3. RETHINKING URBAN SUSTAINABILITY THROUGH CLIMATE GOVERNANCE

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

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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.

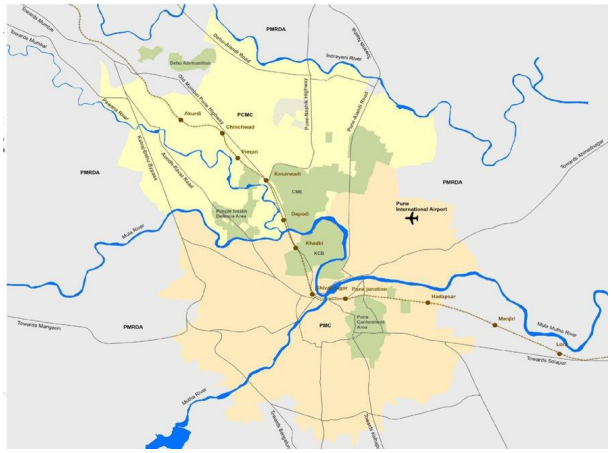


Figure 1 Map of the Twin Cities of Pune and Pimpri Chinchwad (Source: PCMC Revised Draft Development Plan 2025)

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.

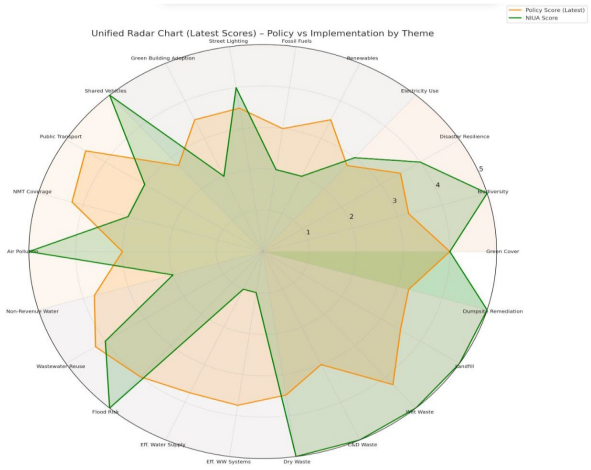


Figure 3 Comparison between CSCAF Performance and Post-2023 Cross Sector Policies of PCMC

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.

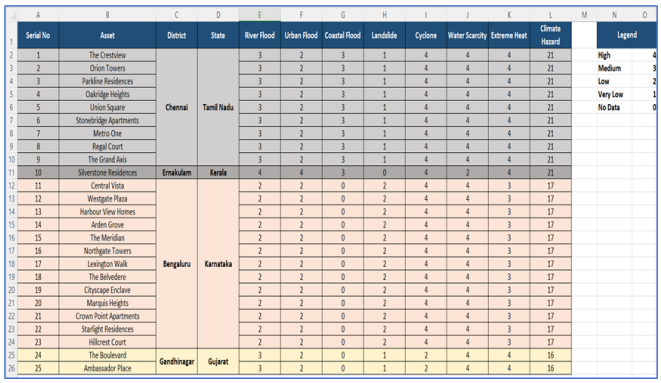
1. ThinkHazard:

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)

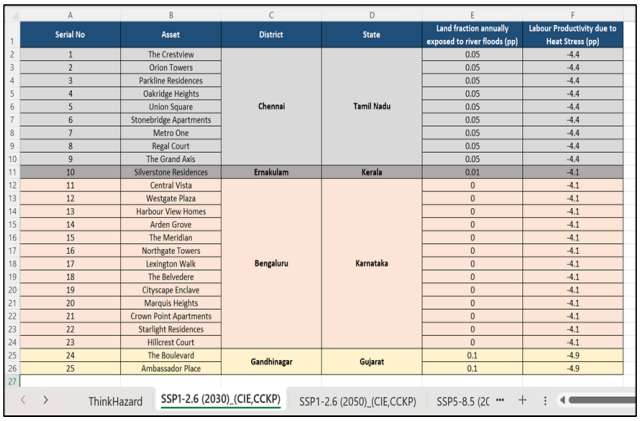
Indicators chosen: Land fraction annually exposed to river floods, Labour productivity due to heat stress

