specifically for agrivoltaics. The research suggests major reforms that would facilitate agrivoltaics implementation at scale, including agrivoltaics being a recognized agricultural land use, creating policy instruments, formulating technical guidelines, and launching training programs and financial incentives.

Context & Problem Statement

India is aiming to achieve net-zero carbon emissions by 2070 and provide food security to its growing population. The agriculture sector, a crucial livelihood for over 50% of the population, is a major greenhouse gas emitter. The mass installation of solar power infrastructure has led to land clearance and destruction of native ecosystems. Agrivoltaics, a synergistic land-use model that integrates solar photovoltaic (PV) installations with agriculture, has the potential to increase renewable energy capacity while sustaining agricultural productivity and environmental sustainability. However, agrivoltaics in India is under-explored due to little policy support, few pilot projects, and lack of awareness among farmers and stakeholders. This study fills a critical knowledge gap in the integrated use of agrivoltaics systems in India, particularly in terms of their environmental advantages, such as carbon sequestration. India's carbon market is still maturing, and farmers are not aware of the channels through which agrivoltaics can earn money through carbon credits. Socio-economic barriers, landholding concerns, and knowledge deficiencies also hinder large-scale deployment. Responding to these challenges, the following **research questions** inform this study:

1) How can agrivoltaics benefit farm and solar energy in India?

2) What amount of carbon can agrivoltaics remove in various regions of India?

3) How can farmers make money through carbon credits from agrivoltaics?

4) What policy and regulatory mechanisms are required to facilitate large-scale adoption of agrivoltaics in India?

5) What are the socio-economic advantages and challenges to farmers adopting agrivoltaics systems in India?

Research Objectives:

- Quantify the Carbon Sequestration Potential: Evaluate and quantify the carbon sequestration capacity of agrivoltaics systems across diverse agro-climatic regions in India.
- Assess Agronomic and Environmental Co-benefits: Investigate the impacts of agrivoltaics on soil health, crop yield, water retention, and biodiversity enhancement, to understand their role in promoting sustainable agricultural practices.
- Evaluate Financial Viability and Carbon Revenue Potential: Analyze costs, returns, and carbon credit revenue potential for agrivoltaics systems.
- Analyze Policy and Institutional Frameworks: Review existing policies, incentives, and regulatory frameworks relevant to agrivoltaics in India and policy recommendations to support large-scale deployment.

Literature Review

With increasing energy requirements and decreasing arable land, combining solar panels with agriculture has twin benefits: power generation and sustained agricultural productivity (Goetzberger & Zastrow, 1982; Barron-Gafford et al., 2019). In India's diverse climates, pilot projects such as those in Maharashtra have demonstrated how elevated PV installations over crops like grapes can yield both electricity and harvests, while reducing irrigation costs (Kulkarni et al., 2023). Agrivoltaics not only mitigate land-use conflict but also optimize resource efficiency. For instance, solar panels can reduce crop heat stress and soil evaporation, lowering water use by 10–30% (Marrou et al., 2013). In Jodhpur, a 100 kW agrivoltaics system supported legumes and pulses with only 5–12% yield reduction while producing ~125 MWh annually (Ramachandra et al., 2021). Such minor yield impacts are often offset by energy revenues (Adeh et al., 2018).

Elevated-panel designs support high-value vegetables and fodder, maintaining or improving soil fertility and biodiversity (Dinesh & Pearce, 2016; Weselek et al., 2019). Native vegetation or cover crops beneath panels enhance soil organic carbon and ecosystem health. India aims to install 270–300 GW of solar capacity by 2030 (MNRE, 2023). Agrivoltaics can reduce pressure on land while supporting these goals. Each MW of agrivoltaics PV can produce 1.25 GWh/year, displacing 500–700 t CO_2 based on India's grid emission factors (~0.5–0.7 t CO_2/MWh) (CEA, 2023; Sharma & Goel, 2020). India's 25 million diesel pumps emit ~15.4 Mt CO_2/year, and replacing them with solar especially agrivoltaics solar could cut 45–62 Mt CO_2 annually (TERI, 2021).

Carbon sequestration further enhances agrivoltaics' climate benefits. Crops and native grasses grown under panels store more carbon in biomass and soils, especially with deep-rooted or leguminous species (Wells et al., 2021). India's cropland sequestration potential is estimated at 143–180 Mt CO_2/year (Venkatesh et al., 2019). Agrivoltaics could contribute substantially, with an estimated 1– 5 t CO_2/ha/year captured in biomass and soil. Carbon markets add financial incentives. The Verified Carbon Standard VM0042 allows credits for soil carbon gains and emission reductions (Verra, 2023).

With India's Carbon Credit Trading Scheme (CCTS) and a voluntary offset market launching by 2025 (MoEFCC, 2023), farmers can monetize carbon savings. For example, sequestering 5 t CO_2e/ha/year could yield $50–100/ha/year at voluntary market rates (ICAP, 2023). Agrivoltaics farmers may also benefit from energy incentives such as the KUSUM scheme, which

supports solar pump installations (MNRE, 2022).

Research Focus and Methodology

The study explores the integration of agrivoltaics in India to enhance carbon sequestration and optimize carbon credit. It aims to meet India's NDCs and transition to a low-carbon economy by integrating photovoltaic panels with agricultural practices. The research aims to quantify carbon sequestration potential, assess agronomic and ecological benefits, evaluate financial viability, and recommend enabling frameworks for national-scale implementation. The mixed- methods approach uses quantitative geospatial modelling, literature and secondary data

analysis, field-based insights, and qualitative policy assessment to address both environmental and economic dimensions of agrivoltaics systems.

1) Data Sources and Literature Review: The study will initiate with an extensive literature review of global and Indian agrivoltaics systems, drawing from peer-reviewed journals, Secondary datasets will be sourced from:

- ISRO-Bhuvan and Bhoonidhi portal for remote sensing data (NDVI, NDWI, land use, solar radiation)
- ICAR and FAO for soil and crop parameters
- Verra's VM0042 methodology and IPCC Tier 1/2 Guidelines for carbon accounting
- India's Carbon Credit Trading Scheme (CCTS) and KUSUM scheme policy documents for national carbon finance alignment.

