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Ecology, Economy and Society - the INSEE Journal

Journal of the
Indian Society for Ecological Economics (INSEE)

Aims and Scope

Ecology, Economy and Society–the Journal of INSEE is an open access peer reviewed journal.

The journal aims to offer authors a forum to address socio-environmental issues from, across and within the natural and social sciences. The journal welcomes contributions at the ecology-economy-society interface that contribute to informed debates. Contributions could be conceptual or theoretical pieces or be methodological and empirical. In order to meet the sustainability challenges, the Journal believes in 'methodological pluralism' and contributions may address broader developmental considerations vis-à-vis ecological systems, sustainability, equity and justice.

It would encourage papers that connect theory with practice. We welcome trans/inter-disciplinary approaches including (but not limited to) ecological economics, environmental economics, political ecology, energy analysis, environmental science & engineering, political economy, environmental sociology, ecological and environmental history, social ecology and human ecology.

Papers could focus on issues such as (indicative and not exhaustive) forests, water, energy, climate change, biodiversity, pollution, agriculture, eco-restoration and conservation, poverty-environment nexus; demography and bio-physical resource base; land-use changes; sustainability and sustainable development (ecological, economic, social, political, etc.); alternative development pathways; socio-ecological transitions and social metabolism; cultural, anthropological and economic analysis of environmental changes; eco-socialist approaches; ecological modelling; environmentalism and ecologic-economic conflicts; environmental law and governance; industrial ecology; valuation of natural resources and green accounting; alternative well-being matrices.

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EDITORIAL

Shifting Sands and Dynamic Borders: Resilience at the Human–Nature Interface

Pranab Mukhopadhyay [*]

Amitav Ghosh, in his book *The Hungry Tide*, describes the Sundarbans as a space where "… there are no borders to divide fresh water from salt, river from sea, even land from water. The settlers of the Sundarbans believe that anyone without a pure heart who ventures into the watery labyrinth will never return" (Ghosh 2004). This encapsulates, in many ways, the essence of life at the margins—not only of humans but also of the shifting boundaries between land and water, and between rivers and seas—an interface that transcends human administrative boundaries and barriers. Three Himalayan river systems—the Indus, Ganges, and Brahmaputra—span multiple countries, terrains, and landscapes. Of the three, the Brahmaputra, often described as a braided river, is the longest and carries the largest sediment load. The combined Ganges–Brahmaputra–Meghna delta is the largest and most populous delta system in the world. Borah, in his article, "Fluid Histories and Unruly Waters: The Brahmaputra River System, Political Ecology, and the Making of Pre-Colonial Assam", describes how, over centuries, the river has defined the region's geography, culture, demography, and politics. He also records the historical resilience of the people who engaged with the river's behaviour, constantly reorienting their lives, economies, and politics. For our current times of climate change, Borah provides recommendations on how to build resilience and navigate nature's unpredictability in a riverine landscape.

This theme resonates with Guha's book, *Ecologies of Empire in South Asia, 1400–1900*, which Suresh reviews in this issue. It provides insights into how

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historical ecological practices have shaped current environmental challenges. From a different angle, Mishra explores the interplay of popular environmental consciousness and majoritarian political processes in the context of Sharma's book, *Green and Saffron: The RSS, Modi, and Indian Environmental Politics*.

The role of communities in navigating various crises has been studied across multiple contexts, including forestry, irrigation, and catastrophic events. This theme is explored in the context of Kerala's coastal fishery by Haridas and Prathap, who analyse the results of a primary survey covering three districts with different levels of composite vulnerability: Kozhikode (high vulnerability), Thiruvananthapuram (moderate vulnerability), and Ernakulam (low vulnerability). Using a stratified random sampling framework, they approached 600 respondents across 5 villages in each of the three districts. Then, they quantified community resilience by constructing a relative importance index. They find that both institutional factors (including social networks) and household characteristics (education and income diversity) significantly affect household resilience. These findings could help coastal communities build resilience to climate change shocks.

Threats to the livelihoods of nature-dependent communities increasingly come from anthropogenic pressures and ecological degradation. There has been growing recognition that biodiversity, by itself, is a natural asset with sustainability and livelihood implications, as highlighted by the Dasgupta report on biodiversity (Dasgupta 2021). This is evident at Loktak Lake, Manipur, where Singh and Mistri note that communities reliant on the lake for water and fishing face increasing risks to their livelihoods due to the deterioration of the lake's ecological status. This wetland is significant because it is the largest freshwater lake in north-eastern India and is probably the only floating national park in the world. It provides the last known natural habitat for the state's brow-antlered deer. Based on the lake's ecological importance, it was elevated to Ramsar site status in 1990. Drawing on a primary survey of 600 households across 12 villages in the wetland, the study identifies the major concerns of farmers regarding the loss of fish diversity. It emphasizes the need for a wetland resource management strategy to conserve the biodiversity and productivity of Loktak Lake and support local livelihoods.

Apart from anthropogenic pressures on wetlands, Manipur is also amidst a development transition in which energy plays a central role. There is a large body of literature on household energy choices, especially among rural households in developing countries (see, for example, Das *et al.* 2023). The choice of fuel by such households is influenced by both individual and

social factors, including information and income (at the individual level) as well as environmental and climate concerns (at the social level). Monica, Adaina, and Rassendren contribute to this debate with a study also set in Manipur. Using primary data from about 500 households in Tamenglong district, the study finds that adoption of liquefied petroleum gas is significantly influenced by energy costs, ease of availability, and deterrence stemming from the region's cultural practices.

Given the critical role that air quality plays in respiratory health and, consequently, wellbeing, there is a need for better information campaigns to help households and decision-makers make suitable choices. Technology can play a key role in this effort. Pathak and Jadhao argue in their review essay that combining technologies such as the Internet of Things, big data analytics, and machine learning can help researchers acquire, analyse, and predict pollution trends to support better decision-making. Their essay speaks to civil engineers, who play a crucial role in creating and altering the built environment, emphasizing the potential of emerging data technologies to improve air quality.

The Indian Society for Ecological Economics (INSEE) held its 13th Biennial meeting on the theme "Ecological Restoration for a Resilient Society: Economics, Policies, and Institutions" at the Indian Institute of Technology Mandi (IIT Mandi), Himachal Pradesh, India, from 12 to 14 January 2026, supported by the International Development Research Centre (IDRC Canada), the Foundation for Ecological Security (FES), and the Indian Council for Social Science Research (ICSSR). As part of its capacity-building mandate, it also held a pre-conference workshop on "Tools and Methods for Decision-Making on Ecological Restoration" and a post-conference fieldwork exercise. Dasgupta and Purushothaman summarize the discussions and takeaways from this conference. At the conference, INSEE conferred the title of INSEE Fellow on two of its founding members, C K Varshney and Jyoti Parikh.

Richa, Hingne, Jyothiprakash and Golechha summarize the proceedings of the workshop held on April 25, 2025 organized by the World Resources Institute, Delhi, at the Indian Institute of Technology, Delhi, to deliberate on the impact of low-carbon strategies for India. The deliberations offered valuable pathways forward for India to achieve its Nationally Determined Contribution (NDC) targets and beyond.

Among the book reviews in this issue are discussions by Wighmal on Angus' *Metabolic Rifts: Capitalism's Assault on the Earth System*, Venkatachalam on Franco and Missemer's *A History of Ecological Economic Thought, and* Patel on Banzhaf's *Pricing the Priceless: A History of Environmental Economics,* Kumar

on Satheesh's *Labour, Nature and Capitalism: Exploring Labour-environmental Conflicts in Kerala, India*, Dhavala on Mohanty and Sarkar's edited volume, *Financing Climate Action: India in a Global Context*, and Sierra-Porta on Ritchie's *Not the End of the World: How We Can Be the First Generation to Build a Sustainable Planet*. Wighmal, Patel, Kumar, and Venkatachalam's comments point to the extractive nature of economic production, the historical evolution of critical assessments of human–nature interactions, distributional issues, and valuations of nature. Dhavala reminds us of the urgent need for climate finance in India and Sierra-Porta leaves us with hope that there is scope for balancing the anthropogenic pressures on nature.

These collectively represent the duality of the human–nature interface that Dasgupta integrates into his macro model. In one avatar, humans are embedded in nature; in another, their survival depends on the extraction of natural resources. Dasgupta, in a brief, simple exposition, proposes a macro model that captures this complex duality and offers a way to conceive of the embeddedness of humans in nature alongside the conventional extractive production function approach. The dynamic model he provides allows us to address sustainability from both a democratic behavioural framework and a command-and-control approach aimed at achieving a policy target. This provides a pathway to a new genre of macro models that allows nature to serve both as hosts and providers for humans.

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RESEARCH PAPER

Fluid Histories and Unruly Waters: The Brahmaputra River System, Political Ecology, and the Making of Pre-Colonial Assam

Anurag Borah*

Abstract: This paper examines the Brahmaputra River system as a central agent in the history of pre-colonial Assam, demonstrating how the ecological rhythms, shifting course, and socio-environmental dynamics of the Brahmaputra and its tributaries shaped the region's social, political, and cultural trajectories. Through a political ecology reading of copper-plate land grant charters, royal chronicles (*buranjis*), and narrative texts spanning the fifth to eighteenth centuries CE, the paper argues that the Brahmaputra's structural "unruliness"—its high sediment loads, catastrophic floods, constant channel migrations, and ecological unpredictability—generated a specific political logic: rulers who mastered hydraulic governance commanded the territory. Importantly, the Brahmaputra system was never static. Its capricious migrations and periodic floods compelled resilience: capitals were relocated, embankments and canals constructed, and new settlements established on the freshly deposited lands. Rulers who recognized the dual nature of rivers—fertility and devastation, connection and division—could better consolidate power and safeguard agrarian regions. The paper further contends that ordinary people were not passive subjects of a river-shaped landscape but active negotiators of its possibilities. By integrating geological dynamics, political ecology, and longue-durée analysis, the study reveals a fluid history in which the Brahmaputra's unruliness was simultaneously a threat to be managed, a resource to be harnessed, and a force that ultimately thwarted every human attempt at mastery.

Keywords: Brahmaputra River system, Pre-colonial Assam, Political Ecology, Environmental history, Kamarupa, Ahom Kingdom, Hydronyms, Fluvial geomorphology

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1. INTRODUCTION

To understand Assam's past, one must first comprehend the physical world the Brahmaputra created. Emerging from the Tibetan Plateau as the Yarlung Tsangpo and carving through some of the deepest gorges on Earth before debouching into the valley below as one of the world's largest rivers by discharge, the Brahmaputra is, in geological terms, an intensely active system. The valley it occupies stretches roughly 700 km from the Dibang confluence in the east to the Manas confluence in the west. It is cradled by the Eastern Himalayas to the north and east, the Patkai and Naga Hills to the northeast, and the Mikir Hills and Shillong Plateau to the south. This orographic configuration funnels some of the world's highest rainfall into a single drainage basin: annual precipitation exceeds 2,000 mm across much of the valley, with pockets in the foothills receiving over 10,000 mm. The result is a river that carries an extraordinarily high sediment load—estimated at approximately 402 million tonnes per year—maintaining a braided, unstable channel that shifts laterally, scours new paths, and deposits islands with remorseless regularity (Sarma 2005, 226). The valley floor is a patchwork of wetlands, riparian forests, tall-grass meadows, and agricultural clearings, bounded by dense tropical and subtropical forests on the surrounding hillslopes. Before modern road construction, this forested terrain made overland movement arduous; rivers were not merely useful; they were essential.

It is this structural character—geologically young, seismically active, perpetually sedimented—that this paper designates as the river's "unruliness". The concept is not merely rhetorical. The Brahmaputra's unruliness has a precise geomorphological basis: its braided planform, driven by enormous bedload, means that it maintains multiple unstable channels simultaneously rather than a single fixed course. Tectonic events—earthquakes in 1697, 1762, and the catastrophic Assam earthquake of 1950 CE—have periodically reorganized drainage patterns across vast areas. Floods of extreme magnitude have, on occasion, forced the river into entirely new courses, most dramatically in 1750 and 1787 CE. This is not a river that submits to human mastery; it is a river that must be continuously negotiated.

It is important to acknowledge Arupjyoti Saikia's *The Unquiet River: A Biography of the Brahmaputra* as a landmark contribution to river-centred environmental history (Saikia 2019). While the work engages with the medieval era, its primary emphasis is the colonial period, and its framework is more thematic than chronological. Consequently, the formative centuries of early Assam—where inscriptions and indigenous traditions vividly reveal the river's role—receive relatively limited attention. This paper addresses

that gap by presenting a sustained, long-term narrative of the pre-colonial Brahmaputra Valley, spanning from the early historical period to the eighteenth century CE. By placing the Brahmaputra at the centre of inquiry, the study argues for an environmental history of Assam that takes seriously the dynamic relationship between nature and society in the longue durée (French for "the long term")—a historical approach, pioneered by the Annales School and most notably associated with Fernand Braudel, which emphasizes long-term historical structures and processes that shape human–environment interactions across centuries.

The paper makes five interconnected arguments. First, rivers in Assam shaped, rather than merely demarcated, political authority, giving sovereignty a territorial reality that was perpetually contested by the river's own dynamism. Second, the sacralization of rivers was simultaneously a political mechanism, embedding royal legitimacy in the cosmological and environmental order. Third, the hydraulic state in Assam—most fully realized under the Ahoms—was a sophisticated political response to the river's unruliness, and its achievements in embankment construction, canal engineering, and capital relocation were as much political as ecological. Fourth, ordinary people—farmers, fishers, and boatmen—possessed sophisticated environmental knowledge and exercised genuine agency within the river system, even though their voices remain muted in the official record. Fifth, the hydronyms of Assam constitute an environmental archive, recording in language what political documents often failed to note: the river's migrations, dying channels, and geological transformations. By deploying a political ecology framework—attending to how power relations shaped and were shaped by environmental dynamics—the paper argues that the Brahmaputra's unruliness was not an obstacle to history but its driving force.

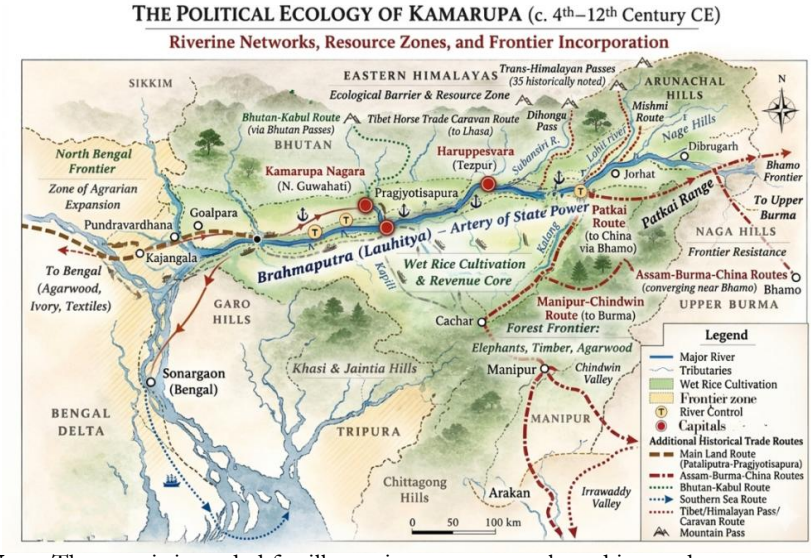
2. METHODS

This study employs an interdisciplinary methodology that combines textual analysis, environmental history, and historical geography to examine the Brahmaputra River system as an active agent in the history of pre-colonial Assam. The primary sources include copper-plate land grant charters, the royal chronicles of the Ahoms, and other literary texts spanning the fifth to the eighteenth centuries. To situate these textual references within their ecological context, the study draws on secondary literature from geology, hydrology, and environmental history. The method emphasizes the longue durée, tracing continuities and adaptations over centuries to demonstrate the evolving human–river relationship.

3. RIVERS AS BOUNDARIES AND POLITICAL FRONTIERS: DEFINING SOVEREIGNTY THROUGH WATER

The standard observation—that rivers in Assam served as boundary markers—understates the deeper political reality. Rivers did not simply delineate political boundaries; they constituted political authority by rendering it spatially legible and ontologically real. A kingdom without rivers was almost unthinkable in the inscriptional vocabulary of early Assam. The copper-plate land grant charters of Kamarupa and subsequent dynasties make this explicit: every donated plot is bounded by water—rivers, streams, ponds, or dried channels—as if the very act of granting land required it to be defined by the surrounding hydrological landscape. This was not mere administrative practice; it represented a political epistemology in which territory was real because it was riverine.

Figure 1: Brahmaputra Valley, the Surrounding Hill Ranges, and the Major Rivers of Early Assam



Note: The map is intended for illustrative purposes only and is not drawn to scale.
Source: Prepared by the author based on Choudhury (1959, 540).

Before examining the epigraphic evidence, it is important to consider the ecological and topographic context that made rivers so indispensable as boundary markers. The Brahmaputra Valley is enclosed on all sides by hills and mountains, and its floor is dissected by hundreds of rivers and streams flowing from both the northern Himalayan slopes and the southern escarpments of the Shillong Plateau and Naga Hills. Dense tropical and subtropical forests used to cover the inter-river zones, making overland

travel arduous, slow, and militarily hazardous. Rivers, by contrast, provided natural corridors for the movement of armies, traders, and pilgrims alike. In this landscape, controlling a river meant controlling a route, a frontier, and a resource simultaneously. The political ecology of early Assam was thus fundamentally riverine: power flowed along the water.

The richest epigraphic evidence for rivers defining political geography comes from the corpus of royal copper-plate land grant inscriptions. The Nidhanpur copper plates of King Bhaskaravarman (seventh century CE, Varman Dynasty)—which reissued an earlier grant by his ancestor Bhutivarman—describe the boundaries of an *agrahara* (a tax-free village established through a royal land grant) named Mayurashalmala in Chandrapuri Vishaya (Sharma 1978, 38). The charter specifies the plot borders, which include two rivers, Kausika and Gangini:

> To the east lies the dry Kauśika, to the south-east, that very dry Kauśika, marked by a hewn fig tree, to the west now the boundary of Gangini, to the northwest a potter's pit and the said Gangini bent eastward, to the north a large jatali tree, to the north-east the pond of the controlling tradesman Khasoka and the dry Kauśika. (Sharma 1978, 53)

The Kausika is qualified as *suska* (dry). While *suska* does explicitly indicate a non-flowing state, the qualifier could plausibly refer to seasonal desiccation rather than the permanent abandonment of the channel. Rivers in a climate as variable as Assam's may experience dramatically reduced or intermittent flow during the dry season, and a channel that appeared "dry" during the season when the grant was issued might have been active during the monsoon. Whatever the Kausika's precise hydrological status, the grant's detailed hydrographic vocabulary reveals how intimately political and administrative space was mapped onto the fluvial landscape, while also demonstrating how even the absence of a river (a dry channel) was politically significant, constituting a boundary as effectively as a flowing one. The description of the Gangini as "bent eastward" is equally significant: it is a notational record of channel morphology that could only have been observed by people who knew this river intimately enough to be able to describe its curvature.

The Nagajari-Khanikar stone inscription of the fifth century CE records a grant by King Vasundharavarman. The grant references the Dibrumukkhada—the confluence or mouth (*mukha*) of the Dibru River (Boruah 2002, 75). That even a minor tributary's confluence could serve as a boundary underlines how deeply rivers were embedded in the region's political geography. The Doiyang-Dhansiri valley, which this grant concerns, was not a peripheral appendage of Kamarupa; archaeological

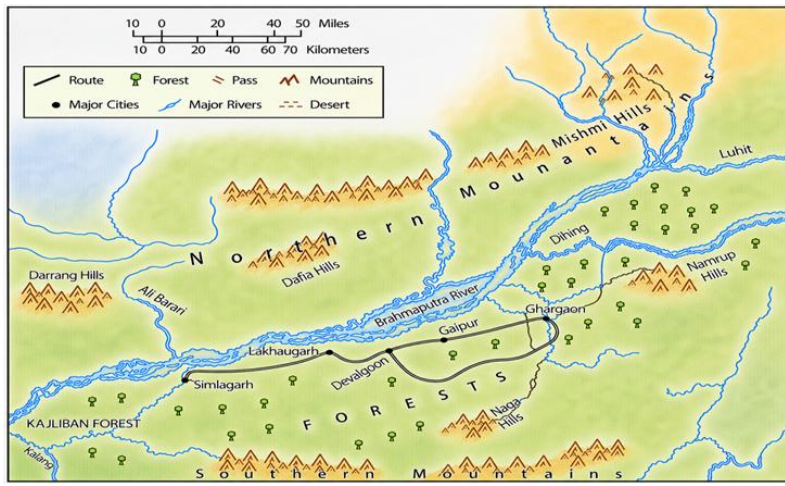
evidence of brick temple ruins and a water fort connected by canals to the Dhansiri River suggests a locally organized polity with its own hydraulic infrastructure (Dutta 1997, 37). These smaller river valleys were not passive recipients of authority from the Brahmaputra-based kingdoms; rather, they were active centres of political life, whose relationship with the main valley was continuously negotiated across riverine frontiers.

The inscriptional evidence of the Salastambha Dynasty (seventh to ninth centuries CE) introduces a further dimension. The inscriptions of the Salastambha kings refer to Haruppeswara (also Hadapeshvara) as a royal capital on the bank of the Lauhitya (Brahmaputra). The identification of this city with the vicinity of modern Tezpur is supported by several convergent lines of evidence. Tezpur sits at a natural constriction of the Brahmaputra, where the river, exiting the broader upper valley, narrows between the Himalayan foothills and the Shillong Plateau escarpment, forming a choke point that granted decisive military and commercial advantages to whoever controlled it. The topographic logic closely parallels that of Guwahati and other strategically chosen capitals: command of a river narrow meant command of lateral movement through the valley. The Tezpur area is archaeologically rich, with sculptural and architectural remains suggesting sustained occupation.

In the medieval period, rivers remained decisive political frontiers. The Ahom chronicles (*buranjis*) document this in considerable detail. When the Ahom King Suhungmung conquered the Chutiya domain in 1523 CE, the Dihing River served as the primary boundary marker; Suhungmung's subsequent decision to relocate his capital to Bakata on the Dihing's banks was simultaneously strategic and symbolic—declaring his possession of the river and, through it, of the territory it bounded (Gogoi 1994, 133). His title, "Dihingia Raja" (King of the Dihing), makes the constitutive logic explicit: the king's political identity was inseparable from the river's identity. Other riverine frontiers reinforced the same principle: the Barnadi River between Ahom and Mughal territories, the Na-noi between the Ahom and Kachari kingdoms, and the Manah as the western boundary of the Ahom Kingdom at different periods (Gogoi 1994, 161). Crucially, rivers not only defined political boundaries but could also destabilize and reshape them as dynamic political agents. When the Dihing changed course following the earthquakes of 1691 and 1696 CE—which reconfigured the Burhi Dihing's drainage—the boundaries it had stabilized were suddenly meaningless (Saikia 2019, 27). This dynamic created a structural tension at the heart of riverine politics in Assam: the river that gave a kingdom its territorial coherence could, through shifts in its course, also dissolve that coherence overnight.

What is frequently absent from the official record—but must be hypothesized from circumstantial evidence—is the agency of those who inhabited these riverine frontiers. At every crossing, ferrymen, boat builders, and customs officials formed communities that mediated between polities. These communities exercised real power. A ferryman who refused to carry troops, a boatman who knew the safe channels through a braided reach, and a fisherman who could read flood signals—these were not politically neutral actors. They formed the capillary network through which state authority at the frontier was either asserted or disrupted. The naming of specific ferry ghats in the chronicles—Kutuha Ghat, Ahom Ghat, Ghiladhari Ghat, and Naga Ghat on the Dihing River alone—suggests that these communities were sufficiently important to be recorded, even if their agency remains largely invisible in the surviving sources (Gogoi 1994, 133).

Figure 2: Map Showing the Major Rivers, Forests, and Riverine Centres of Medieval Assam



Note: The map is intended for illustrative purposes only and is not drawn to scale.
Source: Prepared by the author based on Nath (2019, 70)

The Ahom Kingdom constructed strategically vital earthen ramparts (*garh*) to defend key riverine entry points. Situated at the confluence of the Manah and Brahmaputra rivers, Jogighopa controlled westward riverine traffic. The twin forts of Samdhara and Simalugarh, positioned on opposite banks of the Brahmaputra, formed a choke point to monitor and block enemy movements (Barpujari 2004, 75). The most formidable system encircled Guwahati, where interlocking ramparts and hills created a defensive ring that forced invading naval forces into narrow, ambush-prone channels. The Mughal expeditions of Mir Jumla in 1662 CE and Raja Ram Singh in 1671 CE learned, at considerable cost, that Assam's network of swamps and

rivers could neutralize a conventionally organized army: the Ahoms opened up embankments to flood the plains and deployed swift river craft to harass enemy flanks (Barpujari 2003, 180, 231). At the Battle of Saraighat (1671 CE), Lachit Barphukan's naval command of the Brahmaputra's narrows proved decisively superior to the Mughal fleet with its numerical advantage, confirming that sovereignty over the river was sovereignty over the territory (Borah 2026, 304).

4. SACRED RIVERS AND CULTURAL LANDSCAPES: THE POLITICAL THEOLOGY OF WATER

The sacralization of Assam's rivers was never purely a religious phenomenon; it was simultaneously a political strategy. To establish divine authority over a river was to claim a form of sovereignty over the landscape it animated—its banks, tributaries, and dependent communities—that transcended the jurisdiction of land grants and military conquest. The political theology of water in Assam wove together cosmological legitimacy, territorial claims, and community identity in ways that were as strategically sophisticated as any military campaign. This does not imply that religious patronage was merely a political instrument or that royal actions were devoid of sincere devotional intent. In premodern South Asia, political authority and religious merit were deeply intertwined rather than mutually exclusive. Acts such as temple construction, pilgrimages, river worship, and the patronage of sacred landscapes could simultaneously express genuine piety, accrue religious merit, and reinforce the moral and cosmological legitimacy of kingship. The political significance of these practices therefore emerged not despite their religious character, but through it. The Brahmaputra's unique mythology illuminates this dynamic. Unlike the goddesses of the Gangetic cultural sphere—the Ganga, Yamuna, and Sarasvati, all conceived as feminine deities—the Brahmaputra is persistently personified as male, the "son of Brahma", in the Sanskrit textual tradition (Hunter 1975, II). This gender asymmetry is politically significant. A river personified as a divine masculine sovereign could be understood as a co-sovereign alongside the human king—a riverine counterpart whose authority was cosmologically prior to that of the human king and whose goodwill was essential to royal prosperity. The Dubi copper plate of King Bhaskaravarman (seventh century CE) describes the king as the "lord of the river" and records his establishment of a new city on the sacred banks of the Brahmaputra (Sharma 1978, 24, 30). The formulation positions the king's authority as complementary to, and legitimized by, the river's divine presence.

The Kalika Purana, composed in Kamarupa (likely between the ninth and eleventh centuries CE), represents the most elaborate theological systematization of Assam's riverine sacred geography. The text enumerates a substantial number of holy rivers—Sitaganga, Kapilaganga, Phenila, Navatoya, Svarnasiri, Divyayamuna, Karatoya, and many others—and prescribes ritual bathing in them for specific spiritual rewards (Shastri 1994, 1185–1202). Crucially, these rivers coincided almost precisely with the territorial claims of the Kamarupa Kingdom. This convergence is most evident in the spatial logic of Assam's major temple sites. Kamakhya Temple atop Nilachal Hill overlooks the Brahmaputra at one of its narrowest and most strategically significant points near Guwahati—the same area that the Ahoms defended in the Battle of Saraighat (Borah and Sarma 2023, 289). Tamreswari Temple near Sadiya stood on the banks of Dibang River, which also marked the eastern limit of Kamarupa's territorial claims. Dirgheswari Temple on the Brahmaputra's northern bank was revered by the Ahoms, who performed rituals there, recognizing the sanctity of the riverbank itself (Barpujari 2004, 227). These temples were not randomly distributed across the landscape; they were concentrated at politically significant points along the region's major rivers—confluences, crossings, and narrows—where the sacred and strategic converged.

Perhaps the most striking example of river sacrality as political performance is King Suhungmung's expedition in 1524 CE to find the source of the Lohit (Tilao), a lake identified with the holy Brahmakunda (Parashuram Kund in present-day Arunachal Pradesh) (Gogoi 1994, 108). This act was simultaneously a religious pilgrimage, cartographic expedition, and imperial performance. By figuratively "possessing" the river from its sacred Himalayan source to the valley floor, Suhungmung inscribed his sovereignty across the entire hydrological system of the Brahmaputra, framing his authority not as mere military dominance but as cosmologically ordained sovereignty, legitimized by the natural and sacred order of the land. The gesture recalled broader South Asian traditions of cosmological kingship. Just as the Chola kings had performed rituals at Gangaikonda Cholapuram to symbolically "bring the Ganges to the south" after their northern conquests (Nandakumar et al. 2023, 171), Suhungmung sought to bring the Brahmaputra's sacred source within his political horizon through this ritualized engagement with the landscape.