*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



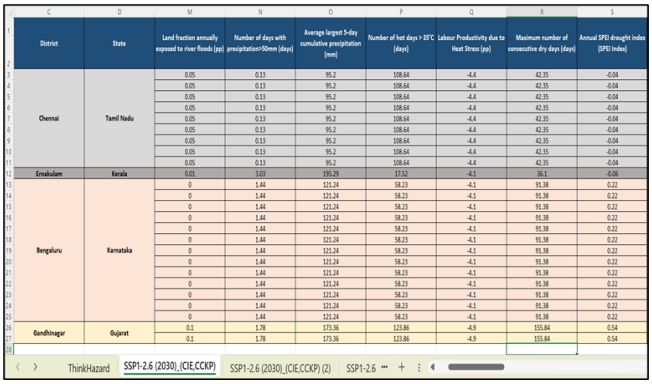
Serial No	Asset	District	State	Land fraction annually exposed to river floods (pp)	Labour Productivity due to Heat Stress (pp)
1	The Crestview	Chennai	Tamil Nadu	0.05	-4.4
2	Orion Towers			0.05	-4.4
3	Parkline Residences			0.05	-4.4
4	Oakridge Heights			0.05	-4.4
5	Union Square			0.05	-4.4
6	Stonebridge 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
		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
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.

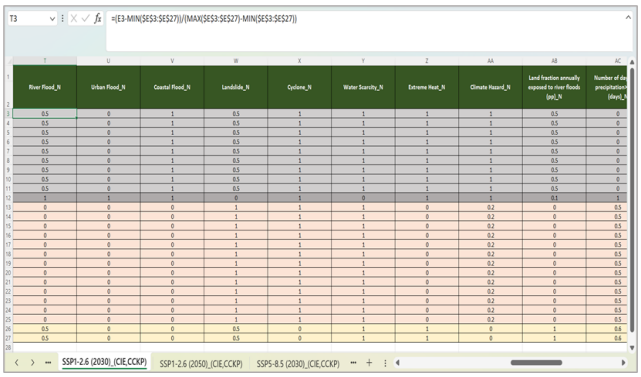


Figure 4: Normalisation of all indicators taken from ThinkHazard, CIE, CCKP

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.