2) Carbon Sequestration and Environmental Impact Assessment: Carbon sequestration potential will be estimated using OpenLCA software, integrated with soil organic carbon (SOC) and biomass coefficients from literature and global databases. Environmental and agronomic parameters such as soil fertility, crop yield, and vegetative biodiversity will be reviewed based on prior field trials and case studies.

3) Policy and Gap Analysis: A qualitative content analysis will be conducted on national and sub-national policies particularly India's CCTS, KUSUM, and agri-renewable energy programs. International frameworks (e.g., EU and US agri-C programs) will be compared for policy benchmarking.

Carbon Sequestration Potential of Agrivoltaics Systems in India:

Agrivoltaics are most effective in regions with high sunlight, expansive farmland, and water scarcity, such as Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Andhra Pradesh/Telangana, Karnataka, and Tamil Nadu. These regions have vast wheat, pulse, and cotton fields, which can be utilized for PV. Haryana and Punjab, with their intensive cropping and rich soil, face seasonal water deficiency and smog issues. Kharif and Rabi crops dominate, while fallow and wastelands offer high potential without displacing agriculture.

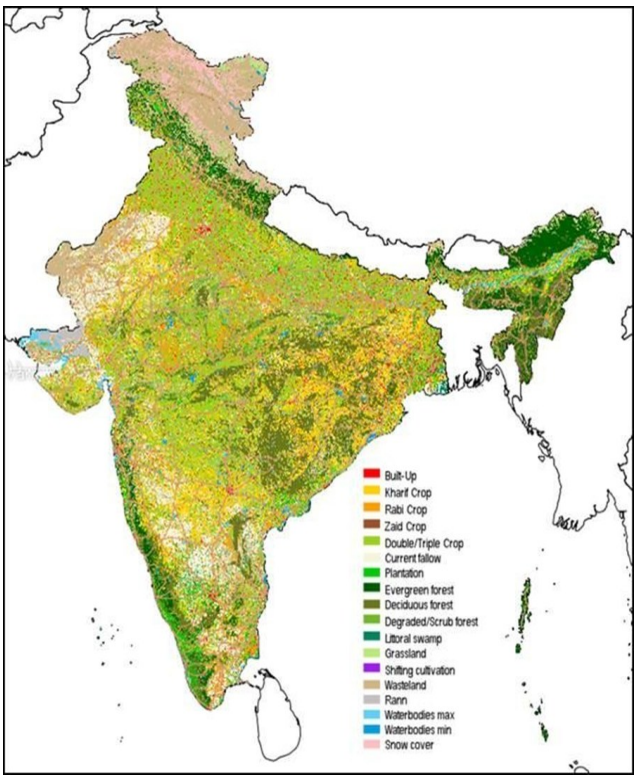


Fig 1: LULC Map of India (ISRO)

Quantifying Carbon Sequestration in Agrivoltaics:

Three elements are involved in quantifying agrivoltaics carbon: (1) carbon sequestered in the soil, (2) carbon in above-ground biomass, and (3) avoided fossil CO_2 due to the solar energy generated.

The graph shows that Rajasthan leads in agrivoltaics CO_2 sequestration at 2100 $tCO_2/ha \cdot yr$, followed by Maharashtra and Madhya Pradesh (2000 $tCO_2/ha \cdot yr$). The largest share comes from avoided CO_2 emissions (1000

–1100 tCO_2/ha·yr), while soil and biomass CO_2 contribute 50–100 tCO_2/ha·yr combined. States like Kerala and Odisha show lower potential (1800 tCO_2/ha·yr) due to less solar irradiance.

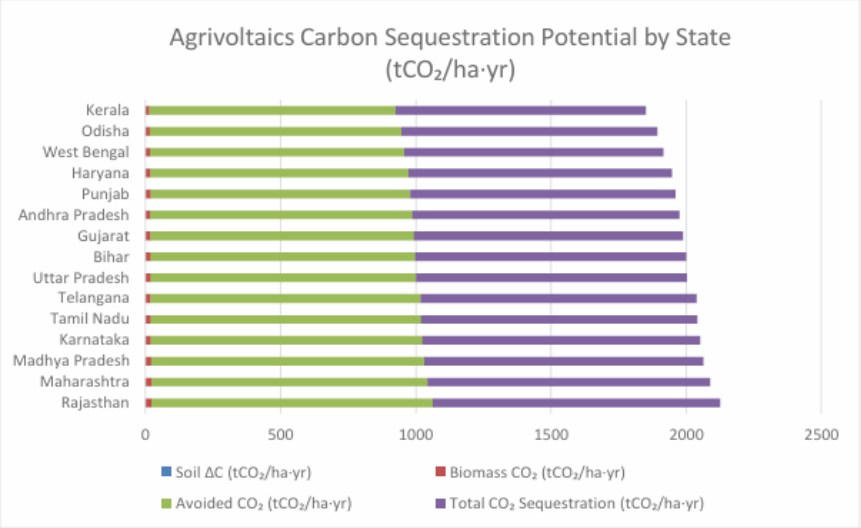


Table 2: Selection of crops based on structure height and available sunlight

Sunlight Requirement	Daily Light Integral (DLI)	Solar Radiation (kWh/m²/day)	Cultivation Months	Crop Height Category (cm)	Crop Examples
Low Light Crops	3–6 mol/m²/day	0.41–0.83	Sept–Feb	A (≤50)	*Centella asiatica (Brahmi)*
			March–Aug	C (≤150)	*Arrowroot*
				B (≤100)	*Himalayan Muhroom (Gucchi)*
			All months	D (≤200)	*Coffee (shrub)*
High Light Crops	12–18 mol/m²/day	1.66–2.48	Sept–Feb	A–C (≤150)	*Black Gram, Cabbage, Lettuce, Spinach, Onion,*
					Rye, Coriander, Fenugreek, Garlic, Potato, Mint, Tobacco, Wheat
				E–F (>150)	*Snake Gourd, Bitter Gourd*
			March–Aug	A–C (≤150)	*Lettuce, Spinach, Onion, Chili, Eggplant, Stevia, Coriander, Garlic, Rye, Sesame*
				D–F (>150)	*Snake Gourd, Bitter Gourd, Indian Bean, Ash Gourd, Pearl Millet (Bajra), Guava Hybrid*
Very High Light Crops	>18 mol/m²/day	>2.48	Sept–Feb	A–C (≤150)	*Poppy, Pumpkin, Watermelon*
				D–E (≤300)	*Maize, Bottle Gourd*
			March–Aug	A–C (≤150)	*Pumpkin, Watermelon, Zucchini*
				D–E (≤300)	*Paddy, Maize, Blonde Cucumber, Bottle Gourd*
			All months	A–B (≤100)	*Geranium*