The legend of the Koch King Naranarayan's canal excavation near Pandu in the sixteenth century CE—said to have straightened the Brahmaputra's course for the benefit of pilgrims and navigation—illustrates the intersection of hydraulic engineering, religious patronage, and political self-presentation. The Darrang Raj Vamsavali's verse records the king's "great

zeal" (*kautuhole*) in directing the river towards Hajo, a major pilgrimage site (Sastri and Chaliha 2013, 85). Whether the intervention was as dramatic as the chronicle suggests, its political significance is clear: a king who could bend the river towards a sacred site was performing a form of sovereignty that transcended military power, presenting himself as a figure whose authority extended to the natural order itself. Even today, the old channel near Hajo is largely a wetland, while the "new", straight channel continues to form the primary course—preserving a physical trace of royal hydraulic ambition long after the dynasty that created it had disappeared.

5. RIVERINE CAPITALS AND TRADE NETWORKS: THE HYDRAULIC CITY AND ITS ARTERIES

The concentration of early Assam's political centres along riverbanks was shaped not by preference but by the ecological imperatives of the region, which made riverine locations a political necessity. In a landscape of dense forest, seasonal flooding, and limited overland infrastructure, rivers were the primary corridors of communication and movement—the arteries through which goods, armies, information, and authority could circulate at scale. Any political centre without direct access to the river was effectively isolated and consequently remained peripheral. The history of Assam's capitals is thus simultaneously an environmental history of the Brahmaputra's riparian edge, reflecting the ecological intelligence required to adapt to a river that refused to remain on course. The Varman Dynasty (fourth to seventh centuries CE) maintained its principal centre of power near the western Brahmaputra Valley. King Bhaskaravarman's Pragjyotishpura is generally identified with the vicinity of modern Guwahati—a location of extraordinary geographic significance. Guwahati is situated where the Brahmaputra exits a narrow gorge between the Shillong Plateau and the Himalayan foothills, before compressing into a relatively slender channel and expanding into the broad lower valley. This constriction had profound geopolitical consequences: as stated earlier, it was the most defensible point on the Brahmaputra's entire course through the valley, forming a natural choke point where a fleet of modest size could prevent the upriver passage of a far larger enemy force.

The defensive ramparts and moats mentioned in Pala-era inscriptions extended this hydraulic logic further—moats filled with river water transformed citadels into water forts, making the conquest of any capital not merely a military challenge but also a hydrological one. The Kalika Purana's reference to the *jala durga* (water fort) as one of six types of fortifications codified this long-established practice (Barpujari 2007, 424);

the *jala durga* at Duboroni in the Doiyang-Dhansiri Valley—connected by canals to the Dhansiri River—confirms that the principle was widely applied across the region's river valleys (Dutta 1997, 37). The Pala Dynasty's oscillations between Durjaya (near modern Guwahati on the south bank) and Hadapesvara on the north bank of the Brahmaputra reflect not so much political instability as a deliberate strategy of maintaining riverine flexibility—the capacity to shift the centre of power along the river's axis as military, commercial, or environmental conditions demanded (Boruah 2002, 93, 212).

The Ahom Dynasty's capital trajectory—from Charaideo (established c. 1253 CE) through Garhgaon and Rangpur to Jorhat (late eighteenth century CE)—traces a pattern of strategic riverine adaptation. The founder, Sukapha, arrived in the Brahmaputra Valley by navigating down the Dihing River, using bamboo rafts to transport his retinue, including men, women, horses, and elephants. After several relocations driven by repeated flooding, he reached Charaideo around 1253 CE, choosing elevated terrain near the Dikhow River that offered both protection from inundation and access to fertile plains suitable for wet-rice cultivation (Nath 2007, 465). The *buranji* accounts of this journey are not mere narratives; they are records of ecological knowledge in action, documenting how the Dihing's course served as a navigational corridor that guided the dynasty's foundational migration.

The subsequent history of Ahom capitals reflects a continuous negotiation between the river's resources and its dangers. Garhgaon and Rangpur, clustered near the Dikhow River system, were positioned to access the Brahmaputra's transportation network while being situated a few kilometres from its main channel—close enough for commerce and communication yet far enough to avoid direct inundation. Guwahati, deployed as a strategic military garrison during the seventeenth-century wars against the Mughals, gave the Ahoms their decisive advantage in the Battle of Saraighat (1671 CE), where Lachit Barphukan's intimate knowledge of the Brahmaputra's currents, shoals, and narrows proved crucial. When the capital moved to Jorhat in the late eighteenth century CE, an artificial channel was created from the Disoi River to ensure the new city had river access—a decision that led to the formation of the Bhogdoi River in one of the most illuminating episodes in Assam's environmental history.

This late-eighteenth-century creation of the Bhogdoi River represents the apex of Ahom hydraulic statecraft. When the capital shifted to Jorhat following the Moamoria Rebellion, there was an inadequate supply of potable water due to the marshy terrain. Under King Kamaleswar Singha (1795–1811 CE), at the direction of Chief Minister Purnananda

Burhagohain, the natural course of the Disoi River was artificially diverted to channel water through the new capital (Saikia and Amin 2016, 556). The resulting waterway—renamed Bhogdoi after the ritual food offerings (*bhog*) made to the workers during its excavation—was simultaneously a hydraulic feat, a political performance of royal benevolence, and a sacred act. In this single intervention, political power, environmental modification, and religious symbolism intersected to reshape both the landscape and the cultural geography of Assam.

Trade and communication in pre-modern Assam were largely river-centric. The Brahmaputra and its navigable tributaries served as natural highways in a landscape where dense forests and hills made overland bulk transport unreliable. The *bar-mudois*, Assam's elite merchant class, deployed their boats on the monsoon-swelled rivers to arbitrate price differentials across the valley (Nath 2002, 156–57). The Katha-Guru-Charit's account of traders from eastern Assam carrying salt and areca nut by boat to western markets illustrates the river's function of economic integration: goods that were cheap in the east were expensive in the west, but the river's navigability closed that gap (Lekharu 2002, 65, 94).

The Ahom state's systematic management of this riverine commerce—through customs checkpoints (chokies) at strategic confluences; royal dockyards (*naosal*) at Garhgaon, Rangpur, Majuli, Dergaon, and Jaipur; and policing of river routes by naval flotillas—reveals a sophisticated political economy of water (Saikia 2019, 123). The five royal dockyards were not just boat-building facilities; they were nodes in a state-managed network of riverine power. The important trading emporiums of Kandahar (Hadira), Rangamati, Goalpara, and Jogighopa—all located at river confluences or crossings—derived their prominence primarily from their strategic position near the river. The suffix *mukh* (mouth/confluence) in place names—such as Dikhowmukh, Bharalumukh, and Kajalimukh—directly encodes this riverine commercial logic, each name announcing the settlement's identity as a river port (Rajkumar 2000, 249). By the late eighteenth century CE, when the British East India Company was granted permission to station agents at Kandahar Chokey and Guwahati, the Company had inserted itself into a commercial geography that the river had constructed over centuries (Saikia 2029, xxiv).

6. THE RIVERINE ECONOMY AND ITS POLITICAL ECOLOGY: HYDRAULIC LABOUR, INDIGENOUS KNOWLEDGE, AND AGRARIAN POWER

The agrarian economy of pre-colonial Assam was inseparable from the Brahmaputra's hydraulic regime: its prosperity depended on the river's annual deposits of silt and water, while its social organization evolved in response to the labour demands of flood control and irrigation. Yet the political ecology of this hydraulic world was far more complex than a simple narrative of state-directed water management might suggest. Alongside—and often in tension with—the state's embankment and canal works, indigenous communities maintained their own hydraulic traditions, exercised ecological knowledge, and occupied distinct positions within the water economy that official records systematically under-represent. Without considering the roles of these communities, any account of Assam's riverine economy will remain necessarily incomplete.

The annual inundation cycle of the Brahmaputra structured the entire logic of agrarian life in the valley. Gentle floods replenished soil nutrients, deposited fresh silt on agricultural lands, and provided the standing water that wet-rice cultivation required; excessive floods could destroy crops, breach embankments, and displace entire communities. The floods in 1240 and 1244 CE compelled the early Ahoms under Sukapha to explore and settle in new areas (Gait 1926, 78). The eighteenth century witnessed several major flood events—1735, 1750, and 1780 CE—of which the 1750 event was particularly transformative, redirecting the Brahmaputra's course and contributing to the formation of the present-day Majuli Island (Sarma and Phukan 2004). Far from viewing floods purely as disasters, local communities historically adapted to these inundation rhythms. This dynamic structured the entire agricultural programme: the *sali* variety of wet rice—the principal crop in the Ahom-controlled eastern regions—required careful water management, including creating puddled and ridged fields, maintaining shallow water depth through the growing season, and achieving dry conditions at harvest (Guha 1991, 64). This was not passive adaptation to the river's rhythms but an active technical programme demanding sustained collective labour.

The earliest evidence of formal water management in the valley can be found in inscriptions. The mention in the Alichiga-Tengani grant of *setu-bandha* (bridge or bund) constructions as early as the fifth century CE indicates that embankment technology was already practised in the Doiyang-Dhansiri Valley (Boruah 2002, 76). The Ulubari copper plate inscription of Balavarman III (late ninth century CE) records a royal initiative to construct a *vrhad ali* (high embankment), indicating the state's

assumption of responsibility for flood management (Lahiri 1991, 94). Evidence of widespread paddy cultivation from at least the sixth century CE—reflected in the practice of denoting donated lands in terms of paddy measures (Choudhury 1959, 359)—confirms that rice agriculture and floodplain management had become integral to life in the valley by the first millennium CE. In the seventh century CE, Hiuen Tsang's observation that the land "lies low, but is rich, and is regularly cultivated" (Beal 1906, 195–96) attests to the transformation of low-lying tracts into well-developed rice fields through active hydraulic management.

Embankment construction required the mobilization of corvée labour—under the paik system, Ahom subjects owed the state a defined quantum of annual labour. The allocation of paik labour to embankment construction was a political act as much as a practical one: flood control was important enough to compete with agricultural production and military service for the state's primary non-fiscal resource. The embankment was a materialization of political power inscribed on the landscape. Its construction embodied the state's authority; its maintenance—or failure—indexed the state's capacity. The Bar Ali and Dhodar Ali, long raised roads in Upper Assam, also doubled as flood embankments. In the sixteenth century CE, King Suhungmung undertook systematic embankment construction along the banks of the Dihing to protect newly settled villages and reclaim land for rice cultivation (Gogoi 1994, 133). Later colonial observers marvelled at this network: Major Briggs, superintendent of works in Assam, congratulated the Ahoms for their "bold engineering skills and wonderful contempt of difficulties", referring to the raised embankment roads they maintained (Saikia 2019, 65).

The Ahom state's hydraulic works, impressive as they were, coexisted with a parallel hydraulic tradition maintained by indigenous communities. The dong system—a gravitational irrigation technology using weirs to divert hill streams into field-watering canals, particularly associated with the Bodo-Kachari peoples—represented a fundamentally different political ecology of water (Guha 1991, 68). Where the state's embankments were large-scale, labour-intensive, and top-down, the dong system was local, community-managed, and adaptive. It required intimate ecological knowledge of specific stream behaviours, seasonal flow patterns, and local topography—knowledge accumulated over generations of community practice rather than commanded from a royal court. The Apatani communities of the Assam foothills extended this principle further, using carefully graded low bunds to irrigate fields on sloping ground in a system characterized by extraordinary hydraulic precision (Saikia 2019, 61). The persistence of the dong system alongside the state's embankment systems demonstrates that the hydraulic

landscape of pre-colonial Assam was plural rather than unitary: multiple approaches to water management coexisted, each addressing different ecological scales and reflecting different social relations of production.

This plurality raises important questions about whose understanding of the river shaped agrarian practice. Much of the ecological knowledge on which formal hydraulic works depended was rarely written down; instead, it circulated through practice, the seasonal rhythms of agricultural labour, and the oral traditions of communities that had managed specific streams for generations. The dong system's complexity—weirs precisely calibrated to stream gradients, canals distributing water across miles of fields—could only have been designed and maintained by people possessing deep, location-specific ecological knowledge. The limited recognition of this knowledge in inscriptions and royal chronicles reflects the political ecology of documentation: the state recorded its own interventions rather than the environmental knowledge of local communities.

Agricultural expansion in Assam's early and medieval periods created a dynamic relationship between sediment, cultivation, and political territory. The Brahmaputra's annual deposition of fresh alluvium on chars (riverine sandbars) and floodplains continually renewed the agricultural frontier, forming new land through its own fluvial processes. Communities that specialized in char cultivation—particularly the Mishing communities, who developed the distinctive *chang ghar* (raised-platform house) as an adaptation to the chars' seasonal flooding—exercised an intimate ecological knowledge of the unstable riverine environment that the state could neither replicate nor fully control (Saikia 2019, 61). These communities were not passive recipients of the land that the river created; they were active ecological managers whose cultivation practices—seasonal planting on receding floodplains, grazing on char grasslands, fishing in associated water bodies—helped sustain the productivity of these unstable lands. Their semi-rotational use of land—facilitated by the multitude of rivers, diversifying agricultural risk—represented a sophisticated response to the Brahmaputra's perpetual instability.

The *jalkar* (water body) tax—levied by the Ahom state for fishing rights in rivers and lakes—makes visible another dimension of the riverine economy (Nath 2002, 109). In a valley with hundreds of rivers, lakes, and seasonal wetlands, fish was the primary source of animal protein for most of the population. The Kaivarttas, mentioned in early inscriptions in association with *jolas* (streams) and *dighikas* (ponds), represent one of several communities whose livelihoods were built around the management of aquatic resources (Lahiri 1991, 38, 102). A grant from the Sundaridiya-sattra in 1738–1739 CE, which included three fishing lakes alongside agricultural

land, demonstrates that control of aquatic resources was a recognized component of landed wealth (Neog 1974, 156). The *jalkar* tax's very existence implies that fishing rights were sufficiently valuable to be taxed and, consequently, to become the subject of political contestation. Questions of who fished where and under what terms carried political stakes as well as ecological ones.

The creative dimension of floods deserves recognition alongside their destructive power. The annual inundation was not simply a hazard to be managed; it was the fundamental mechanism by which the valley's agrarian wealth was renewed. The Brahmaputra's enormous sediment load—deposited across the floodplain during high-water events—maintained soil fertility across millions of hectares without the need for the complex irrigation infrastructure that sustained comparable areas in drier regions. The adaptations of Assam's farming communities—raised-platform houses, deep-water rice varieties (bao) capable of elongating faster than floodwaters could rise, seasonal rotation between floodplain and highland crops—represented sophisticated ecological responses to the river's rhythms (Guha 1991, 64). These were not passive survival methods but active agrarian strategies that turned the river's unruliness to agricultural advantage. It was in the fields and waters of the valley that the agency of ordinary people was most continuously and consequentially exercised—even if it left only the slightest trace in the written record.

7. HYDRONYMS AND THE UNRULY RIVER: NAMES AS ENVIRONMENTAL ARCHIVES

The names by which Assam's rivers have been known across the centuries constitute a form of environmental archive distinct from—and in many ways more revealing than—the inscriptions and chronicles that explicitly address fluvial history. A hydronym preserves the intersection of language, ecology, and historical memory, providing evidence of the communities that inhabited a river's banks, the characteristics they observed, and the environmental changes the river underwent over time. Reading Assam's hydronyms against the grain of the official record reveals aspects of the region's environmental history that no charter or chronicle explicitly records, including the gradual drying of abandoned channels, the reorganization of drainage networks following tectonic events, and the slow accumulation of sediment that transformed sandbars into islands and redirected rivers into new courses. In this sense, the hydronym functions as a community environmental record, preserving evidence of landscape transformation long after it faded from official memory.

The argument of this section rests on a basic observation about the Brahmaputra system's geology. The river carries one of the highest sediment loads in the world—approximately 402 million tonnes per year—derived from the intense tectonic uplift and high erosion rates of the Eastern Himalayas. This sediment is deposited across the valley floor, progressively raising the bed, forcing the river to seek lower-resistance paths and producing the characteristic braided planform visible in satellite imagery of the upper Assam valley. Over centuries and millennia, this process has generated a landscape of abandoned channels, nascent islands, and river network reorganizations that can be seen, in part, through the accumulation and transformation of names. Every river name bearing the local-usage prefixes *Mara* (dead), *Burhi* (old), or *Sukan* (dried) is evidence of a channel that the Brahmaputra's sediment dynamics eventually silenced.

The most striking demonstration of hydronyms as environmental archives is the naming history of the Dihing River system. The name Burhi Dihing (Old Dihing) for a former channel implies the prior existence of a Noa Dihing (New Dihing)—a name that encodes earthquake-driven course change. Tectonic events in 1691 and 1696 CE reorganized the Dihing's drainage, causing a segment to capture the upstream Lohit and creating a channel subsequently labelled "new" to distinguish it from the pre-seismic course (Saikia 2019, 27). The naming sequence—the original unnamed river, the earthquake, and the new channel labelled "Noa" and the old channel retrospectively labelled "Burhi"—is preserved in toponymy long after the geological event that generated it has faded from political memory. These are not poetic inventions; they are empirical records of fluvial geomorphology encoded in the vernacular.

The formation of Majuli Island—presently the world's largest riverine island—is the most dramatic instance of the Brahmaputra's sediment-driven landscape transformation, and its history deserves consolidated analysis here as the fullest expression of the river's structural unruliness. Prior to the seventeenth century CE, the region that would become Majuli was a modestly sized landmass, with the principal Brahmaputra channel flowing to its north. Sources document a progressive reorganization. By the later seventeenth century, references to a distinct "Gabharu Lohit" channel imply that the river had begun bifurcating around the growing landmass; references to "Sukan Suti" (dried channel of Lohit) in Majuli indicate that portions of the northern channel were already silting up (Gogoi 1994, 109; Nath 2007, 464–74). King Jayadhvaj Singha (r. 1648–1663 CE) is recorded to have halted at the mouth of the Gabharu-Lohit during an expedition, confirming that this bifurcating channel was sufficiently established to be named and navigated. Susan Wade's later reference to "Gabroo-Looicheh"

indicates its continued recognition as a distinct feature of the river system (Wade 1927, 31). This progressive sedimentation—driven by the Brahmaputra's enormous bedload—was the geological engine of Majuli's enlargement. As the northern channel silted, the southern channel captured an increasing volume of discharge and gradually became the dominant channel.

The flood of 1750 CE—one of the most catastrophic in the Brahmaputra's recorded history—dramatically accelerated this process, making the southern channel the primary course and converting the northern arm into the "Kherkutia Suti" and "Lohit Suti", which progressively shrank to secondary status (Sarma and Phukan 2004). The Majuli that emerged from this event was not merely physically larger; it was a new cultural and ecological entity. The Vaishnava sattras (monasteries) established on the island gained a distinctive institutional environment, simultaneously protected from the mainland's military disturbances and dependent on ferry crossings for communication and commerce (Nath 2009, 28). Majuli's sacred-institutional geography was thus, in its very foundations, a gift of the Brahmaputra's unruliness, shaped by sediment dynamics rather than human design.

The cataclysmic sequence that culminated in 1787 CE extends this argument to a larger scale. That year, the coincidence of an exceptionally severe Brahmaputra flood with the avulsion of the Teesta River—which shifted eastward, dramatically increasing the Brahmaputra's lower-course discharge—forced the Brahmaputra in present-day Bangladesh from its historic Mymensingh-Jamalpur course into what would become the Jamuna River (Rahman et al. 2024, 21). By the early 1800s, the Jamuna had become the principal downstream channel, and the Old Brahmaputra had diminished to a secondary distributary. No political authority, however sophisticated its hydraulic engineering, could prevent or control reorganizations of this magnitude. Instead, the most resilient societies adapted, relocated, renamed, and rebuilt.

The cumulative pattern of dead channels (identified by the *mara*, *burhi*, and *sukan* prefixes), new channels (*noa*), and renamed rivers (Bhogdoi from Disoi) across Assam's river network is not random; it reflects the geology of the valley floor. The Kopili–Kalang system's documented changes—the Kopili's shifting junction with the Kalang; the Kalang's own abandoned courses across central Assam, recorded as Mori-Kalang and Pota-Kalang; the references to Bekka Suska and Mara-Manas—trace the footprints of tectonic and sedimentological processes on the cultural landscape (Boruah 2007, 66–80; Hunter 1975, 173). To read the hydronyms of Assam is to read the geological history of the Himalayas, translated into the languages of

the communities that have lived alongside its rivers for millennia. Hydronyms is, in this sense, a form of vernacular geology—an archive of environmental change maintained not by state institutions but by the everyday speech of communities who have continually named and interpreted the river's transformations.

8. CONCLUSION

The rivers of early and medieval Assam thus emerge as central agents of history. They nurtured a distinctive agrarian society, shaped cultural and religious life, and could alternately connect or divide polities. The historical record also reveals instances of remarkable resilience: capitals were relocated when river movements rendered old sites untenable, and new settlements arose on lands freshly deposited by the waters. In the longue durée of Assam's history, the Brahmaputra and its tributaries connected Assam to neighboring regions—carrying pilgrims, traders, and invaders—yet also protected it by their very force and complexity. They generated prosperity through fertile alluvial soils and abundant aquatic resources, yet periodically imposed devastating environmental costs. The most successful rulers were those who recognized the river's dual character and adapted their political and hydraulic strategies accordingly. The kingdoms of Kamarupa and Ahom were not polities that happened to be located near rivers; they were polities structured around rivers, whose territorial sovereignty was hydraulically constituted and whose legitimacy was continuously re-negotiated through the management of water. When rivers shifted, boundaries dissolved and had to be re-constituted; when floods overwhelmed embankments, state authority was tested; and when a king could divert a river to supply his capital, he was performing a form of sovereignty that transcended military power. The Brahmaputra was not merely the backdrop against which Assam's political history played out; it was a character in that history, with its own agency, its own dynamism, and its own capacity to make and unmake political arrangements.

The interface between the river and society was a dynamic one: floods could devastate yet also fertilize; rivers could isolate communities yet also link them through networks; water could be a bounty to be gifted (as when kings granted fisheries) or a force to be mitigated (by raising dykes). The people of Assam, in turn, exhibited a pragmatic reverence for the river—worshipping it while also dredging it, diverting it, and even legislating its use (as seen in royal edicts regulating ferry rights and fishing on certain stretches). Indigenous communities exercised genuine environmental knowledge and genuine agency, even though the official record reduced

them to instruments of state policy. Their knowledge of the river, accumulated over generations and embedded in practice, was the basis on which every grand hydraulic project was built. The hydronyms of Assam provide an archive that no official record preserves: the memory of how the Brahmaputra changed and how its people changed with it. This archive is still being written. The issues of flood control, riverbank erosion, and sedimentation that preoccupy Assam today are not problems created by modernity; they are the latest chapter in a long-standing relationship between this remarkably unruly river and the people who have made their homes alongside it for over two millennia. The story of Assam's rivers is ultimately a story of negotiation between nature's rhythms and human aspirations—a negotiation that is ongoing and shows no sign of ending.

Ethics Statement: I hereby confirm that this study was conducted in accordance with all applicable ethical requirements and standards for research.

Consent to Participate: Informed consent was obtained from all respondents before the survey, ensuring their voluntary participation, with assurance of anonymity and confidentiality.

Consent for Publication: Consent for the publication of the research findings in a journal was obtained from all participants.

Data Availability Statement: The data have been anonymized and are not publicly available to ensure the privacy and confidentiality of the respondents.

Conflict of Interest Statement: The author declares that he has no competing financial, professional, or personal interests that could have influenced the work reported in this manuscript.

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RESEARCH PAPER

Deterioration of Wetland Ecology and Livelihood Crisis: A Study from Loktak Wetland, Manipur, India

Ongtham Kipjen Singh,[*] Avijit Mistri [**]

Abstract: Loktak Lake, a Ramsar wetland of international importance, is vital to the livelihoods of people in Manipur. The wetland's ecology has been degrading for various reasons, particularly anthropogenic activities. Hence, it was listed in the Montreux Record in 1993. This study investigates risks associated with fishing and farming livelihoods in the area and identifies the factors that drive them. It is based on a field investigation of 600 households from 12 villages in the wetland. The study employed a mixed-methods approach, incorporating participatory risk mapping, various indices such as the Standard Livestock Unit Index, Policy Index, Wealth Index, and Simpson Diversity Index, and, finally, Ordinal Logistic Regression (OLR) model to identify significant predictors. The findings show that the extinction and decline of fish species, the proliferation of *phumdis*, water pollution, siltation, and submergence are major concerns that severely impact fishing. Non-ecological stressors, such as lack of irrigation infrastructure, market risks, and input costs, severely affect farmers. The OLR model indicates that household size, age range of the household members, sex ratio, migration, religion, and livestock ownership are significant predictors of ecological risks. Conserving wetland ecology is a prerequisite for ensuring sustainable livelihoods in Loktak; accordingly, an integrated natural resource management strategy is urgently needed.

Keywords: Wetland Ecology, Livelihood Issues, Participatory Risk Mapping, Fishing, Farming.

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1. INTRODUCTION

Wetlands play a significant role in maintaining the ecological balance and supporting human livelihoods. They offer several environmental benefits, including freshwater for domestic use and irrigation, food security, wildlife habitats, and carbon sequestration. In addition, they also contribute to flood control, help manage groundwater recharge and discharge, and reduce nutrient contamination. There is a strong, inseparable connection between wetlands and communities, particularly in developing countries, where people are reliant on wetland ecosystems for their livelihoods (Wondie 2018). Globally, one in eight people depends on wetlands for activities such as fishing, farming, ecotourism, and handicrafts (Convention on Wetlands n.d.). Globally, wetlands support rice production that feeds 3.4 billion people and meet more than 40% of fish demand through aquaculture (Convention on Wetlands n.d.).

However, wetlands in different parts of the world are increasingly being degraded by various human activities (Sica *et al.* 2016; Oberholster *et al.* 2014; Wang *et al.* 2012). Between 1990 and 2015, the average annual loss rate of wetlands (–0.78%) was estimated to be three times that of natural forests (–0.24%) (FAO 2015). Approximately 35% of marine, coastal, and inland natural wetlands were lost between 1970 and 2015, with regional losses ranging from 12% in Oceania to 59% in Latin America (Convention on Wetlands 2018). Some of the impacts of wetland degradation include loss of biodiversity, decline in water quality and water shortages, increased vulnerability to flooding, and reduced carbon sequestration (Zedler and Kercher 2005).

According to the *Millennium Ecosystem Assessment* (2005), various anthropogenic factors are the primary drivers of changes in wetland ecologies, which in turn affect the livelihoods of households engaged in fishing and farming in the area. Since the communities dependent on wetlands are usually the poorest and most directly affected by them, they are among the most affected by the changing ecology of the wetland (Kundu *et al.* 2024; Huq *et al.* 2020). As a result, diversifying livelihood activities—whether *in situ* or through migration—has become a crucial strategy for sustaining livelihoods. Studies on coastal mangrove swamps, the Sundarbans wetland (Mistri and Das 2020), inland freshwater wetlands, and the Loktak wetland complex show that people are migrating in large numbers from wetlands to either nearby cities or distant metropolitan areas outside their states in search of employment (Mistri *et al.* 2025a; Singh and Mistri 2025). For instance, in the Nijhum Dwip coastal wetland of Bangladesh, fishing communities have shifted from fishing to alternative

income sources, including livestock rearing, farming, daily labour, and handicraft activities (Rahman *et al.* 2012).

This study focuses on Loktak Lake, a Ramsar wetland (designated in March 1990) in the Northeast (NE) Indian state of Manipur. Loktak Lake, spanning about 260 sq km, is the largest freshwater lake in NE India, and along with 19 freshwater marshes, forms the Loktak wetland complex. The Loktak wetland supports rich biodiversity, including 54 fish species, 68 reptiles and amphibians, 22 mammals, 116 bird species, and more than 200 plant species (MoEFCC 2025). Approximately 3 lakh people residing in 55 rural and urban settlements in and around the wetland depend directly or indirectly on it for their sustenance (LDA n.d.; Bharati *et al.* 2017).

According to the *Ramsar Sites of India Factbook* (2025), approximately 5,000 fishers depend on Loktak Lake for their livelihoods (MoEFCC 2025). It is a major source of fish throughout Manipur. Fishing in the wetland includes two types: open-water fishing and aquaculture along the lakeshore. Three types of farming activities are practised along the periphery of the wetland: aquaculture cum paddy cultivation; intensive subsistence farming, primarily rice cultivation; and commercial farming, primarily horticulture. The wetland also provides various edible and medicinal plants as well as raw materials for handicrafts, which constitute an important source of income for many households (LDA n.d.). Owing to its immense importance to Manipur's economy, the lake is known as the "Lifeline of Manipur" (LDA n.d.).

Three years after its Ramsar designation, Loktak Lake was listed in the Montreux Record in June 1993 due to ecological issues. According to the Ramsar Sites Information Service (23 March 1990), "deforestation in the catchment area, water hyacinth infestation, and pollution" were identified as primary causes of ecological degradation of the Loktak Lake (Ramsar Convention 1990). The commissioning of the Ithai Barrage (in 1983) on the Manipur River under the Loktak Hydro Electric Project (LHEP), which blocked the wetland's outlet, was the turning point for the rapid deterioration of the lake's ecology. The cofferdam has "caused the local extinction of several native fish species" (Ramsar n.d.). Before the construction of the barrage, many fish species would migrate from the Chindwin–Irrawaddy River system through the Manipur River into the lake. However, with the barrage blocking their migratory pathway, the number of fish species and their population in the lake have declined or disappeared altogether (Singh 2018). Because the lake water was maintained above the flood level, the lake's periphery, including residential and agricultural land, became submerged, resulting in displacement and loss of economic activities (Thakur 2020).