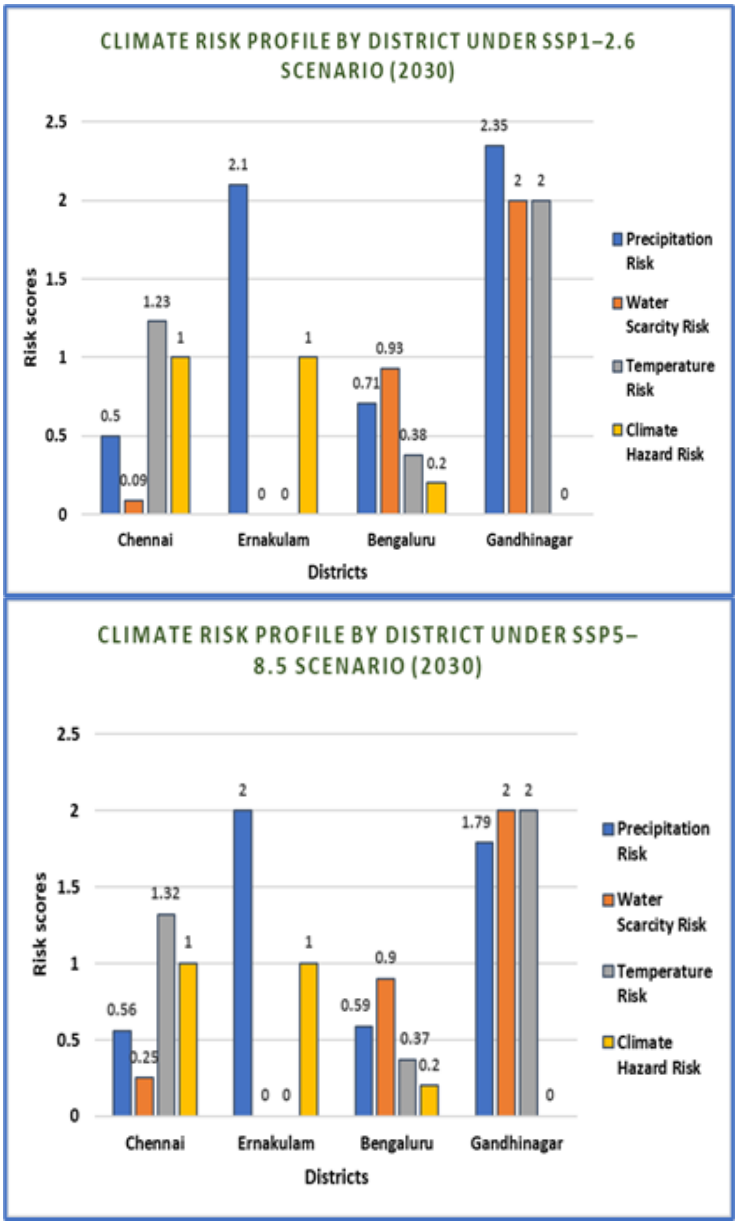


Figure 6: Climate Risk Profile by district under SSP1 2.6 & SSP5 8.5 Scenario (2030)

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.

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Physical Risks

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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.

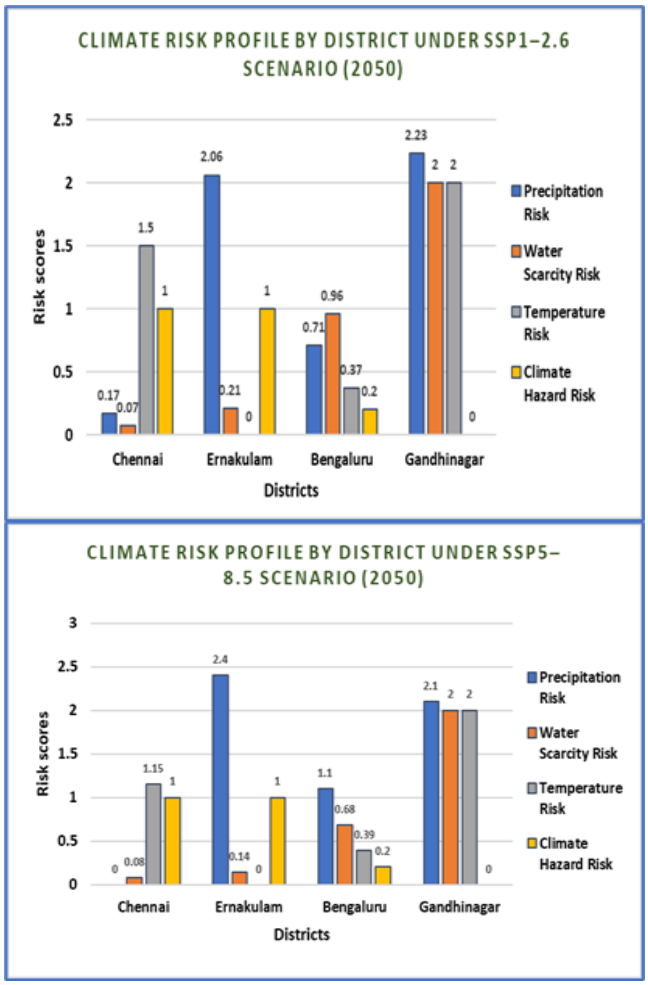


Figure 7: Climate Risk Profile by District under SSP1 2.6 & SSP5 8.5 Scenario (2050)

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:

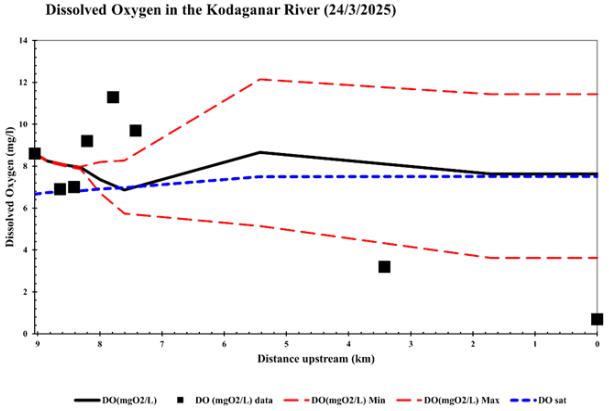
- To assess the impact of sewage discharge from the town of Vedasandur on the surface water quality of the Kodaganar River downstream.
- To identify critical points of pollution along the Kodaganar River resulting from drain outfalls within Vedasandur.
- To propose mitigation strategies to reduce and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

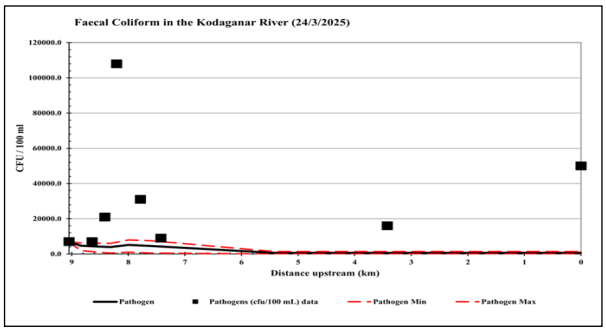
Key Findings and Observations

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.

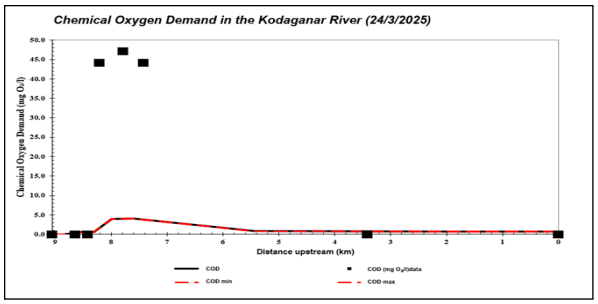
2. **Extremely high microbial contamination**

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.

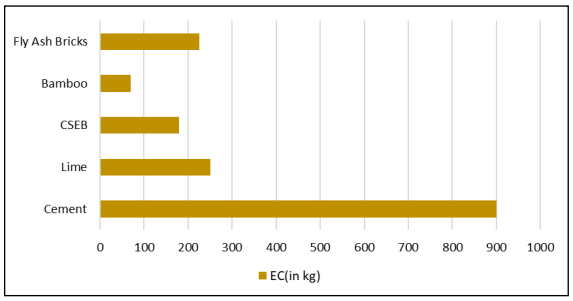


Figure 1: Comparative Embodied Carbon (EC) of Indigenous and Conventional Materials (per tonne)

- 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:

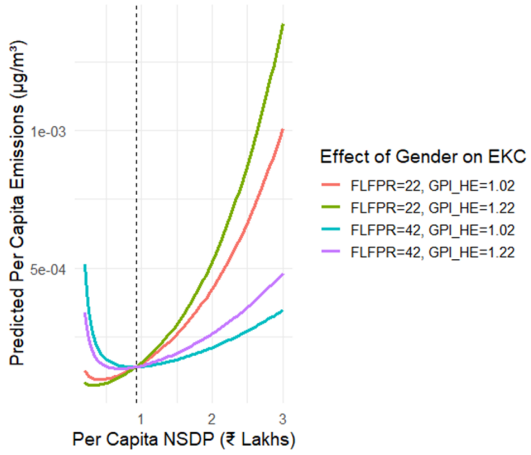
The key findings with regard to the income-pollution relationship and the moderating effect of the two gender-related variables (Gender Parity Index for Higher Education and Female Labour Force Participation Rates) on this relationship remain consistent across all three air pollutants—SO2, NO2, and PM10.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