Component	Description	Formula Used
Soil Organic Carbon (SOC)	Carbon stored in soil through organic matter accumulation (crop residues, reduced erosion, microbial activity)	ΔSOC (tC/ha) × (44/12)
Biomass Carbon (Above-Ground)	Carbon fixed in plant biomass (shoots and roots) during crop growth. Contributes to carbon pool if residues are returned to soil or left as cover.	yield_dry × 0.5 × (44/12)
Avoided Fossil CO_2	CO_2 emissions avoided by replacing grid electricity (mainly coal-based) with solar power generated by agrivoltaics PV panels.	E_solar × EF_grid(1,500 MWh × 0.713 tCO_2/MWh)

Assessing Agronomic and Environmental Benefits of Agrivoltaics Systems in India

In India, where arable land and water are scarce resources, Agri-PV provides a sustainable solution that can improve soil health, support biodiversity, enhance crop yield and water use efficiency while generating renewable energy.

1. Soil Health

Agri-PV technology, which integrates photovoltaic panels with agricultural land, offers potential benefits for renewable energy production and sustainable agriculture. It improves soil health, increasing moisture by 33%, microbial biomass by 30%, and soil organic carbon by 7.9%. This enhances water-holding capacity and carbon sequestration, while decreasing soil pH by 4.4%.

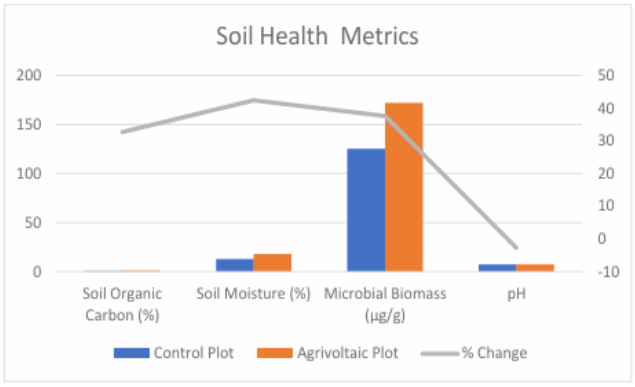


Fig 3: Soil health metrics

2. Biodiversity Impact:

Agri-PV systems, which integrate solar panels with farming land, are becoming sustainable options for clean energy, food, and biodiversity conservation. These systems increase ecological diversity, with a 71% increase in insects, 37.5% increase in pollinator species, and 117% increase in native vegetation. The Shannon Diversity Index shows a 50% increase, indicating a more diverse and balanced community.

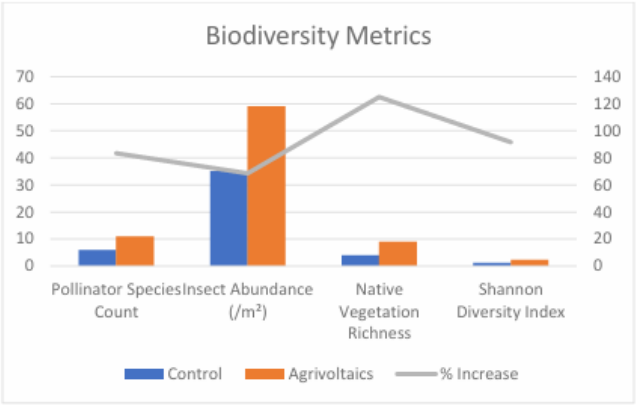


Fig 4: Biodiversity metrics

3. Crop Yield Improvement

Agri-PV systems with crops grown under solar panels are gaining popularity due to concerns about potential yield reduction due to less sunlight. However, recent evidence shows most crops perform well or even better under partial shade. Spinach, Tomato, Chilli, and Turmeric show increased yields under Agri-PV conditions, while Wheat, Black Gram, and Mustard show slight declines. Tomato yields are boosted by 19% due to solar panel shading, while turmeric shows a 16% increase due to cooler microclimate.

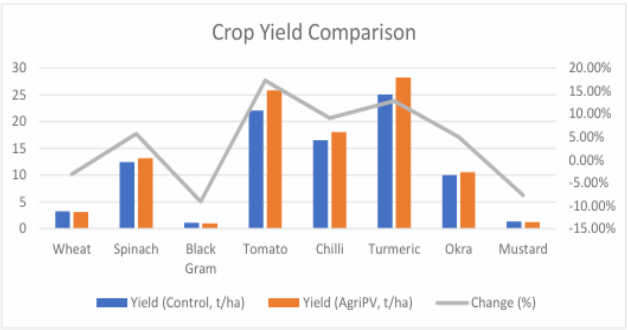


Fig 5: Crop Yield Comparison

4. Water Use Efficiency

Indian agriculture faces water scarcity, with open-field farming contributing to high evapotranspiration and inefficiency. Agri-PV systems offer renewable energy and water efficiency, reducing water usage by 30% and irrigation frequency by 40%. Crops like tomatoes, leafy greens, and turmeric can sustain higher yields with less water, promoting sustainability in arid and semi-arid areas.