Siltation is another major issue, as rivers and canals deposit sediment in the lake. This results in the lake bed filling and blocking water flow at the Ithai Barrage (Singh 2018). According to the *Ramsar Sites of India Factbook*, "water regime alteration by Ithai barrage" is identified as a "high threat" in the Loktak wetland; other medium-level threats are the proliferation of *phumdis* (heterogeneous floating masses of vegetation, soil, and organic matter), siltation, water pollution, unsustainable water abstraction for Loktak hydropower, and fragmentation by road construction on the wetland (MoEFCC 2025, 82).

The "Wetland Health Card" prepared by the Ministry of Environment, Forest and Climate Change (MoEFCC 2021), which is based on information collected in 2019 on nine parameters[1] across four broad categories—area, hydrology and catchment, biodiversity, and governance—paints a gloomy picture of the Loktak wetland's health. Invasive macrophytes cover approximately 21–30% of Loktak Lake, and since 2000, 1–5% of the wetland has been converted to non-wetland uses. The ratios of the number of natural inlets choked and diverted to the total number of natural inlets, and of the number of natural outlets choked and diverted to the total number of natural outlets, were estimated at 0.4–0.6 for each; i.e., evaluated as "B category", whereas the "desired value" is <0.2 for each parameter. Notably, data on annual waterbird counts as a proportion of the five-year average are unavailable, constraining biodiversity assessment. In short, Loktak's degraded ecology threatens biodiversity, natural resources, and the livelihoods of wetland-dependent communities.

Several studies have focused on ecological issues and their impacts. Yet, economic issues and their impact on the livelihoods of communities dependent on the Loktak wetland are rarely explored with empirical rigour. A handful of studies (Mistri *et al.* 2025a, 2025b; Singh and Mistri 2025; Paonam and Chatterjee 2023; Oinam and Khoiyangbam 2017) have examined the status of and challenges to livelihoods in and around Loktak Lake. However, these are small-scale studies, limited to one or two villages, blocks, or islands, with a narrow scope, focusing only on fishing issues or on fishers' health. Moreover, research on the impact of ecological changes

[1] The nine parameters in the "Wetland Health Card" are the percentage of wetland converted to non-wetland use since 2000; the ratio of the number of natural inlets choked and diverted to the total number of natural inlets; the ratio of the number of natural outlets choked and diverted to the total number of natural outlets; the percentage of samples conforming to desired biochemical oxygen demand/ dissolved oxygen/ chemical oxygen demand levels; the percentage of wetland area covered by invasive macrophytes; annual water bird count as a proportion of average count of last five years; clearly demarcated wetlands map; wetland management plan; and wetland notification.

on the livelihoods of island and lakeshore communities—particularly in relation to fishing, aquaculture, and farming, as well as their adaptation to these adverse conditions—has remained empirically underexplored. Therefore, the present study aims to bridge this gap by assessing the perceived risks associated with the principal means of livelihood generation—fishing and farming—in and around Loktak, given the wetland's deteriorating ecological conditions. The study also examines how demographic, social, and economic factors influence ecological risk perception among individuals engaged in fishing and farming.

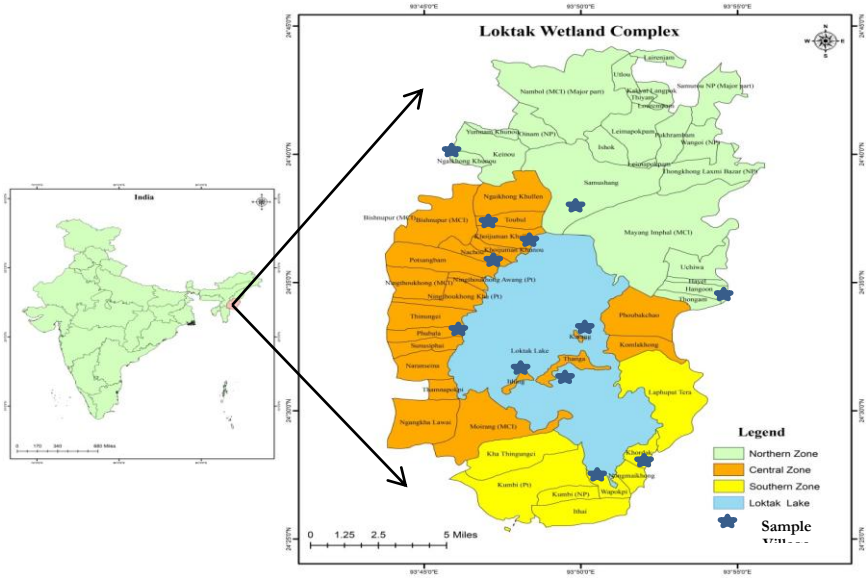
2. METHODOLOGY

In order to fulfil the objectives of the study, primary data pertaining to livelihood risks and socio-economic conditions were collected. The data were analysed using a mixed-methods approach that combined descriptive and inferential techniques. The detailed methodology adopted in this study is described in the following sections.

2.1 Data Sources and Sample

This study is primarily based on a field survey conducted in 12 census villages in the 55 settlements in and around the Loktak wetland (Census of India 2011). A census village is the smallest geographical unit, while the household is the smallest social unit for sampling. The study area, along with the sampled villages, is illustrated in Figure 1. Multistage sampling was employed to select villages with the highest share of households dependent on farming and fishing in the 2011 Census. The Loktak Development Authority (LDA) divides the Loktak wetland into three distinct zones—Northern, Central, and Southern—based on factors such as vegetation type, density of *phumdis*, drainage system, location of open water areas, and human activities. In the Northern Zone, three villages—Samusang, Hangoon, and Ngaikhong Khunou—were selected; these had the highest share of households practising fish farming combined with agriculture. Similarly, in the Southern Zone, two villages—Wapokpi and Khordak—were chosen for their predominant reliance on fishing. In the Central Zone, three islands—Ithing, Thanga, and Karang—were purposively selected to observe the effects of capture fishing in the lake's open waters. Additionally, four lakeshore villages in the Central Zone—Phubala, Nachou, Toubul, and Khoijuman Khullen—were included, as fishing and farming are their primary economic activities.

Figure 1: Map of the Study Area with Sample Villages Marked



Source*:* Authors' compilation

A total of 600 households—on average, 50 per village—were selected from the 12 sample villages. The sample size was decided based on Cochran's sampling formula (1977). At a 4% margin of error, 95% confidence level, and population variance of 0.5, the required sample size is approximately 600 for an unknown study population. A census village comprises different wards, locally called *leikai*. From each *leikai*, roughly an equal number of households that engaged in either fishing or farming were selected randomly. A household survey was conducted using a structured questionnaire. The survey was conducted after obtaining the respondents' informed consent. Only adult fishers or farmers were chosen as respondents.

2.2 Study Design

The study employed a mixed-methods approach. It incorporated descriptive statistics, such as mean, median, mode, and standard deviation, as well as other inferential statistics. Indices such as the Standard Livestock Unit Index, Policy Index, Wealth Index, and Simpson Diversity Index were constructed. The study included participatory risk mapping (Smith *et al.* 2000), a method used to assess risk perception in fishing and farming activities in Loktak. Participatory risk mapping is a subjective approach based on the perceptions of respondents. In this method, respondents are first asked to identify risks associated with fishing or farming that they have

experienced in the last five years. If they do not remember or struggle to articulate these, they are provided with a predefined list of risks derived from the existing literature (Paonam and Chatterjee 2023; Singh 2018; Oinam and Khoiyangbam 2017) and pilot surveys. After identifying the risks, respondents are asked to rank them from most severe to least severe. Based on these perceived risks and their ranking, three indices—Incident Index (I_j), Severity Index (S_j), and Risk Index (R_{ij})—were constructed. The I_j and S_j were constructed for the entire sample and graphically represented using quadrant mapping (risk mapping). Risk perception at the household level was assessed using the Risk Index (R_{ij}).

2.3 Incident Index

The Incident Index quantifies the proportion of respondents who identified a specific risk, indicating its prevalence in the population (Smith *et al.* 2000). The index ranges from 0 (no households are affected) to 1 (all households are affected). The formula for the Incident Index is given as:

$$I_j = \frac{n_j}{s} \qquad \text{(i)}$$

Where I_j is the Incident Index for the risk j, n_j is the total number of households identifying a particular risk j, and s is the total number of households in the study.

2.4 Severity Index

The Severity Index assesses the severity of each risk on a scale from 0 (least severe) to 1 (most severe). The index is based on the respondents' ordinal rankings. In the study, the Severity Index (vide formula ii) for a particular risk (j) perceived by a household (i) was computed using the formula adopted by Bunting et al. (2013), modified from Smith et al. (2000):

$$S_j = \left[\frac{r-1}{n-1}\right] x\,(-1) + 1 \qquad \text{(ii)}$$

Where S_j is the Severity Index of a particular risk j identified by a household, r is the ordinal rank of risk j, and n is the total number of risks identified by a household. The mean of all S_j values for the whole sample is the Severity Index for risk j.

2.5 Risk Mapping

Risk mapping with quadrants provides a graphical representation of risk combining I_j and S_{ij}. Since the Incidence and Severity indices range from 0 to 1, 0.5 is used as the midpoint for both the x-axis and y-axis, dividing the figure into four quadrants: upper-right quadrant (+, +), upper-left quadrant (–, +), lower-right quadrant (+, –), and lower-left quadrant (–, –). Risks in

the upper-right quadrant are characterized by high prevalence and severity, while those in the lower-left quadrant have low prevalence and severity. The lower-right quadrant has high severity and low prevalence, while the upper-left quadrant has low prevalence but high severity.

2.6 Risk Assessment at the Household Level

Doss *et al.* (2008) and Nnaji *et al.* (2023) developed the Risk Index, based on Smith *et al.* (2000), to assess risk at the household or unit level. The formula is given as:

$$R_{ij} = 1 - \left[\frac{(r_{ij}-1)}{n_i}\right] \qquad \text{(iii)}$$

Where R_{ij} is the risk index for household i for the risk j, r_{ij} is the ordinal rank of risk *j* for the household *i*, and n_i is the total number of risks identified and ranked by household *i*.

2.7 Simpson Diversification Index

Livelihood diversification was assessed to examine household income diversity in the wetland beyond fishing and farming. The livelihood diversification index was constructed based on the Simpson Diversification Index (SDI) (Simpson 1949), which is calculated using the number of sources and the proportion of income from each source. The formula for SDI is as follows:

$$SDI = 1 - \sum_{i=1}^{n} P_i^2 \qquad \text{(iv)}$$

Where *n* is the total number of income sources, and *Pi* is the proportion of income from the *i*-th income source. The SDI value ranges from 0 to 1, where 0 indicates no diversification—meaning the household relies on a single wetland-dependent activity, either fishing or farming. As the SDI value increases and approaches 1, it indicates an increase in the number of income sources and a more even distribution of income across those sources. Based on this value, the SDI is categorized into four categories of diversification: no diversification, low, medium, and high. When a household engages in a single activity, such as fishing or farming, it is tagged as "no diversification". These households do not generate income from any economic activities other than wetland-based fishing or farming, or farming combined with fish farming. A low diversification household is engaged in two economic activities, with one activity (e.g., fishing or farming) contributing the predominant share of income. A medium-diversification household engages in two or three activities, with income distributed more or less equally; one of these activities is dependent on the wetland, such as fishing or farming. A high diversification indicates a

household with income from four or more sources that are evenly distributed, one of which is a wetland-based activity.

Finally, an Ordinary Logistic Regression (OLR) model was constructed to examine how 13 predictors influence perceived ecological risks in fishing and farming. The formula for the OLR model (Cameron and Trivedi 2005) is:

$$\Pr(\mathrm{Yi} > \mathrm{j}) = \frac{\exp(\alpha \mathrm{j} + \mathrm{Xi}\beta \mathrm{j})}{1 + [\exp(\alpha \mathrm{j} + \mathrm{Xi}\beta \mathrm{j})]} \quad \mathrm{j} = 0 - 2 \qquad \text{(v)}$$

Where Y_i is the dependent variable of three categories of ecological risks (low, moderate, and high) (see Section 2.8), αj is the intercept, and βj is the vector of the parameter to be estimated. Xi denotes independent variables.

2.8 Variables Used in the Study

This section presents the dependent and independent variables, including their categories, descriptions, and the techniques used for deriving them. These variables are incorporated into the OLR model to examine the demographic and socio-economic determinants of the perception of ecological risk.

2.8.1 Dependent variable

The dependent variable of the study is ecological risk. Ecological risk is estimated by summing the *Risk Indices* for all the ecological and climatic risks that a household experiences in relation to fishing and farming. The risk perception score is divided into three categories: low risk (< 0.94), moderate (0.94–3.64), and high (> 3.64), based on the mean ± standard deviation.

2.8.2 Independent variable

The influence of 14 independent variables on the perception of ecological risks was assessed. These are (1) household size, which includes the total number of household members; (2) age group, which comprises the age range of household members (15–29 years, 30–59 years, and 60 years and above); (3) educational level, which refers to the highest level of education—primary, secondary, or higher—attained by any household member; (4) sex ratio, i.e., number of females per 1,000 males living in a household (calculated by dividing the total number of female household members by total number of male household members and multiplying by 1000), based on which households are categorized as male-dominated, balanced, and female-dominated; (5) household migration status, conceptualized in the study as the migration of any household member for at least a month at a stretch for work or employment purposes within the

last two years; (6) social group, which includes Scheduled Caste (SC), Other Backward Classes (OBC), and General (Gen) (i.e., non-SC/OBC/Scheduled Tribe (ST)); (7) religion, comprising Sanamahism, Christianity, and Hinduism; (8) household type, defined by the household's principal activities—fishing, farming, and both; (9) income, measured by the household monthly income in Rupees (□); (10) landholding, referring to the total land held by households in hectares; (11) SDI, which was used to measure the level of livelihood diversity among wetland communities; (12) the Standard Livestock Unit Index, which is a summary index of livestock possession computed by multiplying the coefficients/weights proposed by the Food and Agriculture Organization (2011) by the number of livestock reared in a household; (13) the Wealth Index, comprising 24 indicators that capture housing, basic amenities, and household assets, which is derived using principal component analysis with varimax rotation, yielding four components that explain 60% of the variance; and (14) the Policy Index, a summation of benefits or facilities obtained by households in the last five years from policies/schemes, which is constructed using the equal-weighted standardization technique.

3. RESULTS

This section presents the findings of the study based on the primary data collected through the field survey. The analysis begins with the perceived risks associated with fishing and farming, the ecological conditions of the Loktak Lake wetland, the background characteristics of the households, and the determinants of perceived ecological risk. The detailed findings are discussed in the following subsections.

3.1 Perceived Risk in Farming

The farmers identified 11 farming risks (Table 1). These are categorized under five heads. Ecological and climatic risks in farming include the submergence of agricultural fields, irregular rainfall patterns, and the sudden onset of climatic events. Highly reported non-ecological risks include the rising cost of agricultural inputs, market price fluctuations, lack of credit and financial support, and health issues. The rising cost of farm inputs, such as fertilizers, tillage costs, and machinery, are the most often cited farming risk reported by 90% of households. However, since its intensity is not severe (S_j = 0.484), it is placed in the lower-right quadrant of the risk map (Figure 2). The unavailability of irrigation is the second-most prevalent concern, affecting 86% of households; its effects are also intense (S_j = 0.810). Irregular rainfall is also the most prevalent and severe farming risk,

Table 1: Farming Risks in the Loktak Wetland

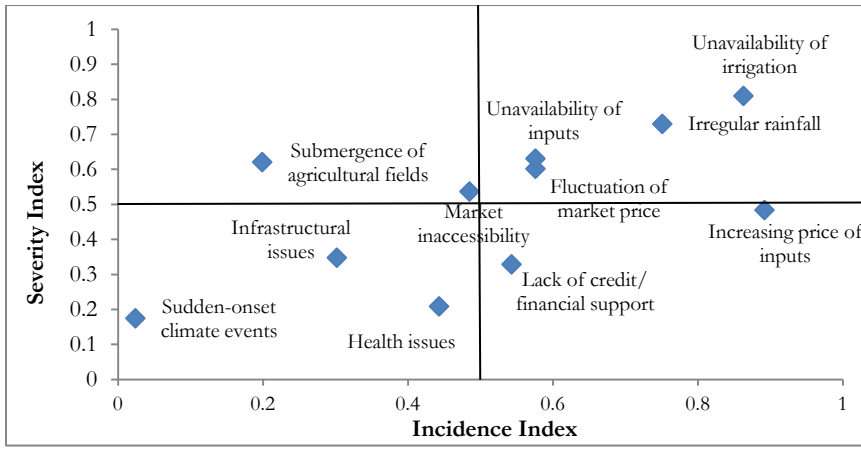
Category	Risks	Incidence (I_j)		Severity (S_j)	
		Value	Rank	Value	Rank
Ecology and climate	Submergence of agricultural fields	0.199	9	0.621	4
	Irregular rainfall	0.751	3	0.73	2
	Sudden-onset climatic events	0.024	10	0.175	11
Agricultural input	Unavailability of irrigation	0.863	2	0.81	1
	Unavailability of l inputs	0.576	4	0.602	5
	Increasing price of inputs	0.892	1	0.484	7
Market	Fluctuation of market price	0.576	4	0.631	3
	Market inaccessibility	0.485	6	0.537	6
Institutional	Lack of credit/financial support	0.543	5	0.329	9
	Infrastructural issues	0.302	8	0.348	8
Personal	Health issues	0.443	7	0.209	10

Note: n = 241.
Source*:* Computed from field survey data

affecting 75% of households and carrying a severity index of 0.73, placing it in the upper-right quadrant of the risk map (Figure 2).

Agricultural fields getting submerged due to the construction of the Ithai Barrage emerged as the most severe risk (S_j = 0.621). However, it is also among the least prevalent, affecting only 20% of households. The risk of sudden onset of a climatic event is the least prevalent risk reported by 2.5% of households and the least severe (S_j = 0.175). Personal health hazards and infrastructure issues are also among the least prevalent and severe risk categories.

Figure 2: Farming Risk Map Overview



Source*:* Computed from field survey data

Table 2: Fishing Risks in the Loktak Wetland

Category	Risks	Risk Index (I_j)		Severity Index (S_j)	
		Value	Rank	Value	Rank
Ecological and environmental	Water pollution	0.574	5	0.638	3
	Phumdis proliferation	0.618	4	0.685	1
	Decrease in depth of water	0.417	10	0.482	9
	Decrease in fishing areas	0.507	8	0.599	7
	Sudden-onset climatic events	0.49	9	0.616	6
	Flooding/submergence of fishponds/ farms	0.385	12	0.619	5
	Seasonality in fish availability/ production	0.404	11	0.635	4
	Decrease in fish species and availability	0.674	2	0.671	2
Fishing input	High price of fishing equipment	0.716	1	0.581	8
	Low availability of inputs	0.206	15	0.453	10
Market	Market inaccessibility	0.517	7	0.424	11
	Fluctuation of fish price	0.287	14	0.346	15
Institutional	Fishing regulations	0.098	16	0.409	12
	Lack of infrastructure in fishing	0.321	13	0.357	14
	Unavailability of credit/ financial support/in fishing	0.625	3	0.379	13
Personal	Health hazard	0.566	6	0.24	16

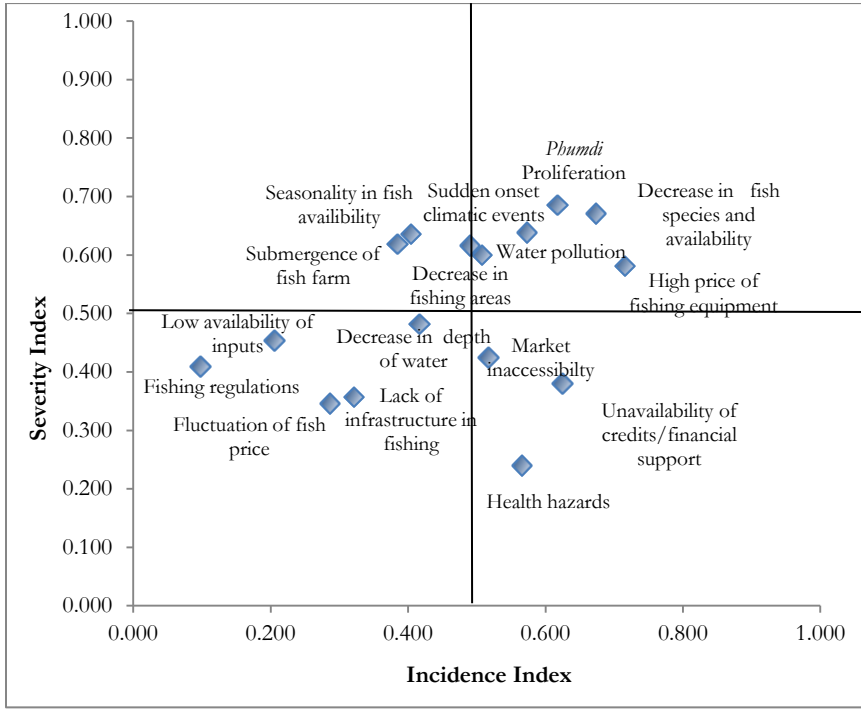
Note: $n = 408$.

Source*:* Computed from field survey data

3.2 Perceived Risk in Fishing

Fishers reported facing 16 risks associated with fishing, disaggregated into five categories (Table 2). The analysis showed that ecological or environmental risks in fishing are more severe than non-ecological risks. Proliferation of *phumdis* is a severe livelihood concern reported by most fisherfolk ($I_j = 62$; $S_j = 0.69$). This is followed by a decrease in fish species and their availability. *Phumdis* proliferation, decrease in fishing species and production, and water pollution are placed in the upper-right quadrant of the risk map (Figure 3), indicating a high prevalence and high severity of risk in fishing. Seasonality in fish availability is the most severe risk ($S_j = 0.635$), but its prevalence is low, reported by 40% of fishing households. A similar trend (severe risk, low prevalence) is also observed in risks associated with sudden-onset climatic events, such as rainfall, gusty winds, and storms.

Figure 3: Fishing Risk Map Overview



Source*:* Computed from field survey data

About 62% of fishing households reported the unavailability of credit facilities, mainly from the government sector, although the severity is relatively lower (S_j = 0.379). This risk is therefore placed in the lower-right quadrant. Health issues resulting from fishing are also placed in the same quadrant, indicating high prevalence but low severity. Price issues, such as volatility in the price of fish products, rules and regulations governing fishing issued by the LDA and other government agencies, and limited availability of fishing inputs, are among the least prevalent and least severe fishing risks faced by fishers (Figure 3).

3.3 Background Characteristics of Households

Table 3 presents the background characteristics of households. On average, there are six individuals in each household. Approximately 67% of households have members aged 30–59 years, while 29% have members aged 15–29 years. This indicates that the study area is in a more favourable stage of the demographic dividend, characterized by a larger share of economically productive people and a lower dependency ratio. About 54%

Table 3: Background Characteristics of Households

Characteristics	Frequency	(%)	Mean	Standard Deviation
Demographic Characteristics				
Household members	600		5.72	1.944
Age group				
15–29 years	77	12.8		
30–59 years	406	67.7		
60 years and above	117	19.5		
Educational level				
Primary	34	5.7		
Secondary	242	40.3		
Higher	324	54		
Sex ratio				
Male dominated	243	40.5		
Balanced	156	26		
Female dominated	198	33		
Migration				
No	293	48.8		
Yes	307	51.2		
Social Characteristics				
Social category				
SC	230	38.3		
OBC	289	48.2		
GEN	81	13.5		
Religion				
Sanamahism	269	44.8		
Christianity	12	2		
Hinduism	319	53.2		
Economic Characteristics				
Livestock possession				
No	233	38.8		
Yes	377	62.2		
Income	600		Rs. 27,643	Rs. 24,187
Landholding	600		0.49 ha	0.81ha
Household type				
Farming	192	32		
Fishing	359	59.8		
Both	49	8.2		
Location of village				
Northern zone	146	24.3		
Central zone	355	59.2		
Southern zone	99	16.5		

Contd...

Characteristics	Frequency	(%)	Mean	Standard Deviation
Livelihood diversification				
No diversification	163	27.2		
Low diversification	75	12.5		
Medium diversification	300	50		
High diversification	62	10.3		

Source*:* Field survey data

of households have at least one member with higher education; only 5.7% have only members with primary education. Households are predominantly male-dominated (40%), while the share of female-dominated households is 33%. Approximately 51% of households reported that one or more members experienced migration due to work and employment purposes in the last two years. The population in the study area was predominantly constituted by low-income OBC communities. A significant number of SC households reside in three islands—Thanga, Karang, and Ithing. Hinduism (53%) is the most followed religion, followed by Sanamahism (45%), a traditional religion of the Meitei community. Christianity (2%) is the least followed of the major religions.

Among the sampled households, approximately 60% are engaged in fishing, 32% in farming, and 8.2% in both. About 40% of households rear livestock. Intensive and commercial rearing are negligible. Nearly 27% of households depend solely on the wetland for their livelihood, while 73% engage in other non-wetland-dependent activities as well as wetland-dependent activities. The average monthly household income is Rs. 27,643, which is above the average monthly income (Rs. 12,698) of rural households in India as per the National Bank for Agriculture and Rural Development (NABARD 2022). The mean landholding is about 0.50 hectares, which is below the average landholding size (0.74 hectares) in rural India (NABARD 2022).

3.4 Factors Affecting Ecological Risks in Fishing and Farming

Table 4 presents the results of the OLR model, which predicts the likelihood of households reporting ecological risks. Of the 14 predictors, 7 significantly account for variations in the response variable, i.e., the ordinal category of ecological risk perception in fishing and farming. For each additional household member, the odds of being in a high ecological risk category increase by 14%. The households with members aged 30–59 are two times more likely to experience high ecological risk than those with members aged 60 and above. Male-dominated households are 48% more likely to perceive high ecological risk than female-dominated households.

Table 4: OLR Model of the Likelihood of Ecological Risk Perception in the Loktak Wetland

Response Variable: Ordinal Category of Ecological Risk (Low: 1, Medium: 2, High: 3)					
Independent Variables	**Estimate**	**Odds Ratio (OR)**	***p***	**95% Confidence Interval**	
				Lower Bound	Upper Bound
Demographic Characteristics					
Household members	0.130	1.139	0.023	0.018	0.242
Age group					
15–29 years	0.521	1.683	0.128	–0.150	1.191
30–59 years	0.690	1.994	0.007	0.191	1.189
60 years and above (ref)					
Education level					
Primary	–0.313	0.731	0.508	–1.239	0.613
Secondary	–0.038	0.963	0.854	–0.440	0.364
Higher (ref)					
Sex ratio					
Male dominated	0.394	1.482	0.025	–0.039	0.827
Balance ratio	0.274	1.315	0.266	–0.209	0.757
Female dominated (ref)					
Migration					
Yes	0.192	1.212	0.041	–0.203	0.587
No (ref)					
Social Characteristics					
Social category					
SC	–0.363	0.696	0.265	–1.001	0.275
OBC	–0.288	0.749	0.318	–0.855	0.278
GEN (ref)					
Religion					
Sanamahism	–0.395	0.674	0.045	–0.781	–0.009
Christianity	–2.333	0.097	0.001	–3.708	–0.958
Hinduism (ref)					
Economic Characteristics					
Household type					
Both	–1.865	0.155	0.124	–2.689	–1.041
Fishing	1.138	3.120	0.003	0.386	1.890
Farming (ref)					
Income	1.02	5.590	3.78	4.91	1.290
Livelihood diversification					
No diversification	0.015	1.015	0.969	–0.761	0.791
Low diversification	0.207	1.230	0.621	–0.615	1.029
Medium diversification	0.354	1.425	0.300	–0.316	1.024
High diversification (ref)					

Contd...

Landholding	–0.063	0.938	0.629	–0.321	0.194
Livestock	–0.342	0.711	0.045	–0.677	–0.007
Policy Index	–0.039	0.962	0.326	–0.116	0.039
Wealth Index	–0.301	0.740	0.352	–0.933	0.332

Note: Model fitting information: $X^2 = 190.034$, $p = 0.000$; $n = 600$; Cox & Snell $R^2 = 0.296$.
Source: Computed from field survey data

Migrant households have higher odds (OR = 1.21) of reporting high ecological risk compared to non-migrant households.

In the social category, religion is a significant factor. Compared with households following Hinduism, those following Sanamahism or Christianity have lower odds of experiencing high ecological risk (OR = 0.674 and OR = 0.097, respectively). Fishing households have a higher likelihood—by three times—of experiencing high ecological risk compared with farming households. Livestock rearing has a negative impact on the likelihood of experiencing ecological risk; for every one-unit increase in livestock, the likelihood of experiencing high ecological risk decreases by 29%.