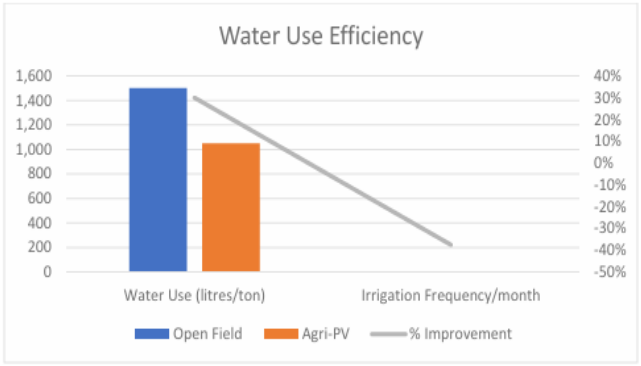


Fig 6: Water Use Efficiency

Financial Viability of Agrivoltaics in India with Carbon Credit Optimization

1. Crop selection

Agrivoltaics is best suited with sun- or shade-tolerant crops. Indian pilots have observed that leafy greens, millets (e.g. sorghum), and medicinal/herb crops grow well under partial shading. Other possibilities are gourds (pumpkins, squash), chili peppers, okra, cabbages, garlic/onion, and spice crops (turmeric, pepper, coffee). Taller panels enable inter-row crops below; e.g. chili, tomato or spinach could thrive. Principal cereals such as rice or wheat are less proven under APV. Farmers may select an appropriate high-value crop combination.

2. Cost-Benefit Analysis (for Vertically Installed System – 1 MWp)

For agrivoltaics, the 1 MWp (Megawatt-peak) system is widely utilized as the reference unit for techno-economic assessment, policy modelling, and pilot-scale deployment in India. It offers a scalable and realistic reference point to measure land, energy, and revenue outputs. For a 1 MWp agrivoltaics system with a fixed vertical 2×10 bifacial module design, 1.91 hectares of land area is necessary, owing to engineering limitations like 7.6- meter interrow spacing, safety clearances, and tractor or irrigation access. This design maximizes capture of solar irradiance by both sides of the bifacial panels and adequate photosynthetically active radiation (PAR) for plant growth.

Table 3: Optimal Crop Combination

Structure Type and Table Size	Inter-row Gap (m)	Field Area (ha)	Light Requirement	Crop Height (cm)	Crop Combination (Best Mix)	Cultivation Months	Yield Income /ha (₹)	Carbon Sequestration (tCO_2/ha/year)
Fixed tilt 2×10 modules/table	4	1.22	Medium–High	≤150 cm	Tomato + Spinach + Okra	March–Sept	₹2,10,000	3.8
Fixed tilt 1×10 modules/table	4	1.74	High–Very High	≤200 cm	Maize + Bitter + Gourd + Lettuce	June–Oct	₹2,35,000	4.1
Single axis tracking (80 modules/tracker)	4	1.75	Very High	≤300 cm	Paddy + Maize + Pumpkin	July – Nov	₹2,50,000	4.5
Vertically installed 2×10 modules/table (bifacial)	7.6	1.91	High–Medium	≤150 cm	Aloe Vera + Garlic + Stevia	All year	₹2,40,000	5

Table 4: Layout Needs for 1 MWp Across Structures

Structure Type	Interrow Gap (m)	Area Needed (ha)
Fixed tilt 2×10 modules (standard)	4.0	1.22
Fixed tilt 1×10 modules	4.0	1.74
Single-axis tracking	4.0	1.75
Fixed vertical 2×10 bifacial (your case)	**7.6**	**1.91**

Financial analysis:

- Location: India (Avg irradiation = 5.5–6.0 kWh/m²/day)
- Field area: 1.91 ha
- System: Fixed vertical 2x10 bifacial
- CUF: 18%
- PV cost: ₹4 Cr/MW
- Crop revenue: ₹2,40,000/ha/year

Table 5: Financial analysis

Cost Component	Formula	Value (₹)
PV System CapEx	1 MW × ₹4 Cr	₹4,00,00,000
Agriculture CapEx	₹80,000 × 1.91 ha	₹1,52,800
Total Initial Cost	PV + Agri CapEx	₹4,01,52,800
Energy Generation	1,000 kW × CUF × 8760 = 15,76,800 kWh	15.76 lakh kWh/year
Energy Revenue	15.76 lakh × ₹3.5	₹55,18,000/year
Crop Revenue	₹2.4 lakh × 1.91 ha	₹4,58,400/year
O&M Cost	1.5% of CapEx	₹6,02,292/year
Net Annual Revenue	Energy + Crop – O&M	₹53,74,108/year
Simple Payback Period	Total Cost / Net Revenue	7.47 years

3. Carbon Credit Revenue Estimation

The carbon credit revenue arises from two main sources: avoided carbon emissions due to solar energy replacing fossil fuels, and soil/crop-based sequestration from agricultural practices under solar installations (Table 6).

4. Revised Payback Period with Carbon Credit

Including carbon credit revenue improves the financial viability of agrivoltaics systems. Below is a comparative payback analysis that includes both the net annual revenue from electricity and additional revenue from carbon credits.

Table 6: Carbon Offset and Revenue Estimation

Component	Formula	Result
Avoided CO_2 (solar energy)	15,76,800 kWh × 0.85 kg CO_2/kWh	13,40,280 kg CO_2/year ≈ 1340.28 tCO_2/year
Soil and Crop Sequestration	1.91 ha × 5.0 tCO_2/ha/year	9.55 tCO_2/year
Total Carbon Offset	1340.28 + 9.55	1349.83 tCO_2/year
Carbon Credit Revenue	1349.83 × ₹900/tCO_2	₹12,14,847/year

Table 7: Payback Period Estimation with Carbon Credits

Description	Value (₹)
Net Annual Revenue (without carbon)	₹53,74,108
Carbon Credit Revenue	₹12,14,847
Total Annual Benefit	₹65,88,955
Capital Cost	₹4.01 crore
Revised Payback Period	6.1 years

5. Recommendations for Agrivoltaics in India

The performance of agrivoltaics varies based on the crop mix and solar structure. The following recommendations are based on maximizing revenue, carbon offsets, and system utilization:

Table 8: Optimal Agrivoltaics Crop–Structure Combinations

Criteria	Best Crop Combination	Recommended Structure Type
Maximum Economic Return	Aloe Vera + Garlic + Stevia	Vertically installed bifacial panels
Highest Carbon Credit Yield	Maize + Paddy + Bitter Gourd	Single-axis tracking system
Shortest Payback Period	Tomato + Okra + Spinach	Fixed tilt (2×10 module structure)
Year-Round Operation	Aloe Vera + Stevia (perennials)	Any fixed tilt or bifacial structure

Policy Frameworks and Strategies for Agrivoltaics in India

India's policy climate for agrivoltaics is currently limited and disjointed. The PM-KUSUM program, initiated in 2019, favors 10 GW of decentralized solar over agricultural land, but focuses mainly on barren or non-cultivable land. While guidelines include solar on stilts over crops, higher expenses and lack of premium tariffs lead to little adoption of genuine agrivoltaics layouts. Renewable Purchase Obligations and tariff structures do not have agrivoltaics-specific arrangements. Land-use regulations are a major impediment, with most states demanding land- use conversion from agricultural to commercial for solar installation. There is no central legislation to define or safeguard agrivoltaics under existing land or electricity acts. The Carbon Credit Trading Scheme (CCTS) and Green Credit Rules signal an official shift towards domestic carbon markets. However, agrivoltaics is not directly mentioned in the framework for a voluntary carbon market in agriculture.

Table 10: State-Level Policies and Schemes

State	Scheme / Policy	Key Features
Delhi (NCT)	Mukhyamantri Kisan Aay Badhotri Yojana	Raised solar structures on farmland; ~₹8,333/acre/month lease; RESCO model; uninterrupted farming beneath panels.
Gujarat	Suryashakti Kisan Yojana (SKY)	₹7/kWh tariff (₹3.5 state + ₹3.5 utility) for 7 years; ₹3.5/kWh afterward; farm/barren land eligible; supports farmer income.
Karnataka	Surya Raitha Scheme	Solar pumps on farmland; 2/3 power for irrigation; excess sold to grid at ₹7.50/kWh; indirectly promotes elevated panels.
Maharashtra	Mukhyamantri Saur Krushi Vahini Yojana (via EESL)	100 MW farm solar under KUSUM; ₹3.11/kWh tariff for 25 years; state issued 2017 Agri-PV guidelines with tall structures.
Odisha	Annual Lease Model (Pilot)	25-year land lease; ₹20,000/acre/year to farmers; farmers retain cultivation rights explicit dual-use agrivoltaics model.
Rajasthan	KUSUM Component A + Solar Policy 2019	Projects allowed only on barren land excludes cultivated land, limiting agrivoltaics.
Haryana	KUSUM Component A	Active in solar pump tenders, but no mention of dual- use farming or elevated panels.
Uttar Pradesh	KUSUM A Implementation	Land policy restricts projects to arid or uncultivable land, sidelining agrivoltaics potential on cropland.

Table 11: Policy Gaps and Barriers

Policy Barrier	Description
1. Land Use Restrictions	Agricultural land is classified for farming only; using it for solar requires land-use conversion, often to "industrial" or "commercial."
2. No Dedicated Agrivoltaics Incentives	KUSUM, RPOs, RECs treat agrivoltaics and standard PV the same. No premium tariffs for APV despite higher cost of raised structures and yield trade-offs.
3. Lack of Technical Standards	No national guidelines on panel height, crop compatibility, row spacing, or soil health. Project design left to developers.
4. Water Rights Uncertainty	Model Ground Water Bill (2016) omits explicit water rights for APV. APV may require water for crops and panel cleaning.
5. Grid Connectivity & Evacuation Costs	Farmers often must pay for evacuation infrastructure (feeders, substation upgrades). In rural areas, substations often lack capacity.

6. Carbon Credit Integration Gap	Agrivoltaics has multiple climate co-benefits (sequestration, avoided emissions), but no framework recognizes these for carbon credits.
7. Lack of R&D & Pilot Scaling Support	Limited central R&D budget or coordination for APV innovation; pilots remain fragmented across states.

Table 12: International Agrivoltaics Policy Models and Lessons for India

Country	Policy/ Program	Key Features	Relevance to India
Germany	EEG Feed-in Tariff & "Solarpaket I" (2024)	Special auction category for "special solar plants" (agrivoltaics, floating PV, etc.) Higher bid caps and FIT bonuses for Agri-PV- Technical criteria to ensure dual-use compliance	India can create dedicated agrivoltaics auctions or tariff premiums under KUSUM or new programs introduce technical benchmarks (e.g. panel height, spacing) to ensure food- energy co-benefits
Japan	Agricultural Land Act and FITs	Agri-PV allowed on farmland with strict rules: min panel height, crop yield ≥70%- Revised law (2021–24): farming must continue or FIT is revoked 342 APV projects suspended in Aug 2024 for violations	India should define panel placement, yield criteria, and enforcement rules Allow conditional solar use of farmland without full land conversion
United States	Federal and State Programs	Agrivoltaics Research & Demonstration Act (2023): USDA-led definitions and pilots- Some states mandate co-location or preservation of farmland (e.g., "smart solar" zoning) USDA REAP grants support APV adoption	India can replicate via ICAR- led Agri-PV pilots; integrate agrivoltaics in rural or agricultural schemes States can embed "smart solar" ideas in land zoning and RPOs Ministries of Agriculture and MNRE should jointly promote agrivoltaics in farm finance and rural support policies

Recommendations: To scale agrivoltaics, India needs to first categorize it under agricultural land use, revising state land legislation to prevent expensive reclassification. Water rights need to be established through revising the Model Ground Water Bill (2016). Implement APV- specific tariffs and recognition of green credits, and enhance KUSUM with exclusive agrivoltaics auctions. Make eligibility for carbon credits under the Carbon Credit Trading Scheme (2023) using APV methodologies. Release national technical guidelines (panel height>2.2 m, compatibility with crops) for Indian regions. Foster RESCO/shared PPA schemes to reduce farmer risk, and provide subsidized insurance and loans under PM-Kisan. Establish local capacity building by incorporating APV into KVK and rural energy training programs.

Identify best zones using GIS mapping and incorporate agrivoltaics into state RPO and solar policies. Promote biodiversity-supportive designs (e.g., legumes, native grasses), and create a monitoring system to monitor performance and provide feedback for adaptive policy adjustments.

Conclusion

This research verifies that agrivoltaics can be a revolutionizing strategy for India in synergistically meeting renewable energy targets, farm productivity, and climate resilience.

Results show that major states such as Rajasthan and Maharashtra can sequester as much as 2,100 tCO_2/ha/year, of which more than 1,100 tCO_2/ha/year comes from reduced fossil emissions, and further carbon accumulated in soil and crop biomass (50–100 tCO_2/ha/year). A 1 MWp agrivoltaics farm on 1.91 ha provides a gross annual revenue of ₹65.88 lakh, integrating energy sales, crop income, and ₹12.14 lakh as carbon credits, bringing down payback from 7.47 to 6.1 years. Ideal crop structure models such as Aloe Vera + Stevia (round-the-year income), Maize + Paddy (carbon credits), and Tomato + Spinach (short payback) are found to be versatile in various Agro-climatic zones. But major challenges still remain land-use conversion barriers, absence of agrivoltaics-specific tariffs or carbon credit entitlement, and lack of national design guidelines. In order to scale agrivoltaics, India will need to define agrivoltaics as agricultural land use, implement APV-specific tariffs and carbon credit regimes, and issue technical guidelines on panel design and crop choice. The experiences from nations such as Japan and Germany indicate that unequivocal dual-use regulations, tax incentives, and effective enforcement systems are imperative. With policy reforms integrated and financial instruments, agrivoltaics can emerge as a key pillar of India's rural development and net-zero strategy.

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Consumer and Producer Perspectives on Circular Economy Transition in Indian Textile Industry

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Executive Summary

The global textile industry, while economically significant, is a major cause of environmental degradation, counting for 10% of global carbon emissions and 20% of wastewater production. In India, the sector is vital, contributing 2% to the national GDP and employing over 45 million people. However, the industry's prevailing Linear Economy (LE) model cantered on mass production, Over-consumption, and irresponsible disposal has led to massive water use, greenhouse gas emissions, resource depletion and escalating textile pollution problem. Despite this, Circular Economy (CE) principles which advocate for sustainable production and consumption, it has seen limited implementation in India. This research explores the barriers and potential for CE integration within India's textile sector using a mixed-methods approach including literature analysis, stakeholder surveys, and interviews. Key objectives include identifying awareness levels, adoption barriers, and opportunities for circular practices among manufacturers, retailers, and consumers.

The study finds growing awareness of sustainability among stakeholders, particularly regarding environmental damage from water-intensive dyeing processes and landfill issues. However, systemic barriers such as complex supply chains, inadequate regulation, lack of technological access, and limited consumer engagement continue to hinder CE adoption. High initial costs and weak incentives also deter businesses from shifting to circular models. The findings underscore the urgent need for policy support, financial incentives, education, and infrastructure development to facilitate a circular transition. This research advocates a clear position: a systemic shift to Circular Economy practices in India's textile industry is not only feasible but essential to achieve environmental sustainability and socio-economic resilience of the sector.

Context & Problem Statement

The Indian fashion and textile industry, a cornerstone of the national economy employing over 45 million people and contributing around 2% to the GDP, is facing a mounting sustainability crisis. As the third-largest textile producer globally, India's sector is marked by a resource-intensive, linear production model that results in significant environmental degradation.

This model drives excessive water consumption (up to 200 liters per kilogram of fabric), high carbon emissions, and the generation of approximately 1 million tons of textile waste annually, of which only 20–25% is being reused or recycled. The environmental footprint extends from toxic dyeing processes to disposal of post-consumer clothing in land-fills often in low-income regions, exacerbating both ecological and social burdens. The urgency of addressing this issue is underscored by the global and local consequences of the current fashion system. In India, the sector's rapid growth, fuelled by fast fashion and rising consumer demand, has intensified pressures on water resources (almost all major rivers have at least one textile hub in its proximity and major source of its pollution), and led to unsustainable waste management practices.

The stakes are high: unchecked, the linear model threatens India's environmental security, public health, and the livelihoods of millions. Conversely, transitioning to sustainable practices could yield substantial benefits, including a 25-30% reduction in sectoral emissions, up to 50% less water consumption, and the creation of lakhs of green jobs.

Despite the promise of the Circular Economy (CE) paradigm which prioritizes waste minimization, resource efficiency, and material circularity adoption in India's textile sector remains nascent.

Literature Review

The Circular Economy (CE) has emerged as a transformative paradigm for rethinking production and consumption, especially within resource-intensive sectors such as textiles. Defined by the Ellen MacArthur Foundation (2012) as a regenerative system that designs out waste, prolongs product life, and closes material loops, is estimated to generate $560 billion in global annual savings by 2030 through resource efficiency and reduced emissions (Ellen MacArthur Foundation, 2017). Scholars widely regard CE as a pathway to decouple economic growth from environmental degradation. However, as Kirchherr et al. (2018) emphasize, CE implementation often remains superficial unless accompanied by deep institutional, cultural, and systemic transformations.

In the textile industry, CE aligns closely with design-led interventions such as slow fashion (Gwilt, 2014) and emotional durability (Chapman, 2009), which promote product longevity and reduce consumption cycles. Circular business models like rental, resale product-as-a-service have gained global momentum (Bocken et al., 2016; Pal, 2017) yet their scalability in India is hindered by infrastructural limitations and affordability concerns..

India's textile and apparel sector contributing 12% to exports and 13% to industrial production, illustrates both the urgency and potential for circular transformation. Despite the presence of recycling hubs like Panipat, studies reveal that only 20–25% of textile waste in India is recovered annually (Narayanaswamy et al., 2022).

Technological innovations such as blockchain and IoT can enable traceability and reverse logistics (KPMG India, 2019), but adoption remains low in MSME clusters due to financial and knowledge constraints.