4. DISCUSSION

Fishing risks related to ecological changes, such as the decline of fish species, the proliferation of *phumdis*, water pollution, and seasonality in fishing, are the most severe. Before the construction of the Ithai Barrage in 1983, seasonal fluctuations in water levels and dry periods limited the growth of *phumdis* (LDA and WISA 2010). However, following the operation of the barrage, between 1989 and 2002, the area occupied by *phumdis* increased from 116.4 sq km to 134.6 sq km (Singh and Moirangleima 2009). The proliferation of *phumdis* is also aggravated by blockage of the wetland's water by the Ithai barrage. Before the construction of the barrage, *phumdis* were used to remove from the wetland through the Manipur River. Chemical fertilizers, pesticides, and insecticides used in the surrounding catchment areas are carried into the wetland by rivers, leading to eutrophication and the proliferation of *phumdis* (LDA 2011). The proliferation of *phumdis* negatively impacts fishing by obstructing the navigation of fishing boats, reducing open-water fishing areas, disrupting fish breeding, increasing water pollution through *phumdis* decomposition, and contributing to Lake Siltation (Singh and Khundrakpam 2011). The risk of *phumdis* proliferation is more pronounced in villages in the Northern and Southern Zones, such as Hanggon, Shamushang, Wapokpi, and Khordak.

Water pollution in Loktak mainly results from the rivers that drain into the wetland (Kangabam and Govindaraju 2019). The Nambul River, which flows through Imphal city, drains directly into the Loktak wetland. It significantly pollutes the wetland because of the discharge of silt, sediment, and urban waste, leading to a reduction in fish species (Meinam et al. 2025). A study by Borah *et al.* (2024) found microplastics in 91% of fish samples from the wetland, underscoring the severity of pollution and potential health risks to humans. The sediments in the wetlands have a high iron concentration. The probable reason for this is the diffusion of iron-rich soils from surrounding catchment areas and other human influences (Laishram *et al.* 2025)

Before 1950, fish from the wetland accounted for more than 60% of Manipur's total fish production, with fish from the Chindwin–Irrawaddy system accounting for 40% of the wetland's production. However, fish production in the wetland has now dropped to 11% (Meinam *et al.* 2025). This decline in fish species and their populations is, therefore, among the most widespread and serious risks facing the Loktak wetland. The Ithai Barrage slows the water current, leading to extensive deposition of debris on riverbeds and in Loktak Lake (Singh 2018). According to local fishers, this sedimentation makes the lake's bottom shallower, making it difficult for them to use their fishing gear and reducing fish breeding, as reported by local fishers.

Windy weather on the lake also poses a serious risk, causing the loss of fishing gear, injuries, and even fatalities. For instance, a fisherman died in the lake when strong winds capsized his boat in 2024 (The Sangai Express 2024). Fishers also experience seasonal fluctuations in fishing activity. From December to April, fish catches are minimal due to a low breeding rate, slower metabolism, and fish migrating to deeper waters. This minimal fish catch makes it difficult for fishers to support their families. Hence, they switch to other occupations, mainly working as construction labourers in their villages or nearby areas, or temporarily migrate elsewhere.

Health risks among fishers in the Loktak wetland are a serious concern. Musculoskeletal issues caused by holding awkward positions for long durations during fishing, skin problems, and infections from cuts and wounds due to exposure to polluted wetland water are becoming increasingly common. Fishing equipment, such as nets and canoes, are also becoming more expensive. For instance, fishers reported that they need approximately Rs. 50,000 to start fishing. With nearly 63% of fishers unable to access credit, the lack of credit facilities further aggravates their challenges.

Irregular rainfall due to the vagaries of the monsoons, as well as flooding of agricultural fields, poses severe environmental and ecological risks for farmers in the wetlands. Due to variations in topography, rainfall in Manipur varies significantly. Imphal Valley, where the Loktak wetland is located, is a rain shadow area with an average annual rainfall of 1,412 mm (Dikshit and Dikshit 2014). An increase in temperature and changes in rainfall patterns have affected Manipur's agricultural sector (Feroze *et al.* 2014). The same effect was reported by farmers in the wetland, who said that irregular rainfall was reducing their agricultural yields. The construction of the barrage submerged approximately 80,000 acres of the lakeshore, resulting in an annual financial loss of Rs. 300 crore, including losses from crops, fishing, and other seasonal vegetable harvests (Singh 2018; Singh 2017). The lack of irrigation facilities poses the greatest risk in the study areas. The Loktak lakeshore area was to be irrigated through the Loktak Lift Irrigation Canal, which was one of the primary purposes of constructing the Ithai Dam under LHEP. The project was estimated to generate an irrigation potential of 24,000 ha in the Bishnupur and Imphal West districts. However, it has failed to irrigate the fields efficiently due to the lack of proper maintenance. A large proportion of the area under canal command does not receive adequate irrigation.

Rice is the predominant crop during the kharif season, and its cultivation remains highly dependent on monsoon rainfall. After the kharif season, most of the fields on the periphery of the wetland have been left uncultivated due to the unavailability of irrigation. The problem of inadequate irrigation facilities is more pronounced for horticultural crops, as these are usually planted after the Kharif season. Some villages in the Central Zone, such as Toubul, Khoijuman, and Kwaksiphai, are famous for horticulture crops in Manipur. Farmers from these villages reported purchasing water through water tankers due to the lack of irrigation facilities. Village farms in this area are facing a severe crisis due to insufficient rainfall and inadequate support from irrigation projects; production remains low despite significant investment and manual labour (Singh 2021).

The lack of agricultural inputs and high prices, especially of fertilizers, are amongst the most severe and prevalent risks farmers face in the wetland's periphery. Farmers reported that fertilizers are very expensive here compared with other parts of India, because they rarely receive them at subsidized rates. Delayed allocation of subsidized urea is a major problem in Manipur, and demonstrations are often staged to demand its timely distribution. Due to distribution delays, farmers often buy from the black market at substantial prices (Takhel 2023).

Fluctuations in market prices and market inaccessibility are a significant concern in the area. A farmer from Phubala who cultivates watermelons reported that the price of one kilogram of watermelon sometimes fell below Rs. 5. The main reason is the import of cheap produce from other states. Due to the state's strategic geographical location, many farm products cannot be exported outside the state. Farmers have demanded the introduction of Minimum Support Prices (MSP) for agricultural produce. Bandhs, strikes, and economic blockades that continue for over a week or a month are very common in Manipur. As a result, farmers are unable to sell their produce on time, leading to the vegetables rotting and incurring substantial losses.

The Meitei–Kuki ethnic conflict, which began on 3 May 2023, has had a severe impact on farmers. Before the conflict, they sold farm produce in hill markets such as Churchandpur and Moreh. Now, they can only sell in the valley area. A farmer from Toubul mentioned that there is no proper venue to sell vegetables in Imphal City. Farmers rely heavily on brokers and intermediaries, who profit from the lack of market mechanisms for direct sales (Thangjam and Jha 2020).

In the wetland, households with many members are more likely to face higher ecological risk. Larger households require more essential materials for their survival. To meet their needs, they depend heavily on the wetland, leading to greater exposure to ecological risks. Male-dominated households in the wetland are more likely to engage in open-water fishing and commercial agriculture and are directly exposed to ecological and non-ecological risks. Migration is a common strategy for sustaining livelihoods amid ecological change (Mistri *et al.* 2025a). Households send one or more members to other places, mainly urban areas, for work and employment purposes. Households that reported experiencing high ecological risk were more likely to have a migrant member; migration increased overall income, stabilizing household income.

Diversification of livelihood activities without migrating to other places or engaging in non-wetland-dependent activities is also an adaptive strategy adopted by fishing and farming households to sustain their livelihoods (Singh and Mistri 2025). Compared to farming households, fishing households face greater ecological and environmental risks, such as *phumdis* proliferation, water pollution, declines in fish species, and sudden onset of climatic events. Thus, the impact of ecological changes on fishing households is more pronounced. In the wetland, livestock provides an alternative source of income for fishing and farming households. This alternative income reduces dependency on the wetland, thereby lowering the risk of ecological impacts.

The LDA was established in 1986 to oversee and mitigate the wetland's deterioration. The main activities carried out by LDA include survey and demarcation, procurement of equipment for de-siltation and de-weeding, removal of silt, removal of *phumdis*, control of water hyacinth by releasing weevils, construction of silt detention structures, afforestation of critical catchment areas by planting appropriate species of plants and fruit-bearing trees, and soil conservation. To improve the livelihoods of people living on the wetlands' periphery, the Government of Manipur initiated the Loktak Livelihood Mission Project, aiming to increase the income of fish farmers who use the wetland's ecosystem without harming it. Periodically, the Government of Manipur also releases thousands of fish fingerlings into the wetland to increase the fish population. Recently, the government implemented measures to irrigate agricultural land near the wetlands. Sometimes, the LDA undertakes coercive measures, such as evicting floating fishing huts, displacing fishers, banning *phumdis* hut homestay tourism, and prohibiting *athaphum* fishing (a traditional circular fishing method), severely harming fisherfolk and hampering their livelihoods. Despite various government efforts, ecological health and people's livelihoods in the Loktak wetland have emerged as serious concerns.

5. LIMITATIONS OF THE STUDY

The study has certain limitations. It adopted a cross-sectional design that involved collecting information at a single point in time. A longitudinal design would improve the study by allowing the examination of how certain phenomena and livelihood activities change over time across the study area. The study employed a subjective approach to assess climatic and non-climatic risks in traditional agriculture, which contains certain limitations. An objective approach to risk measurement could be complementary to the subjective approach, but there is a dearth of secondary data on (physical) parameters. The data void can be minimized by using remote sensing data alongside geographic information systems. In addition, gender plays an important role in livelihood diversification. In NE states, women are comparatively more empowered in traditional parameters—sex ratio, labour force participation rate, and education. Within the limited scope of the present study, the gender dimension could not be captured separately.

6. CONCLUSION

This study examined the livelihood risks associated with ecological change alongside non-ecological stressors for the principal means of living—fishing and farming—in and around the Loktak wetland and identified the factors that affect ecological risk. The findings of the study indicate that fishing in the Loktak wetland is affected by changes in the lake's ecology, such as *phumdis* proliferation, water pollution, and siltation, which contribute to the decline of fish species and their stocks. The submergence of vast, low-lying, and fertile agricultural fields along the lakeshore due to the construction of the Ithai Barrage is directly related to changes in the wetland's ecology. Apart from ecological issues, the lack of irrigation facilities, rising agricultural input costs, and market issues significantly affect farmers and pose severe threats to farming. The ecological risks associated with their work in the wetland are influenced by multiple factors, including demographic, social, and economic factors, as well as governmental policies. In the study, household size, age group, dependency ratio, migration, and livestock rearing were found to significantly predict the likelihood of experiencing ecological risks in fishing and farming.

Based on the findings, the study advocates inclusive economic policies focusing on sustainable development in the wetland. To maintain the long-term sustainability of livelihoods in and around the Loktak wetland, ecological degradation must be addressed with earnest care, and the sustainable use of natural resources must be encouraged. To reduce livelihood risks in fishing and farming, it is necessary to promote the adoption of multiple income sources through skill development, improve market accessibility and linkages, and enhance financial inclusion and access to credit to support sustainable farming. Within the limited scope of the present study, it was not possible to delve deeper into livelihood diversification and migration. Hence, future research is suggested to explore alternative livelihood options and diversification strategies, including labour migration from the region.

Author Contribution: OKS: conceptualization, first draft and final version; AM: review, editing, quality control and final revision.

Ethics Statement: We hereby confirm that this study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Consent to Participate: Informed consent from the respondents was obtained before the survey to ensure their willingness to participate. Assurances of anonymity and confidentiality of the information, and consent to publication, were part of the informed consent.

Consent for Publication: The participants in this research had consented to the publication of the findings in a journal.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

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RESEARCH PAPER

Patterns and Key Determinants of Clean Cooking Fuel Adoption in Tamenglong District, Manipur

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Abstract: This study examines cooking-fuel use patterns and the determinants of clean-fuel adoption in households in Tamenglong District, Manipur, a remote and socio-economically marginalized region. Using a cross-sectional survey of 500 households across three subdivisions and employing a multinomial logit model, the study analyses the factors that determine households' reliance on firewood and use of mixed (firewood-dominant or liquefied petroleum gas (LPG)-dominant) fuel for cooking. Findings indicate that firewood remains the primary cooking fuel for 57% of households, while 43% use LPG either exclusively or in combination with biomass. Fuel stacking is widespread, particularly among middle-income households, reflecting a "bulky-middle effect". Income, education, employment status, the gender of the energy decision-maker, and spatial location relative to distribution centres emerge as significant determinants of LPG adoption. Decision-making by female heads of households and higher educational attainment strongly increase the likelihood of LPG use. Importantly, the study highlights that beyond economic and infrastructural constraints, traditional kitchen practices exert a powerful cultural influence. Households that adhere to traditional hearth-based cooking continue to prefer firewood due to its multifunctional role in food preparation, preservation, and socio-cultural practices. The results underscore that for policy interventions to be effective, they must move beyond initial provisioning

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of access to LPG and address affordability, last-mile delivery, and culturally embedded practices.

Keywords: Cooking Energy, Household Energy Transition, Fuel Choice, Fuel Stacking, Traditional Kitchen Practices.

1. INTRODUCTION

Despite the global commitment under Sustainable Development Goal 7 (SDG 7) to achieve universal access to clean energy by 2030, around 2.3 billion people worldwide still rely on health-hazardous fuels for cooking (IEA 2023). In India, about 95% of households now have access to liquefied petroleum gas (LPG), facilitated largely through the Pradhan Mantri Ujjwala Yojana (PMUY) (Mani *et al.* 2020). PMUY has significantly expanded LPG access amongst low-income households (Asharafa and Tol 2024; Gill-Wiehl *et al.* 2020), claiming to have established over 103.3 million LPG connections in Phase 2.0 of the scheme (Press Information Bureau 2025). However, nearly 660 million people continue to rely on solid biomass, primarily firewood, for cooking (IEA 2021), effectively living in energy poverty (Manasi and Mukhopadhyay 2024). Studies point to persistent challenges, such as gaps in the implementation of regional subsidies and sustained LPG adoption (Gupta *et al.* 2020; Kar *et al.* 2019; Ranjan and Singh 2020). The COVID-19 pandemic further weakened the progress of the energy transition, with domestic LPG consumption, including subsidies, declining by 1.5% as of March 2023 (PPAC 2023; United Nations 2022).

These challenges are particularly acute in the Northeast Region (NER) and a few other states, including Uttar Pradesh, Bihar, and Rajasthan, where access to clean energy remains limited. This is especially evident amongst Schedule Tribe (ST) households, which are disproportionately disadvantaged (Asharafa and Tol 2024; Dabadge *et al.* 2018). Such a persistent lack of access not only reinforces households' continued reliance on biomass but also contributes to a substantial health burden from household air pollution (Sharma *et al.* 2023; Swain and Mishra 2020). Achieving SDG 7 will therefore require not only improved access but also a sustained and affordable transition to clean energy sources (Gunnarsdottir *et al.* 2021).

Understanding household energy practices is central to the clean energy transition, as everyday fuel choices reflect broader economic, social, and cultural realities. Energy consumption patterns are often driven by cost minimization strategies, with households prioritizing the most affordable fuel options within their budgetary constraints (Ekholm *et al.* 2010). This

behaviour aligns with the rational choice theory, which posits that households make decisions based on utility maximization and cost efficiency (Daioglou *et al.* 2012). These insights—broadly linked to the conventional energy ladder hypothesis[1]—suggest a positive relationship between rising income and the adoption of cleaner fuels (Heltberg 2003), confirming income as a key determinant of household energy choice (Abdul-Wakeel Karakara and Dasmani 2019; Campbell *et al.* 2003; Daioglou *et al.* 2012; Muller and Yan 2018; Remigios 2014; Srivastava *et al.* 2012; Weiss de Abreu *et al.* 2021). Empirical evidence from India (Pandey and Chaubal, 2011), Tanzania (Choumert-Nkolo *et al.* 2019), and Bhutan (Rahut *et al.* 2016) shows greater uptake of LPG amongst higher-income households. Similarly, a study in northern China (Demurger and Fournier 2011) shows a reduction in biomass fuel use with an increase in income. Consistent with this pattern, urban households, benefiting from higher economic status and better infrastructure, are more likely to transition to modern fuels (IEA 2021; Khandker *et al.* 2012).

In contrast, energy use in rural households rarely follows a linear transition from traditional to modern fuels. Instead, fuel stacking—the simultaneous use of multiple fuels, such as firewood, LPG, and electricity—is a widespread practice (Ai *et al.* 2021; Debebe *et al.* 2023; Guta 2012; Masera *et al.* 2000; van der Kroon *et al.* 2013). This reflects the continued dominance of biomass, with firewood remaining the primary and most accessible energy source in rural areas. The *Indian Residential Energy Survey* (IRES) confirms this rural–urban divide in energy type prevalence (Mani *et al.* 2021). Similar disparities can be observed elsewhere, including China (Mainali *et al.* 2012; Pachauri and Jiang 2008), underscoring the role of regional and infrastructural factors in shaping household energy choices. Consistent with the multidimensional nature of household energy use (Kowsari and Zerriffi 2011; Manasi and Mukhopadhyay 2024; Tikadar and Swami 2025), household fuel choices and usage are influenced by the interaction of broader economic and sociocultural factors and institutional, technological, accessibility, affordability, and policy contexts (Nathan and Hari 2020; Sovacool 2014). Therefore, income alone does not fully explain household fuel choices.

Rural and remote communities often face structural barriers, including limited market penetration and inadequate supply chains, financial

[1] The energy ladder model describes fuel switching in three stages: households initially rely on biomass fuels such as wood, dung, and crop residues, then shift to transition fuels like kerosene and charcoal, and eventually adopt cleaner fuels such as LPG, natural gas, and electricity as incomes and living conditions improve.

constraints, and high shadow fuel prices, which collectively shape household energy decisions (Hiemstra-van der Horst and Hovorka 2008; Muller and Yan 2018; Guta *et al.* 2022). Thus, fuel transition challenges in rural households are multifaceted and linked to contextual socio-economic-behavioural complexities. Various studies attest to the limited role of income in influencing LPG adoption amongst PMUY beneficiaries in rural Odisha (Swain and Mishra 2020) and across rural Indian households (Malakar 2018), where use of multiple fuels is often prevalent (Sabyrbekov and Ukueva 2019).

Beyond income, other household-level socio-economic factors mediate energy decisions (Gupta and Köhlin 2006; Heltberg 2003; Karimu *et al.* 2016; Muller and Yan 2018; Twumasi *et al.* 2021). The characteristics of the household head, including attainment of formal education (Acharya and Sadath 2018; Dutta and Sahu 2022; Muller and Yan 2018; Ogwumike and Ozughalu 2015; Zhang *et al.* 2023), occupational status (Choudhuri and Desai 2020; Twumasi *et al.* 2021; Zheng *et al.* 2023), age (Gupta and Köhlin 2006), and gender (Adusah-Poku *et al.* 2022; Sharma and Dash 2022), significantly shape household energy choices. This indicates that various factors may reduce the likelihood of clean-energy adoption while increasing reliance on lower-quality fuels. Gender-specific patterns are particularly pronounced, with female-headed households exhibiting a greater propensity to adopt clean fuels than male-headed households (Dutta and Sahu 2022; Gould and Urpelainen 2020; Sharma and Dash 2022; Yan *et al.* 2024). However, contrasting evidence from Karimu *et al.* (2016) and Aryal *et al.* (2019) underscores the contextual variability of these influences. Furthermore, gendered energy-use patterns are often determined by other household characteristics, reinforcing the complexity of these interactions.

Disparities in energy consumption are evident across rural and urban areas (Dash and Chinara 2022), with residential location also exerting a significant impact on energy access and choice (Daioglou *et al.* 2012; Pachauri and Jiang 2008). Twumasi *et al.* (2012) report that households located far from LPG distribution centres are less likely to adopt LPG, instead favouring traditional biomass fuels. Additionally, energy use is deeply embedded in sociocultural traditions, with established practices, habits, and preferences shaping consumption patterns (Crosbie 2006; Rehfuess *et al.* 2010). Households adhering to such traditions may develop a preference for inexpensive but hazardous fuels—especially considering their economic constraints and limited access to LPG (GNESD 2014)—thereby hindering the transition to clean energy (Ochieng *et al.* 2020; Ouedraogo 2006; Ravindra *et al.* 2019; Hiemstra-van der Horst and Hovorka 2008). While these studies identify key determinants such as income, access, and

sociocultural practices, they are largely based on evidence from more accessible mainland regions. The operation of these factors in geographically remote, infrastructure-deficient, and culturally distinct areas, such as Tamenglong District in Manipur, remains insufficiently explored.

Despite extensive research on household energy use in India, studies specifically focusing on rural cooking fuel use in the NER remain limited. Early work, such as Bhatt and Sachan (2004), identified firewood as an accessible energy source amongst tribal communities but did not examine the underlying region-specific determinants of fuel choice. Major national surveys such as the IRES (Agrawal *et al.* 2020) provide limited coverage of the NER, excluding states beyond the Assam valley. Similarly, studies on LPG adoption have largely focused on the mainland plains (Mani *et al.* 2020; Patnaik *et al.* 2018), overlooking persistent energy poverty in the NER.

Although studies such as Gupta *et al.* (2020) and Manasi and Mukhopadhyay (2024) highlight that the north-eastern states exhibit some of the highest levels of energy poverty, and Dabadge *et al.* (2018) acknowledge the challenges in PMUY implementation in the NER, their analyses lack region-specific depth. Notably, 54% of households in the NER still rely on biomass, compared with the national average of 40.6% (Ministry of Health and Family Welfare 2022). The region accounts for only 6.8% of PMUY LPG connections, the second-lowest share nationally (Ministry of Petroleum and Natural Gas 2025), despite the high concentration of poor and marginalized tribal households. Moreover, within the NER, intra-regional disparities are striking: Manipur receives just 0.2% of the region's PMUY connections, and Tamenglong District accounts for only 2.1% of the state's connections (Ministry of Petroleum and Natural Gas 2025). These patterns underscore how remoteness, weak infrastructure, and indigenous contexts remain underexplored in the existing literature.

Taken together, the existing literature confirms the significance of key determinants in cooking fuel decisions but offers limited information on how these factors operate within remote and marginalized regions such as the NER. In areas such as Tamenglong District, these factors are mediated by the rugged terrain, inefficient LPG delivery systems, reliance on forest-based resources, and culturally embedded cooking practices. This paper does not seek to identify entirely new determinants, but it demonstrates how the established factors acquire distinct characteristics and policy relevance when shaped by the region's unique geographical, infrastructural, and sociocultural conditions.

Against this backdrop, this study offers a district-level, context-sensitive analysis that addresses important gaps in the understanding of the region's specificities in clean-energy adoption and informs more tailored policy interventions. It captures both the continued reliance on traditional fuels and the practice of fuel stacking, offering a nuanced perspective on the energy transition process, which is becoming increasingly common in rural households. While grounded in a localized context, the study also contributes to the broader discourse on the sustainable energy transition by highlighting how household-level characteristics shape fuel choices in socio-economically and geographically marginalized regions. In particular, the study aims to examine the pattern of cooking fuel use and assess the determinants of cooking fuel choices amongst households in Tamenglong District.

With these research objectives, the study seeks to identify the challenges associated with transitioning from traditional to modern energy sources in the region. The study attempts to answer the following key questions: What is the pattern of energy use amongst rural households in the mountainous regions of Tamenglong District? What factors influence their fuel adoption decisions? What are the primary challenges hindering the transition to clean cooking fuel in the region? The paper is structured as follows: Section 2 outlines the data collection methods and the methodological approach. Section 3 presents the results. Section 4 provides a discussion of the key findings, followed by policy recommendations and suggestions for future research in Section 5.

2. METHODS AND DATA

The study was conducted in Tamenglong District, located in the western part of Manipur, a state in northeast India. The district is predominantly inhabited by indigenous tribal communities, including the Zeme, Liangmei, Rongmei, and Inpui tribes. Administratively, the district is divided into three subdivisions: Tamenglong, Tamei (Tamenglong North), and Tousem (Tamenglong West) (Figure 1). Amongst these, Tousem is significantly more remote and less connected to essential services and infrastructure, making travel to the district headquarters especially challenging.

Geographically, the district features steep hills and dense forests, which cover nearly 90% of its area. It is situated at an elevation of 1,260 m above mean sea level, and the only major transport connection to the state capital, Imphal (located 147 km away), is the hilly Khongsang–Tamenglong Road (National Highway [NH] 53). The physical isolation—coupled with poor

road conditions, which worsen during the rainy season due to frequent landslides—contributes to the district's infrastructural limitations and to its

Figure 1: Map of Tamenglong District, Manipur



Source*:* Author's own work based on Maps of India (2026)

being regarded as one of the most marginalized and socio-economically backward areas in Manipur.

The local economy is primarily agrarian, with about 74% of the population engaged in cultivation or agricultural labour. Strong cultural and economic ties to the land define the region's identity and shape certain household practices, including energy use.

The district's limited connectivity poses significant infrastructural challenges in accessing basic services, including clean modern energy. Despite the implementation of subsidy-based clean energy schemes, such as the PMUY, the district is characterized by low uptake of modern clean fuels, such as LPG, and heavy reliance on traditional biomass fuels for daily cooking. These conditions make Tamenglong District a highly relevant site for examining household fuel choice in a marginalized and vulnerable energy context.

We employed a cross-sectional research design to identify the key determinants of household fuel choice. We conducted a household survey using semi-structured questionnaires; primary data were collected through

face-to-face interviews across the three subdivisions of Tamenglong District, namely Tamenglong, Tamei, and Tousem.

The study adopted a non-probability, convenience sampling due to logistical, geographical, and accessibility constraints in the rural subdivisions. A total sample of 508 households was initially surveyed to ensure adequate coverage and sufficient representation of the socio-economic and geographic heterogeneity across subdivisions and villages. This was reduced to 500 households after excluding the incomplete responses. While the sampling design does not permit strict statistical generalization, the sample size is sufficiently large to allow robust descriptive statistics and exploratory econometric analysis.

We were careful in selecting multiple villages within each subdivision to reflect the heterogeneity in income groups and energy users. The final sample of 500 households was distributed as follows: 150 from Tamei, 201 from Tamenglong, and 149 from Tousem. Of these, 261 households (52%) were PMUY beneficiaries, while the remaining 239 households were non-beneficiaries. The distribution of PMUY beneficiary households was 36 from Tamei, 154 from Tamenglong, and 71 from Tousem. Furthermore, the chosen sample size reflects a balance between statistical precision and complexities in the management of survey operations, survey cost, and non-sampling errors—consistent with established guidance on conducting household surveys in developing countries (United Nations Statistics Division 2005).

Primary data were collected between October 2022 and January 2023 using a semi-structured questionnaire designed to capture information on household socio-economic characteristics, energy access, and energy-use practices, with a focus on cooking fuel. Face-to-face interviews were conducted primarily in participants' homes to ensure both participant comfort and accuracy of their responses. The primary respondents were women, who were chiefly responsible for household chores such as cooking and had in-depth knowledge of daily energy use. In addition to the survey responses, field observations and survey diaries were also maintained to supplement and contextualize the analytical findings of the study.

To ensure content validity, the questionnaire was reviewed by subject matter experts for relevance and clarity. Pre-testing was conducted in January 2022 with a sample of 50 households to refine the wording and format of the questions, ensuring that they were comprehensible and culturally appropriate. The reliability of the questionnaire was assessed using Cronbach's alpha, which yielded a value of 0.75, indicating this measure's acceptable internal consistency (Cronbach 1951).

A key revision from the pilot study was the income variable, as most respondents engaged in informal, seasonal work and struggled to report precise monthly earnings. To address this, the mean income of the pre-test sample was used to construct an income range within two standard deviations. This approach is supported by Pachauri (2004) and Deaton (2019), who advocate for a context-specific income classification based on preliminary survey insights. This allowed respondents to identify their income group more easily and thus improved response accuracy.

2.1. Model Specification and Variables

To assess the determinants of household cooking fuel choice, the study employed a multinomial logit model (MNL). The dependent variable, Fuel Choice, was classified into three mutually exclusive categories based on primary and secondary cooking fuel use combinations, as reported in the household survey. This classification draws on the concept of primary and secondary fuel use—outlined by Masera *et al.* (2000)—distinguishing between fuels used for cooking main meals, typically larger in quantity and with a longer time in use (Kojima 2021; Silwal and McKay 2015), and those used complementarily for lighter meals, such as snacks or tea.

The field data show that LPG is the only clean cooking fuel used, while firewood remains the predominant fuel in most households. These patterns are consistent with findings from the 2020 IRES (Mani *et al.* 2021), which identified LPG and firewood as the two cooking fuels most used across Indian households. This classification captures both regular and occasional practices, reflecting the full spectrum of household fuel use. It thus incorporates both traditional fuel dependence and fuel-stacking practices, a key feature of rural energy transition.

The three categories are defined as follows:

> 0 = Firewood_only (reference category): Households relying exclusively on firewood for all their cooking needs
>
> 1 = Firewood_dominant: Households primarily using firewood but supplementing it with other fuels (e.g., LPG, kerosene, electricity [cook-stoves])
>
> 2 = LPG_dominant: Households primarily using LPG for cooking, either exclusively or with secondary fuels (e.g., firewood, kerosene, electricity [cook-stoves])[2]

[2] Households that use LPG exclusively were also classified under Category 2 (LPG_dominant) due to their smaller proportion (0.8%). Similarly, households that

The general form of the multinomial logistic regression is given by Equation (1):

$$\log\left(\frac{P(Yi=j)}{P(Yi=0)}\right) = \beta_{jo} + \sum_{(k=1)}^{k} \beta_{jk} X_{ki} + \varepsilon_i, \qquad j = 1, \ldots, J \quad \text{.....(1)}$$

The probability form is expressed as:

$$P(Yi=j) = \frac{\exp(\eta_{ji})}{1+\sum_{m=1}^{J} \exp(\eta_{mi})}, \qquad P(Yi=0) = \frac{\exp(\eta_{ji})}{1+\sum_{m=1}^{J} \exp(\eta_{mi})} \quad \text{.... (2)}$$

Specifications of the model for 0 = Firewood_only, 1 = Firewood_dominant, and 2 = LPG_dominant are as follows.

The log-odds equation for Firewood_dominant versus Firewood_only can be written as:

$$\log\left(\frac{P(Yi=1)}{P(Yi=0)}\right) = \beta_0 + \sum_{k=1}^{8} \beta_{1k} X_{ki} + \varepsilon_i \text{.....(3)}$$

Similarly, the log-odds equation for LPG_dominant versus Firewood_only can be written as:

$$\log\left(\frac{P(Yi=2)}{P(Yi=0)}\right) = \beta_0 + \sum_{k=1}^{8} \beta_{2k} X_{ki} + \varepsilon_i \text{ ....(4)}$$

where $i = 1, 2, \ldots, N$ indexes the households.

$\sqrt{\beta_{1k}}$ and $\sqrt{\beta_{2k}}$ are are the estimated coefficients for the k-th independent variables in Firewood_dominant and LPG_dominant versus Firewood_only, respectively. $\log\left(\frac{P(Yi=1)}{P(Yi=0)}\right)$ and $\log\left(\frac{P(Yi=2)}{P(Yi=0)}\right)$ are the log-odds of being Firewood_dominant and LPG_dominant relative to Firewood_only, respectively. Table 1 presents the description of the variables included in the MNL model.

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use LPG with electricity as a secondary fuel (9.4%) were also included in this category to mitigate estimation issues associated with sparse data, such as large standard errors and convergence failures. The final distribution of the dependent variable is as follows: 20.2% Firewood_only, 36.4% Firewood_dominant, and 43.4% LPG_dominant.

Table 1: Variables Used in the Study and Their Description

Variable	Type	Description
Household income (in Rs.)	0 = ≤.10,000 (Low) 1 = 10,001–20,000 (Lower middle) 2 = 20,001–30,000 (Middle) 3 = 30,000–40,000 (Upper middle) 4 = ≥ 40,001 (High)	Monthly household income categorized into five groups. This grouping also aligns with policy-relevant income brackets and is expected to determine affordability and fuel choice.
Household size	No. of family members	Number of family members currently living in the house. Larger households may have different cooking fuel needs and demands.
Gender of the EDM	0 = Male 1 = Female	The EDM is the primary household member who decides on the type of fuel to use. Gender roles may shape preferences and priorities.
Education of the EDM	0 = No schooling 1 = Primary 2 = Secondary 3 = Higher secondary 4 = Degree and above	The level of education attained by the EDM is assumed to affect access to information, awareness, and the ability to adopt cleaner fuels.
Employment status of the EDM	0 = Subsistent farmer 1 = Casual labour 2 = Self-employed 3 = Salaried	The employment status of the EDM determines the household's purchasing power and its capacity to adopt modern, cleaner fuels.
Area of residence	0 = Outside a 10-km radius 1 = Within a 10-km radius	The geographical location of the household, referring to its distance from the main town area, affects physical access to modern clean fuels; for example, proximity to LPG distribution centres.
Traditional kitchen practices (TKP)	0 = High 1 = Medium 2 = Low	TKP is measured using nine equally weighted items, grouped into three levels.* Each increase in level corresponds to three additional items. Such practices are assumed to influence fuel choice.
Land ownership	No. of acres	The size of the land owned by the household indicates its asset base and potential access to biomass resources.

Abbreviation: EDM = energy decision-maker

Note: * The construction of the traditional kitchen practices (TKP) measure is grounded in the pilot study; information on kitchen practices was collected through open-ended questions. This approach allowed respondents to describe their practices in detail, ensuring that the measure captured the full range of culturally specific behaviours instead of relying on pre-defined assumptions. The qualitative responses were then systematically analysed, coded, and consolidated into nine key indicators: slow-cooking techniques; preference for smoky flavours; space heating; insect repelling; prevention of fungal and mould growth; food preservation using smoke and heat; preparation of animal feed; adherence to traditional beliefs (e.g., use of fire or protection against negative spirits); and hardening of materials and wooden house structures through smoke deposition (tar). Together, these indicators represent the major dimensions of TKP in the study context and are directly related to the use of fire in household practices.

Source: Authors' analysis

Prior to data collection, ethical approval was obtained from the university's institutional review board to ensure compliance with social science research standards. The participants were fully briefed on the study's purpose, their role, and their right to voluntary participation; they provided informed consent orally due to their low literacy level. All personal information remains confidential to protect the participants' privacy throughout the study.

3. RESULTS

3.1. Household Demographic Details

Amongst the households surveyed, nearly 89% belonged to low- to middle-income categories, and only 11% were in the high-income categories. Land ownership was relatively widespread, with 76% owning land suitable for plantations—often used as a source of firewood—ranging from 1 to 50 acres. Additionally, 81% of the households reared livestock—including chickens, ducks, turkeys, goats, cows, buffaloes, dogs, and pigs—primarily for self-sustenance, income generation, or both. However, ownership of durable goods was limited; only 28% owned items such as vehicles, refrigerators, washing machines, grinding machines, and television sets, indicating modest levels of material wealth despite owning land and livestock.

Household socio-demographic characteristics are presented in Table 2.

Table 2: Descriptive Statistics of Household Socio-Demographic Variables

Variable	%	Min.	Max.	Mean	Standard deviation
Household income (in Rs.)	100	1	5	2.61	1.230
Low (up to 10,000)	19.2				
Lower-middle (10,001–20,000)	33.6				
Middle (20,001—30,000)	25.2				
Upper-middle (30,001–40,000)	10.8				
High (40,001 and above)	11.2				
Land assets (acre)	75.6	1	50	12.60	11.141
Livestock	100	0	1	0.81	0.389
Yes (1)	81.4				
No (0)	18.6				
Durable goods	100	0	1	0.28	0.449
Yes (1)	28				
No (0)	72				
Family type	100	1	2	1.47	0.5
Nuclear (1)	53				
Joint (2)	47				
Household size	100	1	17	6	2.052
EDM gender	100	`1	2	1.48	0.5
Male (1)	52.4				
Female (2)	47.6				
EDM education	100	1	5	2.87	1.254
Illiterate (1)	13.6				
Primary (2)	30.2				
Secondary (3)	27				
Senior secondary (4)	14.2				
Higher education (5)	15				
EDM employment status	100	1	4	2.34	1.167
Subsistence farmer (1)	37.6				
Casual labour (2)	10.4				
Self-employed (3)	32.8				
Salaried (4)	19.2				
Area of residence	100	1	2	1.53	0.499
Within 10 km (1)	46.6				
Outside 10 km (2)	53.4				

Source*:* Primary field survey data, authors' analysis

Table 3: Descriptive Statistics of Household Fuel Consumption

Fuel used	%	Mean	Standard deviation
Primary cooking fuel	100	1.43	0.496
Firewood (1)	56.8		
LPG (2)	43.2		
Secondary cooking fuel	100		
Firewood (1)	51.4	1.62	0.751
LPG (2)	36.8		
Charcoal (3)	1.8		
Electricity (cook-stoves) (4)	9.8		
Kerosene (5)	0.2		
Fuel for lighting	100	1.07	0.435
Electricity (1)	96.8		
Kerosene lamp (2)	1.2		
Solar lamp (3)	0.8		
Solar battery (4)	0.6		
Paraffin candle (5)	0.6		
Fuel for water heating	100	1.26	0.455
Firewood (1)	74.2		
Electric cooker (2)	25.2		
Electric induction (3	0.6		
Fuel for space heating	100	1.15	0.355
Firewood (1)	85.2		
Charcoal (2)	14.8		

Source*:* Primary field survey data, authors' analysis

3.2. Details of Household Fuel Use

The households in the study utilized various locally available fuels for cooking, lighting, water heating, and space heating (Table 3). The majority of households (57%) reported using firewood as their primary cooking fuel, indicating a significant reliance on biomass. The rest (43%) reported LPG as their primary cooking fuel. As a secondary fuel, firewood remained dominant (51%), with LPG (37%) also widely used. A smaller proportion of households used electricity (cook-stoves) (10%), charcoal (2%), and kerosene (0.2%) as supplementary cooking fuels.

For lighting, almost all households relied on electricity (97%), while a small fraction reported using kerosene lamps (1%), solar lamps (1%), solar batteries (1%), and paraffin candles (1%) during the survey. For heating

water, the majority used firewood (74%), followed by electric cookers (25%) and electric cook-stoves (1%). For space heating, firewood remained dominant (85%), with charcoal used by 15%. Space heating is essential in the region due to high precipitation during the monsoon and low temperatures in winter. Households in the lower-income groups typically used firewood for both cooking and heating, while households in the higher-income groups used charcoal exclusively for heating. The limited use of charcoal is due to its high cost (Rs. 800 per bag, typically packed in a 50 kg rice sack) and its limited availability, as it is purchased from a few local producers.

3.3. Pattern of Cooking Fuel Use

A distinct local energy management practice observed during the survey highlights the challenges of inadequate access to clean energy. To optimize fuel use, households typically employ a sequential cooking method: water is first heated using firewood or an electric rice cooker (when electricity is available); rice is then cooked on an LPG stove in a pressure cooker, using the preheated water to save time and reduce LPG consumption. Snacks and teas are also prepared on an LPG stove, while curries that require longer cooking are prepared on an open fire. Boiled water is practically essential for low-income households, as it helps save fuel and thereby reduces fuel costs and cooking time. These practices reflect fuel stacking (Debebe *et al.* 2023; Masera *et al.* 2000), where a primary fuel is used for cooking main meals and a secondary fuel for lighter and quicker preparations (Kojima 2021; Silwal and McKay 2015). Ravindra *et al.* (2019, p. 1031) used the phrase "short-term quick services" to describe the use of LPG as a secondary fuel in Indian households.

Table 4 indicates an energy-use pattern consistent with the energy ladder hypothesis. There is zero representation by the low-income households under household type C, and, likewise, zero representation from high-income households under household type A. This indicates a strong correlation between low income and high usage of traditional non-clean biomass fuels and between high income and the adoption of modern clean fuels. A key finding is that approximately 70% of the households fall under household type B, demonstrating widespread energy stacking across income groups. The data reveal a "bulky-middle" effect, whereby middle-income households dominate mixed fuel use, while low- and high-income groups form smaller proportions. This underscores that fuel stacking is primarily a middle-income phenomenon.

Table 4: Descriptive Statistics of Household Cooking Fuel Use Combinations by Income Group (%)

Household income (in Rs.)	Household type			
	A	**B**	**C**	**Total**
≤ 10,000 (Low)	10	9	0	19.2
10,001–20,000 (Lower-middle)	8.6	22	3	33.6
20,001–30,000 (Middle)	1	21.6	2.6	25.2
30,000–40,000 (Upper-middle)	0.6	8.2	2	10.8
≥ 40,001 (High)	0	8.8	2.4	11.2
Total	20.4	69.4	10.2	100

Note*:* Household types: A = exclusive use of non-clean fuels; B = mixed fuel use (both traditional and clean fuels); C = exclusive use of clean fuels.

Source*:* Primary field survey data, authors' analysis

Amongst the surveyed households, 261 (52%) were PMUY beneficiaries (Table 5). PMUY coverage varies considerably across subdivisions. Tamenglong records the highest coverage (59%) and exhibits relatively higher LPG adoption, though mixed fuel use remains widespread. In contrast, Tamei (14%) and Tousem (27%) report lower coverage, with negligible or no exclusive clean fuel use.

Fuel-use patterns, even amongst PMUY beneficiary households, reveal that the majority (78%) practised mixed fuel use, while exclusive clean fuel (primarily LPG-based) use was rare (10%) and confined to Tamenglong and Tamei. A small but notable share (12%) still depended solely on non-clean fuels, especially in Tousem; despite having active LPG connections, several households do not use them. Overall, only 39% of PMUY beneficiary households used subsidized LPG as their primary cooking fuel, while about 50% relied on it as a secondary fuel.

Table 5: Cooking Fuel Use Combinations Amongst PMUY Beneficiary Households by Subdivision (%)

Subdivision	Household type			
	A	**B**	**C**	**Total**
Tamei	1.1	10.6	1.9	13.8
Tamenglong	3	47.5	8.4	59
Tousem	7.2	19.9	0	27.2
Total	11.5	78.2	10.3	100

Note*:* Household types: A = exclusive use of non-clean fuels; B = mixed fuel use (both traditional and clean fuels); C = exclusive use of clean fuel.

Source*:* Primary field survey data, authors' analysis

The analysis indicates that exclusive LPG adoption remains limited, with fuel stacking persisting despite PMUY coverage. In rural areas, households combine the readily available firewood from private and community forests with LPG, which, though less accessible, is valued for its efficiency. This mix allows households to optimize energy use according to access, cost, and convenience.

Subdivisional variation reveals policy implementation gaps. While Tamenglong records relatively better outcomes, the weaker performance of Tamei and Tousem reflects their remoteness and poor connectivity. These patterns point to the challenges of extending scheme benefits to less-accessible areas and raise concerns about whether the initial LPG connections provided by the PMUY translate into sustained adoption. More broadly, they highlight that household fuel choices are shaped not only by conventional factors such as income but also by a set of household-level characteristics.

3.4. Key Determinants of Cooking Fuel Choice

The multinomial logistic regression model was estimated with Firewood_only as the reference category. The likelihood ratio (LR) chi-square test indicates that the model is highly significant overall ($p < .001$). McFadden's pseudo R^2 suggests that the model explains a substantial share of the variation in household cooking fuel choice, demonstrating strong explanatory power. The Hausman–McFadden test further supports the independence of irrelevant alternatives assumption, confirming the suitability of the multinomial logit specification.

Table 6 presents the results of the MNL model, which examines the determinants of household cooking fuel choices in Tamenglong District. The dependent variable distinguishes between three categories, namely firewood-only households (reference group), firewood-dominant households (those engaging in fuel stacking with firewood as the primary source), and LPG-dominant households (those primarily dependent on clean fuels). By adopting firewood-only households as the baseline, the model estimates the likelihood of households transitioning towards either firewood-dominant or LPG-dominant usage patterns.

We report the results in two complementary forms: the log-odds coefficients and the average marginal effect (AME). The former indicates the direction and magnitude of the effect of each predictor on the odds of belonging to either the firewood-dominant or the LPG-dominant group, relative to the firewood-only group. The AME for the same category provides a more intuitive interpretation, indicating the percentage point increase in the probability of LPG use associated with the predictor

Table 6: Multinomial Logistic Regression of Household Cooking Fuel Choice (*N* = 500)

Variable (base category = Firewood_only)	Firewood_dominant		LPG_dominant	
	Coefficient (1)	AME (dy/dx) (2)	Coefficient (3)	AME (dy/dx) (4)
Household income (in Rs., ≤Rs.10,000: Ref)				
□ 10,001–20,000	0.666* (0.361)	–0.001 (0.068)	1.254** (0.593)	0.084 (0.063)
□ 20,001–30,000	2.040*** (0.631)	0.035 (0.078)	3.114*** (0.782)	0.164** (0.068)
□ 30,001–40,000	0.142 (0.875)	–0.163 (0.100)	1.951* (0.999)	0.222*** (0.083)
≥□ 40,001	14.342 (552.421)	0.021 (0.097)	16.050 (552.421)	0.263*** (0.096)
Household size	0.032 (0.080)	0.004 (0.010)	0.011 (0.103)	–0.001 (0.008)
Gender_EDM (Male: Ref)				
Female	1.010** (0.389)	0.018 (0.050)	1.577*** (0.495)	0.080* (0.042)
Education_EDM (No schooling: Ref)				
Primary	0.926** (0.429)	0.062 (0.064)	1.142* (0.624)	0.047 (0.059)
Secondary	1.757*** (0.485)	0.138** (0.067)	1.909*** (0.661)	0.053 (0.061)
Higher secondary	3.626*** (1.163)	0.215*** (0.080)	3.951*** (1.261)	0.088 (0.071)
Degree and above	2.411* (1.290)	0.050 (0.109)	3.719*** (1.375)	0.203*** (0.086)
Employment_EDM (Subsistence farmer: Ref)				
Casual labour	0.572 (0.493)	–0.054 (0.079)	1.359** (0.672)	0.114 (0.072)
Self-employment in non-farm	0.050 (0.640)	–0.285*** (0.067)	2.427*** (0.694	0.336*** (0.061)
Salaried	–0.041 (0.687)	-0.159* (0.088)	1.233 (0.807)	0.175** (0.076)
Area of residence (Outside 10 km: Ref)				
Within a 10-km radius	1.545*** (0.474)	–0.026 (0.052)	2.790*** (0.540)	0.183*** (0.044)
TKP (High: Ref)				
Medium	–0.306 (0.458)	–0.013 (0.058)	0.664 (0.586)	0.045 (0.047)
Low	0.951* (0.576)	–0.090 (0.065)	2.511*** (0.717)	0.189*** (0.054)
Land ownership	0.003 (0.017)	0.000 (0.002)	–0.003 (0.021)	–0.000 (0.001)
Constant	-2.911*** (0.858)	—	–7.024*** (1.214)	—
Model summary				
No. of observations = 500				
LR χ^2 (38) = 452.91				
Probability > χ^2 = 0.0000				
Pseudo R^2 = .4300				

Note*:* Standard errors are in parentheses. ***p < .01, **p < .05, *p < .10. AME = average marginal effect.

Source: Primary household survey data, authors' analysis

variable, say income level. Further, although we have presented them in the same table for economy of reporting, we emphasize the importance of treating the firewood-dominant and LPG-dominant outcomes as analytically distinct. This means the determinants of fuel stacking (firewood-dominant) and clean fuel transition (LPG-dominant) may not operate in the same way.

The regression results highlight a set of socio-economic and contextual factors that influence household cooking-fuel adoption in Tamenglong District. Household income emerges as the most decisive determinant of the transition to clean cooking fuels. Compared with the poorest households (earning ≤ Rs. 10,000 annually), those in the higher income brackets exhibit significantly higher odds of being in the LPG-dominant category, with the AME indicating 16% to 26% increases in the probability of clean-fuel adoption. This demonstrates a clear energy ladder effect, whereby increases in income enhance the affordability of LPG refills and associated appliances. At intermediate income levels, however, households are more likely to fall into the firewood-dominant category, reflecting a fuel-stacking strategy. These households acquire partial access to LPG but continue to rely heavily on firewood, underscoring that income growth alone does not guarantee a total transition to clean energy. Overall, the pattern shows an income gradient towards LPG dominance—consistent with earlier studies (Weiss de Abreu *et al.* 2021)—with any tendency towards firewood dominance peaking at lower- to middle-income levels and declining as income rises.

The gender of the energy decision-maker (EDM) also shows a notable influence on a household's cooking-fuel choices. Households in which women make decisions regarding cooking-fuel usage are significantly more likely to adopt LPG as the primary fuel. The marginal effect of female decision-making raises the probability of LPG adoption by about 8%, indicating that women's preferences, shaped by considerations of convenience, health, and time savings, play an important role in driving clean-energy adoption. Amongst female EDMs, around 67% are salaried or self-employed, which means that they have financial autonomy and agency, not just a preference, to opt for cleaner cooking fuels. There is greater prioritization of the health and time-saving aspects of clean fuels, which aligns with the findings of previous studies (e.g., Choudhuri and Desai 2020). A respondent aptly summarized this preference:

> Firewood is, in reality, costlier if we truly account for the labour and effort spent collecting it. We walk several kilometres and spend many hours, sometimes an entire day to gather just two to three loaded baskets of

firewood. Moreover, the increasing difficulty of finding dry wood adds to the burden.

Education levels of EDMs reveal a dual pattern. Households with secondary and higher secondary education levels are more likely to belong to the firewood-dominant category, suggesting that partially educated households supplement traditional fuels with LPG without fully transitioning. This outcome indicates that while some level of education improves knowledge of LPG's advantages and facilitates partial access, it does not immediately lead to the replacement of traditional fuels with LPG. This pattern illustrates how education expands awareness and aspiration, but, in the absence of sufficient income or a reliable supply infrastructure, does not result in a complete shift to clean fuels.

By contrast, households headed by decision-makers with higher levels of education (degree and above) show a distinct shift towards LPG dominance. The large and statistically significant coefficients translate into AMEs of approximately a 20% increase in the probability of LPG adoption compared with households with no schooling. This transition underscores that higher education not only increases awareness of the health and time burdens associated with biomass use but also tends to correlate with higher income, salaried employment, and urban proximity, which jointly lower the barriers to LPG adoption. In other words, education plays both a direct role by contributing to knowledge, preferences, and health awareness regarding clean fuel and an indirect role through association with socio-economic mobility and market integration.

EDM employment status shows a differentiated effect on household fuel choice. EDMs who are casual labourers are more likely to practise LPG-dominant mixed fuel use than EDMs who are subsistence farmers, with a positive marginal effect of 11 percentage points. However, the significance level is lower, indicating only a modest tendency towards LPG use. Households with heads who are self-employed in non-farm activities are 28.5 percentage points less likely to be in the firewood-dominant category than households headed by subsistence farmers. At the same time, they show a strong and highly significant positive association with LPG-dominant mixed fuel use of about 34 percentage points.

For salaried EDMs, firewood-dominant mixed fuel use shows no significant difference relative to subsistence farmer EDMs, although the marginal effect is moderately negative by about 16 percentage points. In contrast, salaried households are positively associated with LPG-dominant fuel use, with a marginal effect of 17 percentage points, indicating a meaningful increase in adoption likelihood despite the coefficients' weaker significance.

These results highlight how employment stability and income potential, especially in self-employed or salaried households, play a critical role in driving the transition to LPG adoption; households with subsistence farmers remain strongly reliant on traditional fuels.

Spatial location emerges as a strong determinant of household fuel choice in Tamenglong District, reflecting the importance of infrastructural access, market connectivity, and distribution networks in driving energy transitions. The multinomial logit results show that households residing within 10 km of the District/Town have significantly higher log-odds of being LPG-dominant relative to firewood-only households. The corresponding AME confirms this substantive effect, with an 18% increase in the probability of LPG adoption. This indicates that households closer to the district headquarters benefit from easier access to LPG distribution centres, reduced transportation costs, and more reliable cylinder delivery.

Field observations corroborate this statistical pattern, showing that rural households encounter higher transportation costs, logistical barriers, and difficulties in sustaining LPG use. A subsidized PMUY 14.2-kg cylinder priced at Rs. 1,050, on average costs around Rs. 1,131 locally (range: Rs. 1,050–1,600) and typically lasts 2.5 months for a six-member household. Hence, it needs to be supplemented with other fuel sources, such as firewood. Survey narratives reveal additional constraints:

> Sometimes, we cannot make it to the dealer's place because we spend nights working in the fields. In such cases, we give our booking details to someone with a vehicle to collect it on our behalf. However, they often fail to inform us when the stock is available, claiming it's not our turn yet.

Reliance on intermediaries to collect cylinders and delays in accessing refills explain the persistence of fuel stacking in rural settings.

Traditional kitchen practices (TKP) capture the cultural and behavioural dimensions of fuel use, beyond purely economic or infrastructural factors. TKP shows a strong and consistent association with household fuel choice. The regression results reveal that adherence to such practices significantly influences household fuel choice, and the persistence of cultural norms and cooking habits shapes energy transitions. The multinomial logit coefficients show that households with low levels of TKP—i.e., those less attached to conventional firewood-based cooking methods—are significantly more likely to adopt LPG-dominant fuel use relative to firewood-only households. In AME terms, low-TKP households exhibit an average 19% increase in the probability of being LPG-dominant compared with high-TKP households. This finding suggests that, even after controlling for income, education, and proximity to supply, cultural orientation exerts an

independent influence on adoption behaviour. Households less bound by traditional practices are quicker to embrace LPG, recognizing its convenience, efficacy, and health benefits.

3.5. Determinants of Cooking Fuel Choice: PMUY Beneficiary Households

Table 7 shows the results of the multinomial logit estimates for PMUY beneficiary households, reported as log-odds coefficients and AMEs, to examine the factors influencing cooking-fuel choices. As in the overall sample (see Section 2.1), the firewood-dominant and LPG-dominant categories are treated as analytically distinct outcomes compared with the reference category of firewood-only users. These results are compared with the full sample estimates in Section 3.4.

The effect of household income is not as prominent here as it is on the full sample. The higher-income level (≥Rs. 40,001) shows a statistically significant reduction in the probability of the household remaining in the firewood-dominant category, along with a decline in LPG-dominant households. This suggests that higher-income PMUY households are less likely to rely on mixed fuel use, indicating a transition away from firewood dependence. However, the middle-income level (Rs. 20,001–30,000) has a negative marginal effect for LPG-dominant use, suggesting that refill-affordability constraints persist, leading to continued fuel stacking rather than full LPG use.

The gender of the EDM has a moderate level of influence; specifically, female-EDM households show a higher likelihood of LPG-dominant use, although the AMEs are not statistically significant. This offers a limited, but suggestive, indication of women's preference for clean-fuel uptake even in beneficiary households.

Education as a factor offers mixed results. EDMs with secondary education are seen as having some association with firewood-dominant as well as LPG-dominant use, but the marginal effects of the same are not consistently significant. This suggests that amongst PMUY beneficiary households, education can play a role in raising awareness, but it does not have a direct, independent influence on the complete shift from firewood to LPG if additional economic and infrastructural support are absent.

Employment status was found to be a relatively more influential factor. Households with a self-employed (non-farm activities) or salaried EDM demonstrate a strong and statistically significant positive marginal effect for LPG-dominant use compared with households with subsistence farmers.

Table 7: Multinomial Logistic Regression of Household Cooking-Fuel Choice Amongst PMUY Beneficiary Households

Variable (base category = Firewood_only)	Firewood_dominant		LPG_dominant	
	Coefficient (1)	AME (dy/dx) (2)	Coefficient (3)	AME (dy/dx) (4)
Household income (≤ 10,000: Ref)				
10,001–20,000	−0.256 (0.603)	−0.117 (0.098)	0.556 (0.905)	−0.104 (0.091)
20,001–30,000	0.311 (0.895)	−0.094 (0.107)	1.200 (1.126)	−0.118 (0.095)
30,001–40,000	−0.664 (1.484)	−0.266* (0.149)	1.160 (1.644)	-0.234* (0.119)
≥ 40,001	15.454(1939.968)	−0.116*** (0.033)	17.645 (1939.968	−0.318** (0.144)
Household size	−0.183 (0.134)	−0.025 (0.015)	−0.063 (0.165)	0.013 (0.013)
Gender_EDM (Male: Ref)				
Female	0.910 (0.617)	−0.020 (0.077)	1.496* (0.785)	0.081 (0.071)
Education_EDM (No schooling: Ref)				
Primary	1.321 (0.861)	0.106 (0.100)	1.276 (1.053)	0.007 (0.077)
Secondary	1.371* (0.827)	0.044 (0.099)	1.891* (1.023)	0.077 (0.078)
Higher secondary	2.115 (1.577)	0.195 (0.125)	1.680 (1.700)	-0.036 (0.084)
Degree and above	17.272 (2067.156)	0.158 (0.128)	17.629 (2067.157)	0.068 (0.113)
Employment_EDM (Subsistence farmer: Ref)				
Casual labour	1.808 (1.190)	0.058 (0.120)	2.153 (1.419)	0.056 (0.111)
Self-employment in non-farm	15.593 (1199.573)	−0.279*** (0.091)	18.119 (1199.573)	0.435*** (0.087)
Salaried	0.361 (0.928)	−0.137 (0.122)	1.598 (1.120)	0.182* (0.110)
Area of residence (Outside 10 km: Ref)				
Within a 10-km radius	1.323*(0.784)	−0.115 (0.074)	2.707***(0.880)	0.202***(0.068)
TKP (High: Ref)				
Medium	0.157 (0.620)	−0.056 (0.074)	0.757 (0.773)	0.072 (0.057)
Low	1.517* (0.876)	−0.137* (0.083)	3.371***(1.035)	0.239***(0.071)
Land ownership	−0.021 (0.030)	−0.000 (0.003)	−0.026 (0.035)	−0.001(0.002)
Constant	0.438 (1.555)	—	−4.810**(2.018)	—
Model summary				
No. of observations = 261				
LR χ^2 (38) = 199.25				
Probability > χ^2 = 0.0000				
Pseudo R^2 = .3959				

Notes*:* Standard errors are in parentheses. ***$p < .01$, **$p < .05$, *$p < .10$.

Source*:* Primary household survey data, author's analysis

This suggests that income stability and regular cash flow remain crucial for sustaining LPG consumption.