Zero Liquid Discharge (ZLD) technologies demonstrate environmental potential (GIZ, 2014) but remain cost-prohibitive without supportive policy ecosystems. Moreover, CE policies in India remain fragmented. While schemes like the Technology Upgradation Fund Scheme (TUFS) target energy efficiency, they lack enforceable circularity mandates. A comparative policy analysis reveals that, unlike the European Union's Extended Producer Responsibility (EPR) mandates and standardized metrics, India's policy landscape relies on vague notions of "sustainability" and "recycling."

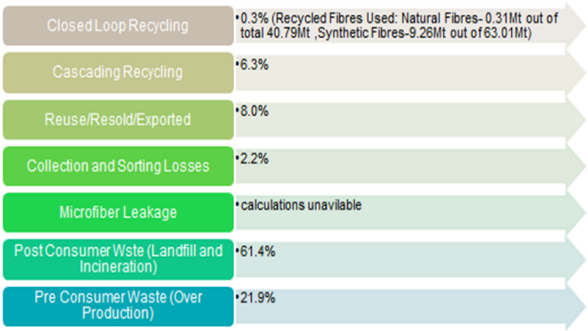


Figure 3: Total Textile Waste Categories and their Percentages

Data Source: CGR 2024 (Circularity Gap Report Dashboard)

Three conceptual debates dominate the literature: Balancing industrial scale with artisanal traditions like handloom and upcycling (Chapman, 2009), the challenge of integrating automated technologies into informal waste economies, and the consumer behavior gap despite 85% of surveyed Indian consumers expressing willingness to pay for sustainable fashion, fast fashion remains dominant (Pal, 2017).

The literature reveals several critical gaps:

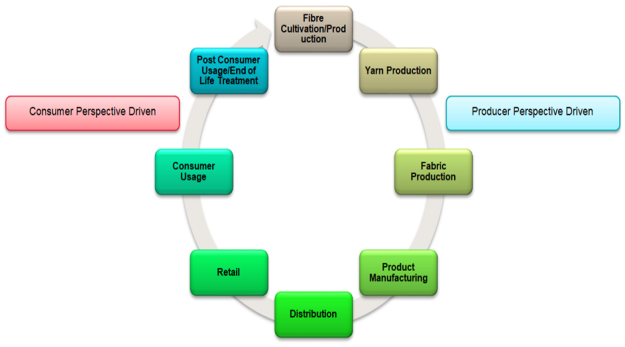
- **Fragmented Evidence on Consumer-Producer Feedback:** Limited research exists on how design-for-disassembly, mono-material designing and consumer engagement can close the loop in textile value chains.

- **Underrepresentation of MSMEs and Rural Clusters:** Most research and interventions focus on large, urban manufacturers, neglecting the vast network of micro, small, and medium enterprises (MSMEs) and rural producers who form the backbone of Indian textiles.
- **Lack of Standardized Metrics and Data:** The absence of robust, standardized circularity metrics and real-time monitoring systems hampers the ability to measure progress and impact.

This research tries to address these gaps by investigating the potential for CE integration in the Indian textile sector by focusing on both producer and consumer perspectives in Textile supply chain (both upstream & downstream) as both stakeholders play critical role in ensuring the success of CE initiatives.

Figure: Complete Lifecycle of a Circular Fashion Product covering Downstream & Upstream

The study aims to illuminate barriers such as high capital costs attached with CE models, technological limitations, and behavioral inertia of consumers, and propose possible pathways to overcome these barriers.



RESEARCH FOCUS

This research aims to:

- Evaluate current practices and challenges in embedding CE within India's textile sector.
- Identify drivers and barriers among stakeholders across the value chain.
- Develop actionable strategies for policymakers, industry stakeholders, and consumers.

METHODOLOGY

This position paper adopts a mixed-methods approach combining quantitative surveys and qualitative interviews to gain a comprehensive understanding of circularity adoption across India's textile and fashion ecosystem. The research design was structured to examine perspectives from both producers and consumers through SPSS study of questionnaires, also integrating qualitative analysis of expert interviews.

1. Producer Questionnaire

A structured questionnaire was circulated among over 90 stakeholders from various segments of the fashion production supply chain, including merchandising managers, production heads, designers, and brand owners. Participants were approached via LinkedIn, WhatsApp, and email, with a final sample of 39 valid responses.

Prior to survey distribution, participants were informed about the purpose of the study, assured of confidentiality, and provided consent to participate. The questionnaire focused on practical challenges and readiness for circular economy in areas: Design, Sourcing, Manufacturing, and Post-consumer Waste Management.

2. Consumer Behavior Questionnaire

To assess consumer engagement with circular fashion, a separate questionnaire was disseminated through online platforms and sustainability-focused communities, targeting individuals with a basic understanding of sustainability. The survey received 78 responses from a pool of 300+ fashion consumers. The instrument measured five key behavioural dimensions: Awareness & Attitude, Purchasing Behaviour, Usage & Care, End-of-Life Management and Future Perspective. Ethical considerations were maintained through informed consent and data anonymity declarations embedded in the Google Form.

3. Semi-Structured Interviews

To complement the survey data, three semi-structured interviews were conducted with: A Merchandising Manager from a textile export house

- The Founder of a Sustainable Fashion Brand (Rachna Swarup, B77)
- A Sustainable Fashion Influencer and Consumer (Tanishka Mishra)

Each interview followed a flexible guide designed to probe key themes such as supply chain fragmentation, consumer perception of sustainability, circular design practices, market barriers, and the role of MSMEs. Interviews were conducted virtually, recorded with participant consent, and later thematically analyzed to extract qualitative insights that enrich and contextualize the survey findings.

KEY FINDINGS AND CENTRAL ARGUMENT

Consumer Study Insights:

- ***Awareness vs. Accessibility Gap:*** Consumers, particularly urban, are aware of sustainability but face limited access to circular fashion options in Tier 2 and Tier 3 cities.
- ***Greenwashing and Lack of Clarity:*** Consumers find it challenging to differentiate genuine sustainability efforts from deceptive marketing.
- ***Cultural Mind-sets and Fashion Attachment:*** Emotional and cultural ties to garments in Indian households' support reuse and gifting, but young consumers often associate second-hand clothing with lower status and lack of fashion appeal.
- ***Lack of Consumer-Centric Circular Models:*** Circular initiatives tend to be brand-driven rather than consumer-inclusive, requiring more community-focused, engaging models like repair hubs and up cycling workshops.
- ***High Price Points as a Barrier:*** The premium cost of sustainable fashion discourages mass adoption, especially price-sensitive youth.
- ***Fragmented Return and Repair Infrastructure:*** Return policies are often unclear or logistically inefficient, deterring consumers from participating repeatedly in circular initiatives.