Spatial access remains one of the strongest determinants, even amongst PMUY beneficiary households. Households located within 10 km of the main town area have a significantly higher probability of LPG-dominant use, with a large positive marginal effect. This underscores the significance of proximity to distribution centres; transportation costs continue to hinder sustained LPG use even after the provision of connections.

Finally, TKP shows a strong and consistent influence in both samples. Households that have lower adherence to traditional practices are more likely to use LPG predominantly, with statistically significant marginal effects. This again indicates the importance of cultural and behavioural constraints even within the context of PMUY.

4. DISCUSSION

The cooking-fuel landscape in Tamenglong District reveals patterns closely intertwined with structural and spatial inequalities in access. Overall, adoption of clean cooking fuel remains limited, suggesting the district is still at an early stage of energy transition, with considerable scope for improvement. These constraints are reflected in both the general adoption patterns and the performance of government interventions. For instance, while uptake of PMUY LPG connections is noticeably higher in Tamenglong subdivision, where better connectivity facilitates access, remote areas, such as Tamei and Tousem, remain disadvantaged by poor infrastructure and weak supply chains. Such disparities reflect a spatial bias in programme implementation and raise broader concerns about energy justice. Dabadge *et al.* (2018) and Asharafa and Tol (2024) have reported that marginalized regions such as northeast India are often left behind in scheme coverage and expansion, particularly ST households. Similarly, Choudhury *et al.* (2024) observes lower clean-fuel adoption amongst ST households in general, underscoring the persistence of social and spatial inequalities in access to clean cooking energy.

Within this context, households tend to rely heavily on biomass, with firewood continuing to dominate despite some signs of an upward shift along the energy ladder. Fuel stacking is widespread, particularly amongst middle-income groups, reflecting the "bulky-middle" effect and field observations of sequential cooking practices that combined firewood, LPG, and electricity to some extent. This behaviour is evident even amongst PMUY beneficiaries; although coverage is moderate, only one-fifth of the

surveyed households used LPG as their primary fuel and just 0.8% relied on it exclusively. The rest either used it as a supplementary fuel or did not use it during the survey period despite holding active connections. Such persistent fuel stacking, even under PMUY coverage, highlights the difficulty of sustaining LPG use beyond initial access (Kar *et al.* 2019). It also explains why a complete transition to clean fuels in the district remains elusive. Ultimately, Tamenglong District faces a layered challenge. Its geographical disadvantages and the socially marginalized position of its largely tribal population combine to restrict both access to and the sustained use of LPG, undermining prospects for a long-term energy transition.

The multinomial logistic regression results (Table 6) offer important insights into the household-level characteristics associated with fuel stacking, shedding light on the dynamics of energy transition, a common feature of rural household energy use. The findings underscore the pivotal role of a household's socio-economic characteristics, gendered decision-making, and the locational and cultural context in shaping household fuel choices in Tamenglong District.

Income emerges as a key driver of LPG adoption, consistent with the energy ladder theory. Those in the lowest income groups largely remain locked into exclusive firewood use, middle-income households predominantly practice firewood-dominant stacking, and higher-income households are more likely to shift towards LPG-dominant mixed fuel use. Still, exclusive LPG adoption remains limited, reflecting affordability constraints. On the other hand, the continued local availability of firewood sustains its role as a fallback fuel. These patterns confirm that income is a crucial determinant of clean-fuel adoption, which is consistent with the findings of prior studies (Ekholm *et al.* 2010; Gill-Wiehl *et al.* 2021; Weiss de Abreu *et al.* 2021); yet the persistence of fuel stacking indicates that economic resources alone are insufficient to achieve full energy transition.

The education level of EDMs is a key determinant of LPG adoption. More educated EDMs are more likely to adopt LPG-dominant fuel use and reduce reliance on firewood, reflecting greater awareness of LPG's health, convenience, and time-saving benefits (Baland *et al.* 2012; Choudhury *et al.* 2024; Zhang *et al.* 2023). Survey narratives indicate that households with lower levels of education face challenges with applying for LPG connections through the PMUY, which limits their access to clean fuel (Patil *et al.* 2021). This highlights the role of education in enabling the adoption of modern energy. Findings from Kerala and Rajasthan have shown that education shapes perceptions of LPG as being health-promoting, further supporting adoption (Gould and Urpelainen 2020). It is

also important to note that education and income level are often correlated, which may partly explain the observed effect of education on fuel choice.

Employment stability is another crucial determinant. Households with salaried EDMs are more likely to transition from exclusive firewood use, as a stable and predictable income improves affordability and reduces liquidity constraints in meeting LPG-related costs. Amongst households with self-employed EDMs, however, the effects are heterogeneous. Self-employment in non-farm activities is positively associated with LPG-dominant fuel use; however, its effect is not uniform across all fuel-use categories, suggesting that such households may adopt LPG alongside traditional fuels rather than completely replacing them. In contrast, subsistence farmers and casual labourers remain more reliant on firewood due to affordability constraints. Overall, these findings indicate that socio-economic empowerment through income, education, and employment facilitates clean-fuel adoption, while households lacking these advantages continue to face multidimensional barriers to sustainable LPG use.

Beyond socio-economic factors, the gender of the household's EDM also influences clean cooking fuel choices. Female EDMs have greater agency, and in choosing clean fuel, they stand to gain the most from benefits such as improved health, increased leisure due to time savings, and general convenience. Survey narratives reinforce this finding, as women frequently highlighted the labour-intensive nature of firewood collection. These results are consistent with those of prior studies showing that women who disproportionately bear the drudgery and health risks of traditional cooking tend to prioritize clean energy when they hold decision-making power (Farsi *et al.* 2006; Gould and Urpelainen 2020; Rao and Pachauri 2017). Choudhuri and Desai (2020) similarly demonstrate that women's empowerment, particularly through engagement in salaried and off-farm employment, enhances their decision-making power and leads to greater investment in clean fuels. However, other studies suggest that male-headed households are more likely to use clean fuels than female-headed households (Motu *et al.* 2025). This indicates that women's agency alone does not guarantee clean-energy adoption, as structural constraints such as economic hardships, women's lower opportunity costs, and regional disparities in fuel access can overshadow their fuel preferences.

This analysis reveals that the spatial dimension of energy access strongly influences a household's fuel choices. Households located within a 10-km radius of the main town area are significantly more likely to fully transition to LPG use, as they have the advantage of proximity to distribution centres and refill points. Prior studies have similarly noted that rural households face higher transportation costs and logistical barriers, limiting sustained

LPG use (Patil *et al.* 2021). These barriers include the lack of home delivery facilities, requiring households to incur additional labour and expense to have cylinders collected directly from the distribution centre. In addition to the transportation costs and logistical challenges observed in the study, the locally inflated price of LPG highlights how supply-side constraints, rather than the availability of connections, lead to continued reliance on firewood. These issues are further complicated by the overwhelming political instability in Manipur. There are frequent protests and bandhs, ethnic conflicts, road blockades, and economic blockades, all of which contribute to delays in the supply of LPG cylinders to the hill districts. The main LPG bottling plant is located in Awang Sekmai (Imphal West) and belongs to Indian Oil Corporation. Highways such as the Imphal–Jiribam Road (NH 37) are critical for bringing supplies to hill districts such as Tamenglong, but when this road is blocked, the deliveries get substantially delayed or reduced.

Moreover, the persistence of fuel stacking in forest-rich regions suggests that the ready availability of biomass provides households with a fallback option, slowing the transition to exclusive clean fuel (Cabiyo *et al.* 2021; Sharma and Dash 2022). Importantly, spatial intersections with social inequalities are evidenced: Only 28% of ST households reported receiving home delivery, compared with 33% of Scheduled Caste, 35% of Other Backward Class, and 42% of General Category households (Patnaik and Jha 2020). Together, the evidence suggests that spatial disparities mediated by structural inequalities and inadequate infrastructure, market access, and resource availability continue to shape household energy transitions despite policy efforts to promote universal clean-fuel adoption.

The association between TKP adherence and fuel choice underscores the deeply embedded cultural dimension of energy use in the study area. The influence of TKP on cooking fuel preferences is deeply tied to the traditional, multifunctional role of the hearth. Beyond cooking, the hearth serves as a central social space that facilitates interaction, reinforces family cohesion, and sustains the transmission of customary practices.

In the context of Tamenglong District, cold weather, mountainous environment, the open-fire hearth is also the source of constant heat in the kitchen, which is especially beneficial for vulnerable members of the household, such as the elderly, the sick, or young children. Tamenglong District's location imposes a distinct thermal requirement as ambient temperatures are often very low. The district receives precipitation for six to eight months a year, resulting in extended periods of cold and dampness. The severe shortage of regular electricity supply in the district makes it impractical to install alternative sources of room heating, such as portable

room heaters. In such a high-altitude and forested region, a constant source of indoor heating is crucial not just for comfort but also to maintain the health of the people. In this setting, the continued reliance on biomass reflects an adaptive response to environmental and infrastructural constraints rather than a mere preference.

Smoke, a by-product of biomass combustion, has several practical uses, which further justify the continued use of traditional fuels in the district. Smoke and heat help repel insects and prevent fungal and mould growth, thereby improving indoor living conditions in a humid environment. Smoke also plays a significant role in strengthening and preserving housing structures made of bamboo and wood. As one respondent noted, "Over time, the smoke from the fire helps to reinforce the house structure, making it more durable and long-lasting." Another respondent was quoted as saying, "My father-in-law insists on keeping a *nrap peng* (frame suspended from the roof above the fireplace) in our kitchen; it is essential for hardening crafted items such as bamboo baskets, head-log, axe, and blade wooden handle." This highlights how fuel use is closely linked not only to cooking but also to house maintenance and durability.

Beyond these functional roles, firewood-based cooking is closely related to food preparation and preservation, and taste preferences. Traditional practices such as roasting, smoking, and slow cooking are integral to local diets, where the flavour imparted by firewood is highly valued. As one respondent explained, "Traditional tea leaves…have a much richer taste with smoky flavour *ahuimei* (charred aroma), and meat slow-cooked on a fire stove is softer and flavourful." These preferences are not merely for the palate but are embedded in customary cooking techniques that require sustained exposure to heat and smoke. In addition, fire-based methods serve as an important means of food preservation in the absence of reliable electricity supply and cold storage facilities such as refrigerators; this further links fuel choice to both dietary practices and infrastructural constraints.

Cultural norms and symbolic meanings also shape fuel preferences. Firewood carries social and cultural significance tied to household identity and responsibility. As reflected in local perceptions, a woman "without a pile of firewood in her house represents a '*kachang pat lak mei pui*' (a woman who does not fulfil her wifely duties)." Moreover, fire itself is imbued with the meaning of life; there is a prevailing belief that "there is no life without firewood," and that the household fire should never be allowed to fully go out. At the bare minimum, a smouldering ash should always be maintained within the house as a symbol of continuity and vitality. Together, such beliefs illustrate how energy practices are embedded within broader social expectations, making transitions away from traditional fuels more complex.

Practical and technical considerations related to cooking processes also influence fuel choice. Traditional stoves are better suited to large-scale cooking in bigger households and for specific preparation methods. For example, dishes such as *nkhui* (a traditional dish prepared from fermented soybeans) need to be cooked over fire for a long time and smoked for preservation and to enhance their flavour. LPG stoves are often considered less appropriate for such cooking methods. For instance, respondents indicated that the smaller, more concentrated flame makes food burn easily, especially when large pots are used. Additionally, activities such as preparing livestock feed require substantial fuel, making exclusive reliance on LPG economically unfeasible. As one respondent explained, "Cooking food for livestock…requires large quantities of fuel. …Since we already rely on wood fuel for livestock feed preparation, we often use it for household cooking as well." These factors contribute to the continued reliance on biomass despite having LPG connections.

Hence, in Tamenglong District, firewood is not merely a fuel but an integral part of the household identity and routines, serving functions that modern clean fuels or stoves cannot easily replicate. The persistence of TKP illustrates that energy transitions are not solely driven by affordability or access but also by social norms, symbolic values, and the perceived utility of traditional systems. Culturally sensitive approaches, such as designing improved cook-stoves that retain some features of open-fire cooking or providing hybrid heating solutions, could potentially preserve the multifunctional role of TKP and thus facilitate a sustainable transition to clean fuels without diminishing traditional customs.

A comparison with PMUY beneficiary households further refines these findings, providing a more nuanced understanding of access-led policy interventions. It reveals that the choice of cooking fuel continues to be determined by a mix of economic, infrastructure, and sociocultural factors. Household income shows a limited but notable effect, suggesting a gradual shift towards cleaner fuel—though not uniformly significant across all income brackets—and highlighting a persistent affordability gap in sustaining LPG use. Further, female EDMs and those with a secondary education are modestly associated with a higher probability of LPG-dominant use—underscoring the supporting role of awareness and inclination—but do not independently drive complete energy transition. In contrast, regular cash flow and income stability enable sustained LPG usage. At the same time, physical access remains a critical constraint even after the provision of free LPG connections, affecting the ease and continuity of use. Most notably, traditional kitchen habits continue to

discourage exclusive reliance on LPG, underscoring the persistence of cultural and behavioural practices even amongst PMUY beneficiaries.

Overall, the transition to clean cooking in Tamenglong District is not solely a question of access but also of sustained usability. Addressing affordability, strengthening last-mile delivery, and accounting for culturally embedded practices are essential to enable a sustainable shift away from traditional fuels. These findings suggest that PMUY partially equalizes access but does not address the structural and behavioural constraints that shape sustained adoption.

5. CONCLUSION

This study examined the socio-economic and spatial characteristics influencing a household's cooking fuel choices in rural Manipur. By analysing primary and secondary fuel use, it offers a fuller understanding of rural energy practices and priorities, capturing both the persistence of fuel stacking and the dynamics of energy transition. The findings lend partial support to the energy ladder theory, showing signs of an upward shift: 57% of households continue to rely on firewood as their primary fuel, while 43% use LPG, indicating that the district is only just beginning to transition to clean modern energy. Yet fuel stacking persists as a widespread practice, even amongst PMUY beneficiaries—with strategic fuel mixing prompted by affordability and accessibility issues—underscoring its role as a defining feature of rural energy transition.

Although government initiatives such as PMUY play a crucial role in providing subsidized LPG connections, uptake is higher in Tamenglong subdivision, where the relatively better connectivity facilitates access, but more remote areas such as Tamei and Tousem remain constrained by poor infrastructure and weak supply chains. These disparities reflect spatial biases in programme implementation and raise broader concerns about energy justice. The analysis also highlights that household income, employment stability, and the EDM's gender and education level significantly influence LPG adoption. However, spatial constraints and TKP shape behavioural fuel preferences, hindering the effective adoption of clean fuels and slowing the complete transition to modern energy, particularly in remote and hilly areas.

Policy implications point to the need for strengthening the PMUY beyond its current access-oriented design towards a sustained-usage framework. Improving refill affordability through targeted subsidies and flexible payment mechanisms remains critical, particularly for households with

irregular incomes. Strengthening LPG distribution systems—by establishing micro distribution centres in remote areas, addressing the lack of reliable home delivery services in the district, and improving integration with rural infrastructure (roads, transport, and storage)—is essential to overcome last-mile constraints. At the same time, linking the PMUY with livelihood support initiatives can enhance income stability and sustained adoption. Behavioural interventions, including awareness creation and community engagement through local institutions, such as non-governmental organizations and self-help groups, are equally important to address culturally embedded practices while recognizing the multifunctional role of the traditional hearth.

Finally, the persistence of firewood usage carries broader implications for attaining the SDGs—underscoring concerns about universal access to clean fuel (SDG 7), ongoing pressures on local forests (SDG 13), and the gendered nature of biomass dependence reinforcing inequalities (SDG 5)—that are linked to community well-being. At the same time, the study is limited by its cross-sectional design, which does not capture the dynamics of seasonal variations that may influence local energy practices. Future research should adopt longitudinal approaches to ascertain the effectiveness of clean fuel consumption, including whether subsidizing LPG connections through the PMUY results in sustained use for a meaningful energy transition. The analysis can also be extended beyond cooking to other end uses often linked to fuel choice, to inform more holistic energy policies. Comparative studies across other northeast Indian states would help assess whether the observed subdivisional disparities, especially under the PMUY, are unique to Tamenglong District or reflective of broader regional patterns.

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Data Availability Statement: The data used to support this research cannot be shared openly to protect the privacy of study participants and is stated in the paper.

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RESEARCH PAPER

Factors Affecting Coastal Community Resilience: Role of Community Preparedness and Social Capital

Niranjana Haridas,[*] Sangeetha K Prathap[**]

Abstract: Coastal fishing communities are highly vulnerable to recurring hazards associated with extreme weather events that can lead to severe environmental degradation, cause loss of livelihoods, and even threaten human lives. It is essential to develop coastal populations' capacity to respond to and recover from such shocks. Community resilience has emerged as an important factor that enhances disaster response and recovery. This study uses primary data to examine community resilience amongst 528 households across three coastal districts in Kerala. Moderate community resilience was observed across these coastal districts, with less pronounced inter-district variations. The results further show that community preparedness and social capital are the strongest predictors of community resilience, followed by income diversification, education, and experiential factors such as age. The study advances the resilience literature by demonstrating that resilience is multidimensional, interaction-driven, and place-specific. The findings underscore the need for integrated, context-sensitive disaster risk reduction strategies that strengthen social networks, enhance preparedness, promote livelihood diversification, and expand educational opportunities to build resilient coastal communities.

Keywords: Coastal Community, Community Resilience, Social Capital, Disaster Preparedness.

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1. INTRODUCTION

Coastal areas face the threat of sea-level rise due to climate change (Roy *et al.* 2023). The rise in sea level has intensified catastrophic coastal hazards, including cyclones, storm surges, and coastal erosion, putting coastal populations across the world at great risk (Karim and Mimura 2008). This has made them more vulnerable to climate change than non-coastal populations (Roy *et al.* 2023). Climate change projections indicate tremendous impacts on marine life, endangering the lives and livelihoods of fishing communities in India. India's extensive coastal exposure and increasing climate variability have led to reduced fishing days, declining catch sizes, and income instability, all compounded by limited adaptive capacity (Das *et al.* 2020; Maiti *et al.* 2015; Senapati and Gupta 2017; Sudhakaran and Varsha 2025). The marine fishing community frequently encounters rising sea surface temperatures, changes in precipitation patterns, and extreme events such as storms, coastal flooding, cyclones, and the El Niño phenomenon (Vivekanandan 2010). These challenges threaten communities that depend directly on natural resources for their subsistence as well as those living near disaster-prone areas (Saha *et al.* 2024). Adaptive management of natural hazards thus assumes critical importance in coastal communities.

Studies conducted across the globe have identified practices that can help communities reduce their exposure to disaster impacts and support long-term disaster recovery. Community resilience is recognized as a key factor that enhances the capacity of communities to respond to and recover from the aftermath of a disaster (Chandra *et al.* 2011). According to Pfefferbaum *et al.* (2007: 349), community resilience is defined as "the ability of community members to take meaningful, deliberate, collective action to remedy the impact of a problem, including the ability to interpret the environment, intervene, and move on". Dessavre *et al.* (2016) suggest that disaster resilience can help mitigate disaster risk and vulnerability among households.

A community's resilience in the face of disasters is determined by factors such as social capital, mitigation capacity, community preparedness, and information and communication systems (Aldrich and Meyer 2015; Cutter *et al.* 2008; Pfefferbaum *et al.* 2015). However, the contribution of these factors to augmenting resilience capacity varies by community type as well as geographical location, cultural beliefs, and social norms (Rapaport *et al.* 2018; Wardekker *et al.* 2023). It follows that gaining insights into the various aspects of resilience capacity—including, but not limited to, the present state and weights and strengths of contributory factors—across different locales will be useful in formulating appropriate policies.

Fishing communities in the Indian state of Kerala are highly dependent on natural resources for their subsistence and are, therefore, particularly vulnerable to environmental and economic shocks. Fishing, their primary source of income, is subject to price volatility, and livelihood diversification is limited (Brugere *et al.* 2008). As a result, many fisher households suffer from financial instability, with incomes being irregular, seasonal, and highly uncertain. This reflects the broader reality that fishing communities often depend on a single, highly vulnerable occupation and have limited scope for alternative employment (Islam *et al.* 2014). Consequently, any disruption—whether due to environmental change, overfishing, policy restrictions, or market fluctuations—can have immediate and severe impacts on household income and food security, further increasing the economic insecurity of fisherfolk (Rahman *et al.* 2021).

Over the past decades, these communities have experienced multiple stressors, including climate-related hazards and livelihood uncertainties (Pavithran *et al.* 2015). The literature on disaster resilience—though largely based on secondary data—identifies social capital and community disaster preparedness as critical factors that can enhance a community's ability to respond to and recover from disasters (Kapucu *et al.* 2013; Pfefferbaum *et al.* 2017). While previous studies examined these factors in relation to community resilience, their combined role in shaping community resilience at the household level has received relatively limited empirical attention, particularly with respect to coastal fishing communities in Kerala. This study addresses this gap. It also provides evidence-based insights that can inform policymaking to reduce disaster-related risks and help devise long-term, post-disaster recovery strategies for fishing communities..

2. REVIEW OF THE LITERATURE

The literature on coastal populations' resilience to extreme weather events traces a few common strands. The entry point to this literature is the twin principles of resilience and adaption in response to the impacts of natural hazards. Resilience pertains to a system's ability to adjust to unexpected disruptions, acknowledging them, and adapting through flexible processes and practices in order to ensure its long-term stability (Adger *et al.* 2005; Cutter *et al.* 2008).

A few studies address the question of what actions communities should take in response to catastrophes and which measures efficiently reduce disaster risk. For example, Arbon *et al.* (2016) emphasize that enhancing community resilience is essential to lower susceptibility to disasters and improve recovery outcomes. Meerow *et al.* (2016) contend that resilience

assessment frameworks help identify the elements that contribute to a community's capacity to endure and recover from disasters.

Several frameworks have been developed to measure community resilience across different contexts. These include the Baseline Resilience Indicators for Communities (BRIC) framework and the Disaster Resilience of Place (DROP) model.[1] These frameworks mainly rely on secondary data sources and macro-level indicators, such as socio-economic characteristics, infrastructure, institutional capacity, and environmental conditions, to evaluate resilience at the regional or national level (Cutter *et al.* 2008; Cutter *et al.* 2014). Although these methods offer important insights into institutional and structural aspects of resilience, they typically capture resilience at an aggregate level and do not account for the social dynamics and community perceptions that affect resilience locally.

The Communities Advancing Resilience Toolkit (CART) framework, in contrast, offers a multifaceted, community-based method of assessing resilience. CART was developed by the Terrorism and Disaster Center of the National Child Traumatic Stress Network (United States) and was formally introduced in 2013 to assess and strengthen community resilience in disaster contexts. It enables the evaluation of perceived community resilience across multiple domains, such as connections and caring, community resources, transformative potential, disaster management, and information and communication (Pfefferbaum *et al.* 2013).[2] This

[1] The BRIC framework was developed by Susan L Cutter, Kevin D Ash, and Christopher T Emrich in 2010. It was further elaborated in 2014 to provide a standardized, empirically grounded measure of community disaster resilience across geographic regions. It was designed to address the lack of consistent metrics for assessing resilience and to enable comparison across places using a composite index of multiple domains, such as social, economic, institutional, infrastructural, community, and environmental capacities. The framework has since been widely applied and adapted across different geographical contexts, including Australia (Singh-Peterson *et al.* 2014) and Norway (Scherzer *et al.* 2019), and in multiple global settings, as highlighted in a systematic review by Camacho *et al.* (2023). The DROP model was developed by Susan L Cutter, Lindell Michael, and Christopher T Emrich in 2008 to provide a conceptual framework for understanding how disaster resilience emerges from the interaction of social vulnerability, the built environment, and natural systems. The model was designed to address the need for an integrated, place-based approach that links pre-existing conditions (inherent vulnerability and resilience) with disaster impacts and recovery processes. The DROP model has been applied across different contexts, including Thailand (Siebeneck *et al.* 2015) and Zimbabwe (Mavhura *et al.* 2021), and has also been discussed in theoretical syntheses (Jones 2021).

[2] "Connection and caring" refer to community belonging and mutual support; "resources" denote the availability of diverse assets; "transformative potential" reflects the capacity for learning and adaptive change; "disaster management" encompasses preparedness, response,

multidimensional structure captures the social and behavioural dimensions of resilience, which may not be reflected in macro-level assessments such as those based on BRIC or DROP.

Social capital has emerged as one of the main factors that influence community resilience. It refers to the networks, relationships, trust, and norms that facilitate cooperation and collective action within communities (Putnam 2000). Social capital is recognized as a form of capital, alongside natural, human, and physical capital, and contributes to the sustainability of economic systems (Dasgupta 2008; Dasgupta and Serageldin 1999). Strong social networks can help communities mobilize resources, exchange information, and co-ordinate a collective response during a catastrophe. Consequently, it enhances community competence and the group's ability to respond to disasters (Norris *et al.* 2008). Aldrich and Meyer (2015) posit that social infrastructure, such as civic involvement and community networks, often plays a more important role in disaster recovery than expensive physical infrastructure. Communities with stronger social ties tend to recover more quickly because neighbours, family members, and local organizations often serve as first responders during disaster events.

Researchers also highlight the importance of community preparedness in strengthening community resilience (Cutter *et al.* 2014; Tierney *et al.* 2002) and enabling communities to reduce their vulnerability and enhance their adaptive capacity (Pfefferbaum *et al.* 2015). Preparedness refers to the activities and measures undertaken by individuals and communities to anticipate and respond effectively to disasters. Communities are better prepared to respond to catastrophes and recover faster when they participate in preparedness activities such as risk awareness programmes, emergency planning, and disaster exercises (Hyvärinen and Vos 2015).

Despite the growing body of literature on this subject, significant gaps persist. First, much of the existing research has examined social capital (e.g., Behera 2023; Panicker and Joseph 2025; Sanyal and Routray 2016; Visave and Aldrich 2025) and community preparedness (e.g., Lin and Lee 2025; Oktari *et al.* 2025; Rajeswari *et al.* 2025) separately, rather than exploring how these two factors interact to influence community resilience. Second, limited empirical research on social capital and disaster resilience has been conducted in developing nations, where socio-economic conditions and disaster management systems are heterogeneous and differ considerably

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recovery, and mitigation; and "information and communication" refer to the availability and reliability of timely information (Pfefferbaum *et al.* 2013; Pfefferbaum *et al.* 2015).

from those in developed contexts such as the US, Japan, and Europe, where most of the existing research has been performed.

3. RESEARCH DESIGN

This study addresses both the gaps identified in Section 2. It examines the combined influence of social capital and community preparedness on community resilience among coastal communities in Kerala using the CART framework. By employing a validated survey-based instrument, the study captures community-level perceptions and social dynamics, thereby offering a more comprehensive understanding of the social factors that shape resilience in disaster-prone coastal communities in developing countries.

Community resilience has been evaluated employing methodologies such as the analytic hierarchy process (Orencio and Fujii 2013), TOPSIS[3] (Elkady *et al.* 2024), the Relative Importance Index (RII) (Ahmad *et al.* 2024), among others. The present study uses the RII with the CART framework, following Pfefferbaum *et al.* (2015).

The objective of this study is trifold: (1) to identify the key determinants of community resilience among coastal households in selected locations in Kerala, (2) to analyse the influence of social capital and community preparedness on community resilience, and (3) to capture variations in community resilience across districts with varying levels of vulnerability.

Most of the concepts used in this study have been introduced earlier. These include community resilience, social capital, and community preparedness.

This study draws on the community resilience framework proposed by Norris *et al.* (2008), which conceptualizes resilience as a set of adaptive capacities, including social capital, information and communication, community competence, and economic development. Amongst these, social capital plays a crucial role in enabling communities to mobilize resources, share information, and co-ordinate responses during crises. Social capital, as defined by Putnam (2000), encompasses the networks, trust, and norms that facilitate cooperation within communities. Szreter and Woolcock 2004 further conceptualized social capital through three dimensions of social capital : bonding, bridging, and linking social capital. Bonding social capital consists of close ties within homogeneous groups, such as families and neighbours; bridging social capital connects individuals across different social groups; and linking social capital connects communities with

[3] Technique for Order of Preference by Similarity to Ideal Solution.

institutions and authorities. These forms of social capital collectively enhance access to resources, co-ordination, and collective action, thereby strengthening community resilience (Aldrich 2012).

Community preparedness encompasses the proactive actions and planning strategies adopted by individuals and households to enhance their capacity to respond to and manage disaster impacts effectively. These include developing emergency plans, preparing emergency supplies, and participating in awareness programmes. The relationship between preparedness and resilience can be explained using Bandura's self-efficacy theory (1977), which emphasizes individuals' belief in their ability to manage challenging situations. Individuals with higher self-efficacy are more likely to engage in proactive preparedness behaviours, persist in difficult conditions, and cope effectively with disruptions. In disaster contexts, such preparedness actions enhance response capacity and reduce potential impacts, thereby contributing to resilience (Hyvärinen and Vos 2015).

Integrating these perspectives, this study posits that social capital and community preparedness jointly shape community resilience. Strong social networks facilitate information sharing, resource mobilization, and collective action, while preparedness behaviours enhance the ability of households and communities to respond effectively and recover from disasters. Together, these factors reinforce the adaptive capacity of coastal communities and contribute to improved resilience outcomes.

4. METHODOLOGY

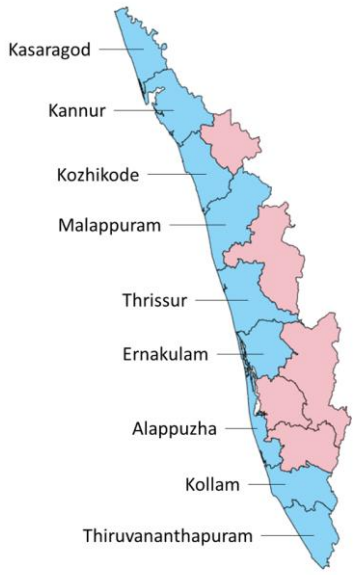
4.1. Sampling

Kerala's coastline is 590 km long (Sreelekshmi *et al.* 2021) and is divided into the southern zone (consisting of Thiruvananthapuram, Kollam, and Alappuzha, spanning approximately 197 km), the central zone (Ernakulam, Thrissur, and Malappuram, 170 km), and the northern zone (Kozhikode, Kannur, and Kasaragod, 223 km) (see Figure 1). To capture the variations in climate-related risk across Kerala's coastal districts, a stratified sampling framework was employed.

The sample districts were selected using the Composite Vulnerability Index (CVI) (DoECC 2022) (Appendix A). The CVI categorizes districts according to their relative exposure and sensitivity to climate-related hazards. Based on this classification, the coastal districts were grouped into three vulnerability categories: high, moderate, and low. One district was randomly selected from each vulnerability category using simple random sampling to ensure representation across different levels of climate-related

risk. Accordingly, Kozhikode (high vulnerability), Thiruvananthapuram (moderate vulnerability), and Ernakulam (low vulnerability) were selected for the study.

Figure 1: A Map of the Coastal Districts of Kerala



Source*:* Created by authors

In the second stage, five marine fishing villages in each district were selected randomly based on the official list of fishing villages from the *Marine Fisheries Census 2016* (DoF and CMFRI 2020). Further, 600 households were selected randomly from each of the sample villages across the three districts. In Thiruvananthapuram District, the selected villages included Bheemapally, Kovalam, Cheriyathura, Kuzhithura, and Kochuveli. Beypore, Marad, Kampuram, Thoppayil, and Vellayil were selected from Kozhikode District. Chellanam, Saudi, Ayyampally, Cheriyakadavu, and Fort Kochi were selected from Ernakulam District. A detailed account of the sample is provided in Appendix B.

The final survey covered 600 households (200 from each of the three districts). After screening the data and eliminating incomplete or inconsistent answers, the final sample consisted of 528 households along the coastline in the three districts. The surveys were conducted using structured schedules from June 2023 to November 2023.

4.2. Measurement Scales

The survey instrument was organized into three sections. The first section captured demographic and socio-economic characteristics, including age, household size, education, and income diversification. The second section assessed community resilience, covering infrastructure resilience, early-warning systems, response effectiveness, recovery processes, institutional co-ordination, and disaster impacts. The third section examined social capital, including trust, social networks, community participation, institutional linkages, and collective action. Together, these sections

provided a comprehensive basis for analysing the determinants of community resilience amongst fishing households.

Community resilience was measured using CART. A 24-item scale was adapted to capture five domains: connection and caring; resources; transformative potential; disaster management; and information and communication. Social capital was measured using the three dimensions of bonding, bridging, and linking social capital (Szreter and Woolcock 2004), with a nine-item scale mapped across these dimensions. Community preparedness was assessed using 10 items covering four indicators, material preparedness, special needs preparedness, awareness, and participation, adapted from Thomas *et al.* (2015). All the variables were measured using a 5-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree").

4.3. Data Analysis

The respondents' opinions about community resilience, social capital, and readiness across the chosen districts were initially analysed using mean score analysis. Composite scores were calculated by averaging responses across the indicators that constituted each construct.

RII was employed to analyse the respondents' perceptions of selected variables, and multiple regression analysis was conducted to understand the factors influencing community resilience among coastal households. RII is widely used in studies involving Likert-scale data to determine the relative importance of factors (Rooshdi *et al.* 2018). It has been used in disaster management contexts and in sustainability studies to evaluate the key determinants of various outcomes (Sodangi *et al.* 2014). The RII method converts Likert-scale responses into a standardized index ranging between 0 and 1, thereby enabling comparison across different variables.

RII was calculated using the following formula:

$$RII = \sum W/A*N \qquad (1)$$

where

W = the weight assigned to each factor by the respondent, ranging from 1 to 5;
A = the maximum possible weight (i.e., 5 in this study); and
N = the total number of respondents.

The RII values were interpreted using the classification used in previous studies, such as Ahmad *et al.* (2024). RII values range from 0 to 1: values closer to 1 indicate that households assign higher relative importance to a given factor in shaping community resilience, while values closer to 0

indicate lower importance. This index measured respondents' perceptions of the relative importance of social capital, community preparedness, and community resilience.

To examine the factors influencing community resilience, multiple linear regression analysis was employed. Community resilience was treated as the dependent variable, while age, household size, educational attainment, income diversity, community preparedness, and social capital were included as independent variables. Regression analysis was used to estimate the strength and direction of the relationships between the explanatory variables (age, education, income diversity, household size, social capital, and community preparedness) and community resilience.

5. RESULTS AND DISCUSSION

To investigate the determinants of community resilience among coastal households in Kerala, the study examines the demographic and socio-economic profile of the respondents, followed by an analysis of the major study variables and regression results. The analysis provides insights into the factors influencing community resilience.

5.1. Demographic Profile

Table 1 outlines the demographic and socio-economic profile of the respondents. It may be noted that the majority (72%) of the respondents were in the age category 31–60 years, and 50% of them belonged to families with six or more members. Further, most of the families (75%) had more than one source of income.

Table 1: Demographic Indicators of the Respondents

Indicator	Frequency	%
Age class (years)		
18–30	126	23.9
31–45	242	45.8
46–60	136	25.8
Over 60	24	4.5
Household size (no. of members)		
2	119	22.5
3–4	144	27.3
5–6	148	28.0
More than 6 (joint family)	117	22.2
Highest education level		
Below secondary	125	23.7
Above secondary	151	28.6

Graduate	147	27.8
Postgraduate and other	105	19.9
Family's income diversity		
No other income source	132	25.0
One additional income source (full-time)	131	24.8
One additional income source (part-time)	124	23.5
Two or more income sources	141	26.7

Source*:* Based on primary survey data compiled by the authors

Table 2 presents the distribution of the mean scores of the variables. As shown in the table, of the 528 respondents, 42.6% perceived community preparedness as a very important factor. The disaggregated percentages place Thiruvananthapuram at the top (48.3%), followed by Ernakulam (43.2%) and Kozhikode (36.4%). Further, 41.5% of the respondents reported high social capital, with only marginal variation across the three districts.

Kozhikode recorded the highest resilience (RII 0.645), followed by Thiruvananthapuram (0.630) and Ernakulam (0.604), indicating spatial variation in resilience levels. However, the RII analysis is descriptive in nature and does not establish causal relationships between variables. Therefore, regression analysis was performed to identify the factors contributing to community resilience.

Table 2: RII and the Distribution of Mean Scores (MS) of Selected Variables

District	**MS: 1–2 (%)[a]**	**MS: 2–3 (%)[a]**	**MS: 3–4 (%)[a]**	**MS: 4–5 (%)[a]**	**RII**
Community preparedness					
Kozhikode	23.9	21.6	18.2	36.4	0.569
Thiruvananthapuram	13.6	18.2	19.9	48.3	0.663
Ernakulam	21	19.9	15.9	43.2	0.608
Total	19.5	19.9	18	42.6	0.613
Social capital					
Kozhikode	19.9	19.3	18.2	42.6	0.602
Thiruvananthapuram	18.8	17.6	22.7	40.9	0.610
Ernakulam	27.3	9.7	22.2	40.9	0.592
Total	22	15.5	21	41.5	0.601
Community resilience					
Kozhikode	5.7	26.7	43.2	24.4	0.645
Thiruvananthapuram	13.6	21.6	35.2	29.5	0.630
Ernakulam	18.8	19.9	23.9	37.5	0.604
Total	12.7	22.7	34.1	30.5	0.626

[a] Percentage of total respondents (n = 528).

Source*:* Authors' analysis, computed from the primary data

5.2. Regression Analysis

Multiple linear regression analysis was performed to examine the influence of the selected independent variables on community resilience, the dependent variable in this study. Based on the theoretical model proposed by Norris *et al.* (2008), economic development (proxied by socio-economic indicators), social capital, and community preparedness were included as independent variables.

The functional form of the regression model is specified as follows:

$$CR = \beta_0 + \beta_1 AGE + \beta_2 EDU + \beta_3 ID + \beta_4 HHS + \beta_5 CP + \beta_6 SC + \varepsilon \quad (2)$$

where
CR = community resilience (the dependent variable);
β_0 = the intercept term;
$\beta_1 - \beta_6$ = regression coefficients of the respective independent variables; and
ε = the error term.

The independent variables incorporated into the model are as follows:

Age (AGE): It is the respondent's age expressed in years. It serves as a proxy for life experience, including prior exposure to disasters, which may influence resilience.

Educational attainment (EDU): This is the highest level of education attained by any member of the household. Education is expected to boost awareness, access to information, and adaptability.

Income diversity (ID): This is a measure of the household's income sources. Increased income diversification is expected to reduce vulnerability and enhance economic resilience.

Household size (HHS): This refers to the number of members in a household. It indicates the household's supply of human resources as well as its dependency burden.

Community preparedness (CP): It is the state of the household's preparedness for a disaster event, calculated as a composite index based on preparedness-related indicators such as awareness, planning, and participation.

Social capital (SC): The extent of social connectedness, trust, and networks in the community, measured in terms of bonding, bridging, and linking social capital indicators.

This model allows the determination of cause–and–effect relationships between both the explanatory variables and the dependent variable

(community resilience). The model explains 26% of the variance in community resilience. The F statistic (29.79) is significant at $p < .001$, confirming that the model predicts community resilience significantly. The variance inflation factor values are <2, indicating low multicollinearity. The Durbin–Watson statistic shows a value of 1.9, indicating that there is no autocorrelation among the variables.

Table 3 presents the results of the multiple regression analysis. All the variables are statistically significant ($p < .01$). Community preparedness and social capital have the highest coefficients ($B = 0.296$ and 0.265, respectively), indicating that they are the strongest predictors of community resilience. Income diversity ($B = 0.215$), age ($B = 0.181$), and education ($B = 0.168$) also play substantial roles, implying that experience and economic and knowledge resources enhance resilience. Household size ($B = 0.146$) shows a positive but relatively smaller effect. The findings reveal that community-based and demographic factors significantly influence resilience levels.

Table 3: Results of the Multiple Regression Analysis (Dependent Variable: Community Resilience)

Variable	***B***	Standard error	***T*** value	Significance level
(Constant)	–0.155	0.263	–0.587	.557
Age	0.181	0.055	3.314	<.01***
Highest education attained by the family member(s)	0.168	0.042	3.976	<.01***
Income diversity (no. of income sources)	0.215	0.039	5.463	<.01***
Household size	0.146	0.042	3.486	<.01***
Community preparedness	0.296	0.038	7.770	< .01***
Social capital	0.265	0.037	7.085	<.01***

*** Significant at the 1% level.

Source*:* Authors' analysis, computed from the primary data

6. DISCUSSION

The distribution of the mean scores and RII values indicates that although a significant percentage of the respondents reported higher levels of community preparedness and social capital, levels of community resilience are largely moderate across the three coastal districts. This implies that an increase in perceived levels of individual elements does not necessarily lead to greater resilience, which further supports the argument that resilience is a multidimensional construct modulated by the relationships amongst various capacities rather than by a single factor (Cutter *et al.* 2008; Norris *et al.* 2008). The differences in RII values among the districts further demonstrate the influence of the local socio-economic and environmental context on community resilience, which is also place-based, as observed in previous studies (Adger 2003).

A key finding of this study is the relatively higher resilience observed in Kozhikode despite the lower levels of community preparedness. This pattern can be explained by the high level of social capital, which appears to function as a compensatory mechanism. Social capital, understood as trust, social networks, and reciprocity norms, plays a crucial role in facilitating collective action, information sharing, and mutual support during disaster events (Aldrich and Meyer 2015). Empirical evidence suggests that communities with strong social ties are better equipped to respond to and recover from disasters, even if they lack robust formal preparedness systems (Aldrich 2012; Nakagawa and Shaw 2004). This is particularly relevant in the context of Kerala's fishing communities, where long-standing social cohesion and collective practices enable rapid mobilization of support during crises. Studies of disaster-affected communities have similarly demonstrated that bonding and bridging social capital enhance adaptive capacity and recovery outcomes significantly (Pelling and High 2005).

In contrast, Thiruvananthapuram exhibits higher levels of community preparedness alongside comparatively low social capital; yet it maintains relatively high resilience. This suggests that preparedness plays a critical role in strengthening immediate disaster-response capacity through improved awareness, planning, and risk reduction measures. Community-based preparedness initiatives, such as cyclone shelters, disaster management training programmes, local volunteer networks, and early-warning response systems, have been widely recognized as essential components of resilience-building and vulnerability reduction (Patel *et al.* 2017). However, the findings also indicate that preparedness alone cannot fully explain resilience outcomes, as resilience depends on the interaction of social, economic, and institutional dimensions, and the absence of strong social capital may limit

the long-term sustainability of resilience despite high levels of preparedness (Twigg 2009).

In Ernakulam, moderate levels of both preparedness and social capital correspond to lower resilience compared with other districts; this further underscores the multidimensional nature of resilience. The findings suggest that resilience outcomes are strongest when multiple capacities reinforce one another, whereas moderate or weak levels of key determinants result in comparatively lower adaptive capacity. This aligns with the systems-based understanding of resilience, which emphasizes that resilience emerges from the interaction of interdependent components rather than from isolated factors (Cutter *et al.* 2008).

Place-based and socio-institutional theories of resilience can help us better understand these district-level differences. Local socio-economic growth patterns, governance systems, and cultural settings all have an intrinsic impact on disaster resilience, as they influence the formation and use of various capacities (Cutter *et al.* 2008). Districts with comparatively higher institutional development and administrative capacity frequently display stronger formal preparedness mechanisms (Tierney 2014), since their infrastructure, early-warning systems, and disaster management programmes are typically better organized and efficient. This could account for the comparatively higher levels of readiness seen in Thiruvananthapuram, which benefits from its centrality to administration and governance. At the same time, variations in social capital can be linked to differences in social organization and livelihood structures. Coastal communities such as those in Kozhikode often feature strong kinship ties, shared occupational identities, and long-standing community networks, which enhance trust, reciprocity, and collective action.

In contrast, Ernakulam can be understood as a more urbanized and economically diversified context, where both social capital and preparedness exist but are less pronounced than in the other two districts. Urban and peri-urban regions often exhibit weaker bonding social capital due to the populations' greater heterogeneity, higher mobility, and reduced dependence on traditional community networks, while their reliance on formal institutions may not fully reach communities at the local level (Granovetter 1973). As a result, resilience in such contexts tends to be low, reflecting neither strong community-based cohesion nor exceptionally high institutional preparedness. Additionally, diversified livelihood structures may reduce dependence on collective coping mechanisms, thereby moderating the role of social capital (Allison and Ellis 2001). Thus, the district-level differences observed in this study reflect distinct configurations in resilience capacities, where resilience emerges from

different combinations of social, institutional, and economic factors operating within specific local contexts.

To further explore these relationships, multiple regression analysis was conducted to identify the determinants of community resilience. The results reveal that community preparedness and social capital are the strongest predictors of resilience, followed by income diversity and educational attainment. The strong influence of social capital is consistent with existing research findings that highlight its role in enhancing cooperation, trust, and collective action within communities (Aldrich and Meyer 2015). Similarly, the significant effect of community preparedness supports the argument that preparedness enhances resilience by improving readiness and reducing disaster impacts (Patel *et al.* 2017). Income diversity emerged as a key determinant, indicating that households with multiple income sources are better able to withstand shocks and recover from disasters—consistent with the livelihood diversification framework proposed by Ellis (2000).

Age is another significant factor influencing community resilience. Adults tend to exhibit higher levels of awareness, preparedness, and trust in institutions than younger groups. Additionally, older individuals' accumulated experience, skills, and knowledge contribute to higher disaster response and recovery capacities. Thus, the findings suggest that age positively influences community resilience. This is identical to the conclusions of Lin and Chen (2022), Ullah *et al.* (2025), and others.

Household size also plays an important role in shaping resilience among coastal households, as it determines the availability of labour, opportunities for income diversification, and internal support systems. This is in tune with the findings of Wu *et al.* (2026) that larger households can enhance resilience through shared resources and collective coping mechanisms.

Education was also found to have a significant positive influence on resilience, as higher levels of education can improve awareness, access to information, and the ability to adopt appropriate coping strategies. This finding is supported by Muttarak and Pothisiri (2013), who found that education improves risk perception and decision-making, enhancing disaster preparedness and response.

Overall, the findings show that community resilience is a multidimensional construct shaped by the interaction of social capital, preparedness, and socio-economic capacities. Due to the variations in reliance observed across districts, it is crucial to employ context-specific strategies for disaster risk reduction rather than relying solely on uniform policy interventions. Thus, building resilience among Kerala's coastal populations requires strengthening social networks, boosting community-based preparedness,

encouraging livelihood diversification, and broadening educational opportunities.

7. CONCLUSIONS AND LIMITATIONS

The present study identified the key determinants of community resilience among coastal households in Kerala, emphasizing that resilience is shaped through the dynamic interaction of social capital, economic resources, and institutional capacities. RII values were found to be moderate across the three coastal districts studied, and inter-district variations in community resilience, social capital, and community preparedness were not pronounced. The regression results show that community preparedness and social capital can predict resilience. Minor variations in RII at the district level indicate that resilience is context-specific and depends on local socio-economic structures and systems of governance.

Income diversity and educational level were identified as important determinants, highlighting the role of economic stability and knowledge in enhancing community resilience in coastal Kerala. Having multiple income sources can help a household withstand economic shocks, while education enhances preparedness and awareness. These results indicate that achieving community resilience necessitates localized and context-specific policy responses that aim to enhance social networks, preparedness programmes, livelihood diversification, and education.

Despite its contribution to the research literature, the study has some limitations. The cross-sectional nature of the data limits its ability to establish causality or capture changes in resilience over time. Future studies can be longitudinal, use mixed methods, cover a wider area, and include additional variables—such as the quality of governance and environmental indicators—to offer a more comprehensive view of community resilience.

At the policy level, disaster preparedness in India is guided by frameworks developed by the National Disaster Management Authority, with state-level implementation by state disaster management authorities. While these provide a structured top-down approach, the findings of this study highlight the importance of local factors, such as social capital and community preparedness. This suggests the need to better align existing policy frameworks with local contexts by incorporating grassroots-level inputs, thereby improving the effectiveness of disaster preparedness and resilience strategies.

Author Contribution: NH conceived the study, conducted the data analysis and drafted the manuscript. SKP supervised and revised the manuscript.

Ethics Statement: We hereby confirm that this study was conducted in accordance with all applicable ethical requirements and standards for research.

Consent to Participate: Informed consent was obtained from all respondents before the survey, ensuring their voluntary participation, with assurance of anonymity and confidentiality.

Consent for Publication: Consent for the publication of the research findings in a journal was obtained from all participants.

Data Availability Statement: The data have been anonymized and are not publicly available to ensure the privacy and confidentiality of the respondents.

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APPENDIX A

Table A1: CVI Classification of Districts in Kerala

Vulnerability class	Vulnerability drivers	Districts
High	1. High percentage of the inherently sensitive population (below six and over 60 years of age; people living with disabilities) 2. Fewer healthcare professionals 3. Fewer relief shelters available relative to the district's population 4. Fewer households with treated water supply 5. High incidence of communicable diseases 6. Poor irrigation coverage 7. High population burden on healthcare facilities 8. Poor spread and coverage of local meteorological monitoring stations 9. Limited groundwater availability 10. High percentage of the population living below the poverty line	Wayanad, Kozhikode, Kasaragod, Palakkad, Alappuzha, Idukki, Kannur, Malappuram, Kollam
Medium	1. Poor irrigation coverage 2. High percentage of the inherently sensitive population 3. Fewer relief shelters available relative to the district's population 4. High population density 5. Limited groundwater availability 6. Poor air quality 7. Poor surface water quality	Thiruvananthapuram, Kottayam
Low	1. Fewer relief shelters available relative to the district's population 2. High percentage of the inherently sensitive population 3. Poor irrigation coverage 4. Poor spread and coverage of local meteorological monitoring stations	Thrissur, Ernakulam, Pathanamthitta

Source*:* DoECC (2022)

APPENDIX B

Table B1: Sample Selection Design

District	Village	Total no. of households	Final sample size
Thiruvananthapuram	Bheemapally	939	75
	Kovalam	60	5
	Cheriyathura	412	35
	Kuzhithura	175	14
	Kochuveli	410	34
	Subtotal	1,996	163
Kozhikode	Beypore	662	62
	Marad	480	45
	Kampuram	252	23
	Thoppayil	295	28
	Vellayil	285	27
	Subtotal	1,974	199
Ernakulam	Chellanam	975	80
	Saudi	240	20
	Ayyampally	239	20
	Cheriyakadavu	324	27
	Fort Kochi	225	19
	Subtotal	2,003	166
Total		**5,973**	**528**

Source*:* Primary survey data, compiled by the authors

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REVIEW ESSAY

Recent Advances in Air Pollution monitoring and forecasting: implications for civil engineering

Prakash L Pathak,[*] Pradip D Jadhao [**]

Abstract: Addressing the growing problem of urban air pollution requires that sophisticated air pollution monitoring and forecasting systems be incorporated into civil engineering practice. New technologies that support smarter and more sustainable urban environments include the Internet of Things (IoT), big data analytics, and machine learning (ML). These technologies allow for real-time data acquisition, high-resolution monitoring, and precise predictive optimization. Continuous, spatially dense air quality monitoring is made possible by IoT-based sensor networks, while big data frameworks can effectively integrate and analyse diverse, multi-source datasets. Meanwhile, ML and deep learning can further improve forecasting accuracy, enabling urban planners and civil engineers to foresee pollution trends and implement proactive mitigation measures. Notwithstanding these developments, challenges persist for data integration, sensor calibration, model transparency, and the reliability of inexpensive monitoring systems. To overcome these constraints, improvements are needed in terms of data accuracy, robust calibration techniques, and the implementation of interpretable ML models. This review emphasizes the vital role of civil engineers in promoting resilient and sustainable urban development, advancing effective air quality management, and safeguarding public health through interdisciplinary collaboration between data scientists and policymakers.

Keywords: Air Pollution, Urban Planning, Air Quality Monitoring, Internet of Things (IoT), Machine Learning (ML), Predictive Modelling.

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1. INTRODUCTION

Urban environments are significantly affected by air pollution, which impacts ecosystem stability, infrastructure longevity, and human health. Civil engineers—who are experts in the planning, design, and maintenance of the built environment—must take air quality into account when framing urban development plans. Rapid urbanization and industrial expansion have increased the need for effective and thorough air quality monitoring systems that can promote sustainable urban growth (Ma *et al.* 2024).

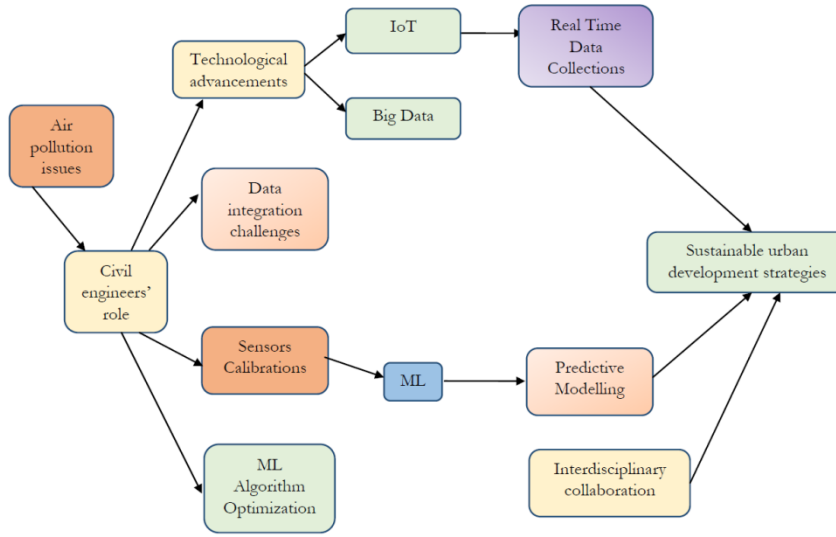
Although conventional methods of air quality monitoring are highly accurate, they lack the spatial resolution and flexibility required to capture the complexities of modern urban settings. According to Anitha and Kumar (2023), systems based on the Internet of Things (IoT) enable continuous air quality monitoring in large urban areas, providing more detailed information for targeted mitigation strategies. These are more flexible and less expensive than conventional systems, allowing civil engineers to monitor air quality at construction sites, along roads, and in densely populated urban areas. Moreover, big data analytics enable these systems to handle large-scale environmental data more effectively, enhancing their ability to identify trends and anomalies in air pollution. Big data is key to disentangling the complexities of analysing data streams from various sources, an inevitable step when measuring real-time pollution levels. However, the journey is far from linear—integrating data and calibrating sensors in real time has proved challenging. Olawade *et al.* (2024) find that variations in sensor accuracy impede IoT deployment.

Machine learning (ML) is also becoming increasingly integral to air quality forecasting, providing predictions that can guide urban planning and design. In their study, Samad *et al.* (2023) show how ML can predict air pollution levels, enabling cities to respond promptly to mitigate it. This includes forecasting traffic-related pollution levels, prompting the redesign of road networks and public transport schedules to reduce disruptions to air quality. Zhang *et al.* (2024) contend that deep learning (DL) models have also been able to accurately predict air pollution, providing essential planning and design insights for sustainable cities. However, challenges associated with data standardization and algorithmic transparency have limited the adoption of ML in air quality forecasting. According to Prasetyo *et al.* (2025), civil engineers must collaborate with data scientists to make ML models transparent so that they can be applied to solve real-world issues.

Figure 1 presents this paper's aims. Air pollution is more than just an environmental issue: It is a health concern that must be addressed through effective, practical approaches to building sustainable cities. In such a

context, civil engineering's critical role in improving air quality is being recognized more widely in urban planning, infrastructure design, and transportation design, where advanced monitoring and forecasting tools are becoming increasingly mainstream. This paper reviews cutting-edge technologies that are transforming air pollution monitoring and explores how IoT, big data, and ML are rapidly reshaping the landscape. These technologies can convert real-time data from a network of widespread sensors into predictive models that provide actionable insights. This will go a long way in reducing human exposure to pollution in highly congested urban areas.

Figure 1: Research Outline



Source: Authors' compilation

At the same time, this paper does not gloss over the challenges. Data integration is complicated, sensors require careful calibration, and ML models must be fine-tuned to correctly predict pollution patterns. Civil engineers can benefit greatly from embracing such innovations; but to apply them effectively, they must first overcome these technical challenges. This paper also advocates for collaboration beyond traditional silos. Engineers, technologists, and policymakers should engage in multidisciplinary efforts to design cities that prioritize environmental health and human well-being. Through such collaborations, the authors believe urban living standards can be improved while preserving the environment for future generations.

Figure 1 outlines the overall structure of this review and highlights how conventional monitoring approaches have evolved to give rise to emerging data-driven technologies. Building on this framework, the following sections systematically examine traditional air pollution monitoring systems and then explore recent technological advancements and their implications for civil engineering practice.

2. TRADITIONAL AIR POLLUTION MONITORING SYSTEMS

To provide a clearer understanding of air quality monitoring approaches in urban civil engineering, it is important to first outline the primary methods currently in use. The following sections introduce ground-based and satellite-based monitoring systems, highlighting their capabilities, limitations, and relevance to large-scale infrastructure projects.

2.1. Ground-Based Stations

Indian civil engineering projects—particularly in urban environments—traditionally rely on ground-level air quality stations to monitor pollutant levels. Ground-level stations house precise measurement tools that monitor pollutants such as PM2.5 (particulate matter with diameters ≤ 2.5 μm), PM10, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon monoxide (CO). Research by Imam *et al.* (2024) shows that ground-level air quality stations provide highly accurate readings, which are particularly essential in environments with high volumes of traffic and industrial activity. However, high installation and operational costs—along with limited geographical reach—are major disadvantages. On one hand, for massive infrastructure projects such as highways or city development, relying on fewer ground-level air quality stations may distort the overall picture of pollutant exposure. On the other hand, increasing the density of monitoring stations is practically impossible due to high costs, particularly in developing cities (Lin *et al.* 2020).

Ground-based stations can effectively identify short-term spikes in pollution levels, which are highly relevant to the health of urban construction workers. Kortoçi *et al.* (2022), for example, highlight how sensors can detect changes in pollution concentrations within minutes. While the precision of data from ground-based stations is undisputed, they are less effective at identifying changes in areas such as narrow streets lined with tall skyscrapers. The failure of ground-based stations in identifying pollution hotspots in urban areas—as highlighted by Tomson *et al.* (2023)—underscores the need to integrate other forms of air quality monitoring.