Producer Study Insights:

- ***Supply Chain Fragmentation and Lack of Standardization:*** Indian textile supply chain operates in silos with no uniform sustainability standards, leading to inconsistent practices and data gaps.
- ***Resistance and Cost Constraints among Suppliers:*** Tier 2 and Tier 3 suppliers often lack awareness, resources and incentives to adopt circular practices, compounded by higher costs of sustainable materials.
- ***Challenges in Traceability and Data Transparency:*** Full visibility of environmental impact from raw materials to finished products remains difficult due to limited data sharing and fragmented supply systems.
- ***Design Constraints for Circularity:*** Designing for recyclability or disassembly often restricts creativity and aesthetics, balancing fashion with sustainability remains a challenge.
- ***High Costs and Certification Overload:*** Eco-friendly inputs and sustainability certifications are expensive and bureaucratic.
- ***Operational Challenges in Reverse Logistics:*** Creating an efficient return and repair infrastructure is expensive and complex, impeding the scaling of circular initiatives.

Interviews Insights:

- Cultural attachment to garments in Indian households fosters reuse and gifting, yet this is often not perceived as 'circular' due to status concerns.
- External support from policymakers and awareness campaigns are vital.
- Consumer misconceptions equate circularity solely with recycling; clear communication is needed.
- The highly fragmented supply chain hampers traceability and full transparency.
- Traceability and upcycling are emerging practices.

POLICY AND PRACTICE RECOMMENDATIONS

Stakeholder	Strategies/Actions	Aligned SDGs	Aligned SDGs	Implementation Steps	Key Performance Indicators (KPIs)
Policymakers	- Enforce EPR for textiles - Fund recycling infra (MRFs) - Incentives for circular SMEs - Ban destruction of unsold goods - Formalize informal waste sector	SDG 12.5, 13.2, 11.6, 15.1	Ellen MacArthur (3Rs), UNEP Sustainable Textiles Roadmap, France Anti-Waste Law	- Enact EPR law with targets - Set recycled-content mandates - Public procurement with recycled fiber - National level campaigns on reuse - Invest in CETPs/ZLD plants	- % textile waste diverted from landfills - % producers complying with EPR - Number of take-back programs funded - Volume of recycled textile waste processed - % increase in formal recycling jobs
Industry (Producers/ Supply Chain)	- Design for disassembly & recyclability (Mono-material designs) - Zero-waste pattern cutting - Use recycled inputs - Internal take-back loops - Collaborate with waste workers	SDG 12.2, 12.5, 13.3, 6.3, 15.1	SAC Higg Index BCI, GRS Certifications OECD Circular Economy Toolkit	- Trace input flows (LCA/ MFA) - Digital tagging/passport for fibers - Join cluster-based CETPs - Partner with startups (fiber-to-fiber recycling) - Set % targets for recycled input	- % recycled content used - Waste generated vs recycled (kg/unit) - Scope 1/2/3 emissions per unit - No. of suppliers engaged in circular sourcing - % products recyclable by design
Brands/ Retailers	- Launch take-back/ repair/resale programs - Use recycled materials (GOTS, RCS) - Disclose circularity data - Promote slow fashion narratives	SDG 12.6, 13.2, 11.6, 15.1	Ellen MacArthur 'Make Fashion Circular' UN Fashion Industry Charter, CTI Indicators	- Setup garment return counters - Eco-label all SKUs - Partner for reverse logistics - Integrate QR-coded clothing info - Join alliances like FashionforGood/ ReSTART	- % lines using recycled/ eco-certified materials - Return rate of garments - % garments reused vs discarded - Customer awareness - Scope 3 emissions
Consumers	- Buy fewer, quality garments - Use repair/reuse/ swapping - Follow labels - Return clothes to take-back - Demand brand transparency	SDG 12.8, 13.3, 15.1	EMF "New Textiles Economy" UNEP Sustainable Lifestyles Fashion for Good Tools	- Participate in clothing swaps - Use second-hand platforms - Scan QR codes for end-of-life info - Join community repair/ upcycling drives - Follow influencers promoting circularity	- % participating in return programs - Clothing donation per capita (kg/year) - % consumers using rental/resale services - Average lifespan of garments owned - Awareness % of circular fashion

CONCLUSION

India's textile industry stands at a pivotal moment, where the adoption of circular economy (CE) principles offers a transformative pathway to reconcile growth with sustainability. This research contributes to the growing body of knowledge by examining the practical, social, and policy-related dimensions of circularity in textiles through a mixed-methods approach, integrating stakeholder perspectives, consumer behavior, and expert interviews.

The findings reaffirm that though the average consumer is getting more aware about the concepts like sustainability and circularity, but the awareness is not backed with actionable steps, circularity initiatives like take back programs, repair options and up cycling initiatives are near to none in Indian ecosystem. Brands are hesitant about investing in these initiatives as certifications and ultra-complex fashion supply chains drain the profit margins & increased product cost market the awareness is not backed with

actionable steps, circularity initiatives like take back programs, repair options and up cycling initiatives are near to none in Indian ecosystem. Brands are hesitant about investing in these initiatives as certifications and ultra-complex fashion supply chains drain the profit margins & increased product cost make the products less desirable.India's transition from a linear to a circular textile model demands a comprehensive ecosystem supported by enforceable policy frameworks, infrastructure for recycling and reverse logistics, technological accessibility for smaller enterprises, and consumer awareness campaigns that resonate across socio-economic segments.

India's traditional strengths such as its rich artisanal heritage and decentralized production clusters can serve as foundational assets in building a culturally grounded, inclusive circular textile economy. However, persistent gaps in data transparency, regulatory incentives, and stakeholder coordination must be addressed.

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