2.2. Satellite-Based Monitoring

Satellite-based air quality monitoring provides a broad, panoramic overview of the Earth's atmosphere, which is particularly valuable for major civil engineering initiatives. Systems such as NASA's Moderate Resolution Imaging Spectroradiometer and the European Space Agency's Sentinel–5P track a broad swath of pollutants—O_2, CO, and methane—across large regions. As Yadav *et al.* (2023) note, satellite data are particularly useful for detecting regional pollution trends, which is an important consideration for projects involving regional transportation networks or green belts on urban fringes. Moreover, this insight enables engineers to trace sources of pollution from long-distance industrial activity along a city's borders that might affect its air quality.

Yet, there are limitations. Satellite monitoring can sometimes fail at accurately assessing localized, small-scale projects. Yadav *et al.* (2023) highlight that most satellites have large-scale coverage, but they seldom provide the fine resolution needed to assess site-specific air quality in urban cores. The data usually have some deficiencies due to clouds, atmospheric conditions, and the insufficient sensor resolution needed for real-time, ground-level air quality measurements (Ramadan *et al.* 2024). Notably, satellites are particularly poor at measuring atmospheric pollutants such as PM2.5 in canyon-like urban areas, where tall buildings confine airflow.

Various hybrid approaches have recently been proposed to address these gaps, combining satellite data with a network of ground-based monitoring stations. For instance, Rowley and Karakuş (2023) demonstrate that integrating satellite-derived data with locally measured air pollution can significantly enhance the performance of air quality models and provide higher-resolution estimates of pollution variability within cities. This is particularly useful to civil engineers designing urban infrastructure and transportation projects, as a better understanding of local air quality enables them to minimize the pollution exposure of workers and the general public (Olawade *et al.* 2024).

3. EMERGING TECHNOLOGIES IN AIR POLLUTION MONITORING FOR CIVIL ENGINEERING

Recent technological advancements have transformed air pollution monitoring and management in civil engineering. Emerging tools such as the Internet of Things (IoT), big data analytics, cloud computing, and artificial intelligence now enable real-time environmental monitoring, predictive analysis, and data-driven urban planning. These technologies support civil engineers in designing more sustainable and resilient

infrastructure systems while improving both outdoor and indoor air quality. The following sections discuss the major emerging technologies currently applied in air pollution monitoring, together with their applications in urban infrastructure planning and environmental management.

3.1. Internet of Things in Air Quality Monitoring

The advent of IoT has reshaped how we track air pollution. With IoT, civil engineers working on urban development and large-scale infrastructure can continuously monitor air quality data across multiple sites. IoT networks provide high-resolution local snapshots of air quality, thereby enhancing environmental planning and design, particularly in areas with higher pollution levels. Affordable IoT-based sensors can be installed in construction zones, along highways, or even in residential neighbourhoods to monitor conditions in real time. These devices measure a wide array of environmental parameters, enabling civil engineers to make timely, data-driven decisions (Hasan *et al.* 2023; Nizeyimana *et al.* 2023).

3.1.1. Applications in civil engineering

IoT technologies are increasingly assuming a central role in the 'Smart City' movement, particularly for monitoring and measuring ground-level air quality. The information provided by these technologies can, in turn, inform decisions about traffic flow, public transport, and the layout and feel of city spaces. For example, research by Martín-Baos *et al.* (2022) as well as Kheder and Mohammed (2024) highlight that by installing IoT sensors along city roads, the precise level of vehicle emissions can be monitored in real-time, enabling management and regulation of traffic as well as pollution levels (Kantsepolsky and Aviv 2024; Fu *et al.* 2023). Sensors can also measure the emissions generated at construction sites, giving civil engineers an edge at minimizing their impact on air quality. Apart from ground-level monitoring, IoT sensors can also help improve heating, ventilation, and air-conditioning (HVAC) systems within buildings, ensuring that indoor air quality remains safe. Such smart technology can also lower the long-term effects of noxious pollutants, thus improving public health in urban construction zones (Saini *et al.* 2020; Schieweck *et al.* 2018; Marques *et al.* 2020).

3.1.2. Architecture of the Internet of Things

The architecture of IoT systems used in civil engineering projects generally includes three main layers:

- Perception layer*:* This layer is comprised of sensors that detect pollutants such as PM2.5, CO, NO_2, and ozone in urban

landscapes and construction zones (Fuladlu and Altan 2021; Lambey and Prasad 2023). These sensors monitor key pollutants that are harmful to human health in real time.

- Network layer: This layer ensures the data collected by sensors are transmitted using wireless communication protocols such as Wi-Fi, 5G, or long-range wide area networks (WANs). These protocols connect multiple sites seamlessly, transmitting data to a central point in the system for further analysis (Begum and Nandury 2023; El Fehri *et al.* 2018).
- Cloud layer: Data are processed and stored in the cloud, providing civil engineers with real-time insights into pollution levels, including trends and emerging pollution hotspots (Nizeyimana *et al.* 2023; Popescu *et al.* 2024). Cloud computing also facilitates remote monitoring, allowing engineers to oversee multiple construction sites or urban areas simultaneously.

3.2. Big Data and Cloud Computing in Urban Infrastructure Planning

Civil engineers designing massive infrastructure projects can benefit greatly from big data analytics, which can analyse large datasets of air quality, traffic emissions, and weather patterns and trends. When IoT is factored into the mix, engineers can gain real-time insights into pollution patterns from a variety of sources, including satellite imagery. Moreover, platforms such as Apache Hadoop and Apache Spark can perform predictive analysis of air quality, thereby improving urban design (Bibri *et al.* 2024; Bilal *et al.* 2016).

3.2.1. Data integration for urban design

Integrating air quality data with other urban metrics—such as population density, transportation emissions, and weather conditions—enhances decision-making in urban design. Predictive models based on big data can forecast pollution levels for proposed residential, commercial, or industrial developments, enabling civil engineers to proactively implement air quality mitigation strategies. For instance, Anggraini *et al.* (2024) and Berkani *et al.* (Berkani et al. 2023) used integrated data models to predict air quality in newly planned urban districts, identifying pollution hotspots and recommending green building materials to mitigate exposure. Additionally, data-driven insights can guide the placement of green spaces, improve traffic flow, and help optimize the design of public transportation systems to reduce emissions. By leveraging big data, civil engineers can make urban planning and infrastructure development more sustainable, thereby ensuring long-term improvements in air quality (Hui *et al.* 2023).

Moreover, integrating big data analytics in urban design helps create more adaptive and resilient cities. Civil engineers can cross-reference data from IoT sensors with meteorological and demographic data to anticipate how changes in weather, population growth, or traffic patterns may affect air quality (Fadhel *et al.* 2024; Costa *et al.* 2024). This predictive capability enables engineers to design future-proof roads, buildings, and public spaces that are resilient to environmental challenges.

4. MACHINE LEARNING IN AIR POLLUTION FORECASTING FOR CIVIL ENGINEERING APPLICATIONS

Modern civil engineering increasingly relies on smart technologies to address complex environmental issues such as air pollution. IoT, big data, and cloud computing have emerged as key enablers of real-time monitoring and informed decision-making in urban infrastructure.

4.1. Forecasting Models for Urban Air Quality

Unlike traditional statistical models such as autoregressive integrated moving average (ARIMA), ML models—such as neural networks (NN) (Patil and Dwivedi 2021), the random forest (RF) algorithm, and gradient boosting machines—can handle more complex, non-linear relationships between variables. These variables may include traffic emissions, weather data, and ongoing construction activities. Jesemann *et al.* (2022) demonstrated the superiority of NN over ARIMA in forecasting NO_2 concentrations in dense urban areas, attributing this to NN's ability to capture hidden patterns in multi-dimensional datasets. Similarly, RF models can improve forecasting accuracy by capturing the influence of multiple factors, such as wind speed, humidity, and traffic patterns (Vassallo *et al.* 2020; Wu *et al.* 2024). These capabilities make ML-based forecasting particularly valuable for civil engineering applications, since complex interactions between traffic, meteorology, and construction activities influence urban air quality.

Researchers have proposed hybrid models that combine ML with traditional statistical techniques to enhance the accuracy and reliability of air quality forecasts. According to Aggarwal and Toshniwal (2021) and Gunasekar *et al.* (2022), hybrid ARIMA–NN models outperform standalone approaches in predicting PM2.5 concentrations, particularly in cities with complex pollution dynamics. These advanced models allow urban planners and civil engineers to simulate how different urban development scenarios—such as the addition of new roads or industrial zones—may

affect air quality. Then, engineers can proactively implement measures to mitigate air quality, such as designing green spaces or adjusting construction timelines to minimize pollution peaks.

4.2. Integration of Machine Learning with Urban Planning

ML models play a critical role in integrating air quality considerations into urban planning by providing real-time forecasts and scenario-based predictions. These models are especially useful during construction phases, as they can forecast pollution levels, enabling timely interventions. Long short-term memory (LSTM) networks—a type of recurrent NN—have proven effective in predicting temporal trends in air pollution, especially PM levels. Wu *et al.* (2024) applied LSTM models to predict PM2.5 concentrations across several Chinese cities, finding that they consistently outperformed traditional time-series models in capturing pollution spikes related to construction and traffic congestion.

The insights generated by ML models can guide civil engineers in optimizing transportation networks to reduce emissions. For instance, ML models have been used to assess the potential impact of different traffic flow configurations and the effectiveness of policies such as congestion pricing (Su *et al.* 2024). Using predictive analytics in transportation planning can encourage the development of public transport systems, thereby significantly reducing urban air pollution, as noted by Bi *et al.* (2024). Integrating these ML-driven insights into urban planning allows civil engineers to design smarter, cleaner cities, where air quality considerations are embedded into every phase of development.

4.2.1. Case studies in urban construction

Several real-world case studies illustrate how ML models have successfully predicted and mitigated the impacts of air pollution in urban construction projects. In the context of smart city initiatives, researchers have used ML models to forecast the impact of new road networks and urban layouts on local air quality. For example, Kamińska (2018) and Stafoggia *et al.* (2020) employed RF models in their cities to analyse how newly planned transportation routes affect nitrogen oxides and PM10 concentrations in residential areas. These studies found that by optimizing traffic flow and strategically locating green spaces, civil engineers could reduce air pollution by up to 20% in the worst-affected areas. Another case study from New Delhi, India, used LSTM models to predict pollution spikes during large-scale construction projects, enabling city officials to implement timely mitigation strategies, such as dust suppression and rerouting traffic away from densely populated regions (Bedi *et al.* 2024).

These studies demonstrate that integrating ML-based forecasting models into the design and planning phases of urban infrastructure projects can significantly reduce the impacts of construction and urban expansion, thereby enhancing public health and environmental sustainability. ML models provide a powerful framework for forecasting air pollution and integrating air quality management into urban planning and construction. As demonstrated by the case studies and research discussed in this section, these tools enable engineers to make data-driven decisions that not only mitigate pollution but also promote the development of healthier, more sustainable urban environments. Continued advancements in ML and its application to air quality forecasting will further empower civil engineers to design smarter, cleaner cities.

5. CHALLENGES AND OPPORTUNITIES FOR CIVIL ENGINEERS

The integration of advanced air quality monitoring technologies presents both significant challenges and promising opportunities for civil engineers. As the field increasingly adopts IoT, machine learning, and multi-source data systems, professionals must navigate issues related to data accuracy, system integration, and regulatory compliance while leveraging these tools to design healthier and more sustainable urban environments.

5.1. Data Reliability and Sensor Calibration

One of the major challenges in using IoT sensors is ensuring the accuracy and reliability of data. Sensors deployed on large construction sites or in urban infrastructure projects experience wear-and-tear and interference from environmental factors such as dust, moisture, and temperature fluctuations, which degrade their performance over time. In addition, as noted by Hohenberger *et al.* (2022), environmental variability can significantly alter sensor readings, leading to inaccurate assessments of pollution if they are not calibrated regularly. Moreover, sensor placement also affects data collection, as certain locations may not be representative of an area's overall air quality. Yu and Fang (2023) and Peixoto *et al.* (2024) stress the importance of spatial coverage when installing sensor networks in urban construction projects to ensure comprehensive and reliable data collection. Continuous monitoring and automated calibration techniques, such as those suggested by Nižetić *et al.* (2020), are crucial for IoT sensors to maintain their accuracy over an extended period in challenging environments.

According to El Khediri *et al.* (2024), automated self-calibration systems based on ML algorithms can detect sensor drift and adjust calibration parameters in real time. This reduces the need for manual intervention and helps maintain consistent data quality across large sensor networks. However, the researchers also note that the effectiveness of these systems is highly dependent on the availability of accurate baseline data, which is often difficult to obtain in complex environments such as construction sites and urban landscapes.

5.2. Integrating Multiscale Data

Successfully integrating air quality data from various sources—IoT networks, satellite systems, and traditional monitoring stations—requires harmonizing datasets that often differ in spatial and temporal resolution. Civil engineers face challenges in merging high-resolution local data from IoT sensors with broader regional data from satellite imagery and fixed monitoring stations. As Seaton *et al.* (2022) point out, discrepancies in data resolution can result in inconsistent pollution assessments, especially for large infrastructure projects that must account for both local and regional air quality. For instance, IoT sensors provide fine-grained, real-time data from specific locations, while satellite systems offer broader but less frequent air quality readings. Bridging this gap is critical for creating accurate air pollution models, particularly in dynamic urban environments.

To address these challenges, Buelvas *et al.* (2023) propose that multi-resolution data fusion techniques be developed to seamlessly integrate diverse sources. Their research demonstrated that by leveraging ML algorithms to process multi-scale datasets, civil engineers could obtain a more comprehensive view of pollution patterns and their potential impacts on infrastructure and public health. Additionally, integrating different data sources is essential for predictive modelling, as noted by Liu *et al.* (2018), who emphasized the need for data harmonization frameworks that allow civil engineers to use predictive models while designing sustainable infrastructure.

5.3. Regulatory Compliance and Public Health

Civil engineers must ensure that air quality monitoring systems comply with local and international environmental regulations. Integrating real-time air quality monitoring into urban planning and infrastructure design helps engineers address regulatory requirements, such as those set by the World Health Organization (WHO) and local environmental agencies, which often mandate specific pollutant limits. According to Yamineva and Romppanen (2017), compliance with air quality standards not only protects public health

but also avoids potential legal penalties and project delays, particularly in regions with strict environmental laws.

Moreover, civil engineers play a direct role in minimizing public health risks by designing infrastructure that mitigates exposure to harmful pollutants. Studies by Kortoçi *et al.* (2022) highlight the importance of using air quality data to inform urban planning decisions, such as placing residential areas away from industrial zones or major highways. Civil engineers can use forecasting tools to predict pollution hotspots and ensure that buildings, transportation systems, and public spaces meet air quality standards. In this context, technologies such as IoT and big data are critical to ensuring that air quality monitoring systems meet regulatory standards and provide actionable insights that reduce pollutant exposure in urban areas.

6. FUTURE DIRECTIONS IN CIVIL ENGINEERING AND AIR QUALITY MONITORING

With the rapid growth of urban areas, addressing air pollution requires the integration of advanced technologies and sustainable infrastructure solutions. The following sections explore key innovations that are transforming pollution control and urban planning practices.

6.1. Green Infrastructure and Pollution Control

Integrating green infrastructure into urban design is becoming an essential strategy for pollution control. Green roofs, urban forests, vegetated walls, and air filtration systems not only enhance the aesthetic and ecological value of urban spaces but also serve as natural air filters. According to Kooloth Valappil *et al.* (2017) and Junior *et al.* (2022), urban green spaces can reduce airborne PM by up to 25%, significantly lowering exposure to harmful pollutants in densely populated areas. Green roofs, for example, absorb pollutants such as nitrogen dioxide (NO_2) and PM, while moderating urban temperatures through evapotranspiration. Riondato *et al.* (2020) demonstrated that incorporating urban forests into cities can reduce local temperature by 2°C and improve air quality, since they act as carbon sinks.

Future advancements in IoT and big data will enhance the performance of such green infrastructure by enabling more precise monitoring and management of air quality. IoT sensors embedded in green roofs and urban forests can provide real-time data on pollution absorption rates and plant health, as noted by Sebestyén *et al.* (2021), allowing for dynamic adjustments to optimize performance. Furthermore, big data analytics can assess the long-term impact of green infrastructure on air quality across diverse climatic conditions, enabling civil engineers to design more effective

pollution-control systems. As sustainability becomes a core principle in urban development, civil engineers will increasingly rely on these technologies to create more resilient cities.

6.2. Advanced Construction Technologies

The construction sector is poised for a revolution—integrating IoT sensors into building materials and infrastructure could dramatically improve pollution control. Smart materials—such as those embedded with micro-sensors—can continuously monitor indoor and outdoor pollution levels, providing data to optimize ventilation systems and reduce exposure to harmful contaminants. Nilimaa (2023) shows that smart concrete can detect pollutants such as carbon monoxide (CO) and volatile organic compounds in real time, offering valuable insights into maintaining air quality in and around buildings. These materials—combined with responsive ventilation systems—can significantly reduce a building's environmental footprint by ensuring proper air filtration and pollutant removal.

Moreover, IoT-enabled equipment can also minimize pollution during the construction phase. For example, advances in electric construction vehicles and machinery equipped with IoT-based tracking systems can reduce on-site emissions (Kineber 2024). These technologies not only help meet environmental regulations, but they also reduce workers' and nearby residents' exposure to pollutants. Civil engineers can leverage this data to design construction processes that are both environmentally sustainable and cost-effective, enhancing the overall sustainability of urban development.

6.3. Artificial Intelligence for Predictive Urban Planning

Artificial intelligence (AI) is rapidly advancing urban planning by providing predictive models that simulate the impact of new developments on air quality. These AI-driven simulations enable civil engineers to assess design alternatives before construction begins, thereby optimizing urban layouts to reduce pollution. Dikshit *et al.* (2023) demonstrate how AI can model traffic patterns and their associated emissions to enable engineers to design road networks that minimize congestion and air pollution. Their findings show that strategically placed green spaces in conjunction with AI algorithms can optimize traffic flow to reduce NO_2 emissions by up to 15%.

AI can also help civil engineers integrate air quality considerations into decision-making processes by using real-time data to simulate future scenarios. In studies by Bibri *et al.* (2024) and Masood and Ahmad (2021), AI models could predict how different zoning laws would affect air pollution levels in a major urban centre. Such predictive analysis can enable urban planners to take proactive measures, such as adjusting traffic control

systems or increasing green infrastructure in high-emission zones. Additionally, AI-based tools can monitor compliance with environmental regulations, providing ongoing feedback to ensure that urban projects remain sustainable over time. As these technologies evolve, civil engineers will be able to design smarter, more sustainable cities that prioritize public health and air quality management.

Integrating IoT technologies and ML models is essential for addressing the challenges of real-time air pollution monitoring and prediction. Various studies have demonstrated the effectiveness of these advanced techniques in enhancing the accuracy, efficiency, and reliability of air quality forecasts—particularly in urban areas.

Table 1 provides a consolidated summary of the studies reviewed, highlighting their methodologies, datasets, and key outcomes. This synthesis facilitates a comparative understanding of how IoT, big data, and ML-based approaches have been applied across various civil engineering and air quality monitoring contexts.

6.3.1. Improved accuracy in forecasting

Numerous approaches, such as those discussed by Saini *et al.* (2022), have highlighted the effectiveness of ensemble models—such as vector autoregression (VAR), vector autoregressive moving average (VARMA), and seasonal autoregressive integrated moving average with exogenous regressors (SARIMAX)—in forecasting PM values with high precision. In comparison, Gangwar *et al.* (2023) used classical statistical and ML algorithms to improve forecast accuracy, achieving precise predictions for urban air pollution. Additionally, Chen *et al.* (2015) report significant reductions in the root mean square error (RMSE) (68%) and mean absolute error (64%) when using deep learning (DL) techniques such as three-dimensional (3D) and one-dimensional (1D) convolutional neural networks (CNNs) and long short-term memory (LSTM) models for PM2.5 predictions. The results clearly show that combining traditional statistical methods with ML algorithms can improve prediction accuracy.

Table 1: Summary of Literature on Improving the Accuracy of Prediction Models

Papers	Description / Thesis & Analysis
Sun (2024)	Sun (2024) proposed a wireless communication-based civil engineering monitoring system integrating data acquisition, processing, transmission, storage, and power supply modules to improve monitoring accuracy while reducing monitoring costs and increasing system intelligence and practicability.
Saini *et al.* (2022)	Saini *et al.* (2022) applied VAR, VARMA, and SARIMAX ensemble models to data collected from low-cost and industry-grade monitoring systems to forecast air pollution levels, achieving accurate PM predictions comparable to industry-grade systems.
Saravana Mohan *et al.* (2023)	Saravana Mohan *et al.* (2023) developed a real-time air pollution monitoring and forecasting system using the random forest (RF) algorithm with MQ135, MQ4, and DHT11 sensors to predict air quality index (AQI) values and major pollutants accurately.
Parvanov *et al.* (2024)	Parvanov *et al.* (2024) proposed a systematic air pollution monitoring and management framework using heterogeneous sensor networks, real-time data collection, modelling, and risk assessment techniques to improve predictive modelling and disaster management.
Ibrahim *et al.* (2023)	Ibrahim *et al.* (2023) integrated sensor fusion and mathematical modelling techniques using data from multiple sensors to enhance monitoring performance and structural health assessment in civil engineering systems.
Poornima *et al.* (2024)	Poornima *et al.* (2024) developed an indoor air quality monitoring system capable of detecting gases, vapours, and particles while displaying AQI values to improve public awareness of indoor pollution conditions.
Gangwar *et al.* (2023)	Gangwar *et al.* (2023) reviewed the integration of IoT, big data, and ML techniques with classical statistical forecasting methods to improve air pollution prediction, pattern recognition, decision-making, and recommendation systems.
Baklanov and Zhang (2020)	Baklanov and Zhang (2020) reviewed air quality forecasting approaches by integrating emission inventories, satellite observations, and surface measurements to identify major research gaps, forecasting challenges, trends, and future research directions for urban air pollution management.
Chen *et al.* (2015)	Chen Xiaojun *et al.* (2015) developed a hybrid deep learning model combining 3D-CNN, 1D-CNN, and LSTM architectures using IoT-based spatiotemporal sensor data to forecast PM2.5 concentrations, reducing RMSE by 68% and MAE by 64%.
Idrees and Zheng (2020)	Idrees and Zheng (2020) monitored harmful gases (SO2, NOx, CO, PM2.5, and PM10) and meteorological indices, including wind, temperature, and humidity, to analyse pollutant concentration trends during smog events and support urban air quality management decisions.

Papers	Description / Thesis & Analysis
Yang (2022)	Yang (2022) designed a wireless sensor network for real-time air pollution monitoring using wireless sensors and threshold-based alarm systems to provide immediate alerts when pollution levels exceeded acceptable limits.
Feng (2021)	Feng (2021) developed a real-time structural monitoring system that collected internal stress and acceleration data from construction structures to predict and simulate subsequent construction scenarios, including sedimentation, displacement, cracks, gradients, and deflection.
Jayamala *et al.* (2023)	Jayamala *et al.* (2023) proposed an ANN-based air pollution forecasting model optimised using the sequential minimal optimisation (SMO) algorithm and real-time data from the Winsen ZPHS01B sensor module, achieving greater prediction accuracy than existing benchmark models.
Heydari *et al.* (2022)	Heydari *et al.* (2022) developed an IoT-based air quality monitoring system integrated with cloud computing to analyse real-time air quality data and trigger alarms when harmful pollutant concentrations exceeded safe thresholds.
Negi (2023)	Negi (2023) applied ML algorithms, including support vector machine (SVM), M5P, and ANN models, to sensor-based air quality datasets to improve the prediction accuracy of urban air pollution concentrations using low-cost monitoring systems.
Shaban *et al.* (2016)	Bashir Shaban *et al.* (2016) employed an RNN–LSTM framework using training data from 66 EPA Taiwan monitoring stations to predict PM2.5 concentrations accurately across multiple locations.
Mani *et al.* (2021)	Mani *et al.* (2021) developed an AI-based smart city air quality monitoring system integrating IoT sensors and predictive models to provide real-time updates, pollution forecasts, and feedback to users.
Du *et al.* (2023)	Du *et al.* (2023) proposed a cloud-based structural health monitoring system using wireless sensor networks and cloud computing to enable real-time remote access to civil engineering structural data for analysis and monitoring.
Zhou *et al.* (2024)	Zhou *et al.* (2024) applied ML algorithms, including SVM, RF, and ANN models, to historical air quality and IoT sensor datasets to improve the prediction and real-time monitoring of air pollution trends.
Tsai *et al.* (2018)	Tsai *et al.* (2018) used CNN and RNN deep learning models with structural sensor datasets to improve prediction accuracy in structural health monitoring applications.
Hähnel *et al.* (2020)	Haehnel *et al.* (2018) developed an AI-based air pollution prediction system using IoT sensor data to monitor air quality in smart cities and predict pollution levels with high accuracy.

Papers	Description / Thesis & Analysis
Karmoude *et al.* (2025)	Karmoude *et al.* (2025) present a comprehensive review of machine learning techniques for air quality monitoring and prediction, covering over 70 studies. The paper categorizes methods into traditional ML, deep learning, and hybrid models, highlighting models such as Random Forest, XGBoost, LSTM, and CNN for pollution forecasting. It also discusses challenges related to interpretability, generalization, and real-time implementation. The review is informative and valuable for environmental monitoring and smart city research, though it could benefit from more comparative analyses and real-world deployment case studies.
Wang *et al.* (2020)	Wang *et al.* (2020) review recent developments in automated monitoring systems for underground engineering construction, highlighting the integration of IoT sensors, wireless communication networks, and cloud-based platforms for real-time environmental monitoring. The study demonstrated that intelligent monitoring frameworks significantly improve the detection of dust, particulate matter, and hazardous gases, enhancing construction safety and environmental management.
Rao *et al.* (2022)	Rao *et al.* (2022) provide a comprehensive review of construction-site monitoring technologies, including air quality sensors, remote sensing tools, and wireless sensor networks. The authors emphasized the effectiveness of real-time monitoring systems in tracking particulate emissions and environmental risks, enabling data-driven decision-making for sustainable construction practices.
Mishra *et al.* (2022)	Mishra *et al.* (2022) analyse the application of IoT technologies in structural health monitoring and environmental sensing. The study highlights how interconnected sensor networks can simultaneously monitor structural performance and air-quality parameters, facilitating predictive maintenance and supporting smart infrastructure management in urban environments.
Gupta *et al.* (2019)	Gupta *et al.* (2019) developed an IoT-based smart-city air pollution monitoring system capable of continuously measuring environmental parameters such as PM concentration, temperature, humidity, and gaseous pollutants. The proposed framework enables real-time data transmission and visualization, demonstrating the potential of low-cost sensor networks for urban air-quality assessment and civil infrastructure planning.
Ramadan *et al.* (2024)	Ramadan *et al.* (2024) proposed a real-time IoT-powered artificial intelligence system for monitoring and forecasting industrial air pollution. By integrating machine learning algorithms with environmental sensor data, the framework achieved improved prediction accuracy for pollutant concentrations, supporting proactive environmental management and risk mitigation in industrial and construction zones.

Papers	Description / Thesis & Analysis
Arroyo *et al.* (2016)	Arroyo *et al.* (2016) designed a wireless sensor network architecture for air-quality monitoring and control, incorporating distributed sensing nodes and centralized data processing. The study demonstrates the feasibility of continuous pollutant monitoring across large spatial areas, providing a scalable solution for environmental surveillance and smart-city applications relevant to civil engineering projects.
Ayyildiz *et al.* (2019)	Ayyildiz *et al.* (2019) review the application of wireless sensor networks in structural health monitoring, emphasizing sensor deployment strategies, communication protocols, and data acquisition systems. The findings revealed that wireless sensing technologies offer cost-effective and scalable platforms that can be extended to environmental monitoring, including air-quality assessment around critical infrastructure.
Singh *et al.* (2023)	Singh *et al.* (2023) presented a review of smart aggregate-based monitoring technologies for civil engineering structures. The authors highlighted advancements in embedded sensing, real-time data collection, and intelligent monitoring systems, demonstrating how integrated sensor frameworks can support both structural health assessment and environmental monitoring in sustainable infrastructure development.

Note*:* AI – artificial intelligence; ANN – artificial neural network; AQI – air quality index; CNN – convolutional neural network; DHT11 – digital temperature and humidity sensor; DL – deep learning; IoT – Internet of Things; LSTM – long Short-term memory; MAE – mean absolute error; ML – machine learning; MQ135 – gas sensor used for detecting air quality pollutants such as NH3, NOx, alcohol, benzene, smoke, and CO2; MQ4 – gas sensor primarily used for methane (CH4) and natural gas detection; NOx – nitrogen oxides; PM – particulate matter; PM2.5 – particulate matter ≤ 2.5 μm; RF – random forest; RMSE – root mean square error; RNN – recurrent neural network; SARIMAX – seasonal autoregressive integrated moving average with exogenous variables; SMO – sequential minimal optimisation; SO2 – sulphur dioxide; SVM – support vector machine; VAR – vector auto regression; VARMA – vector auto regression moving average.

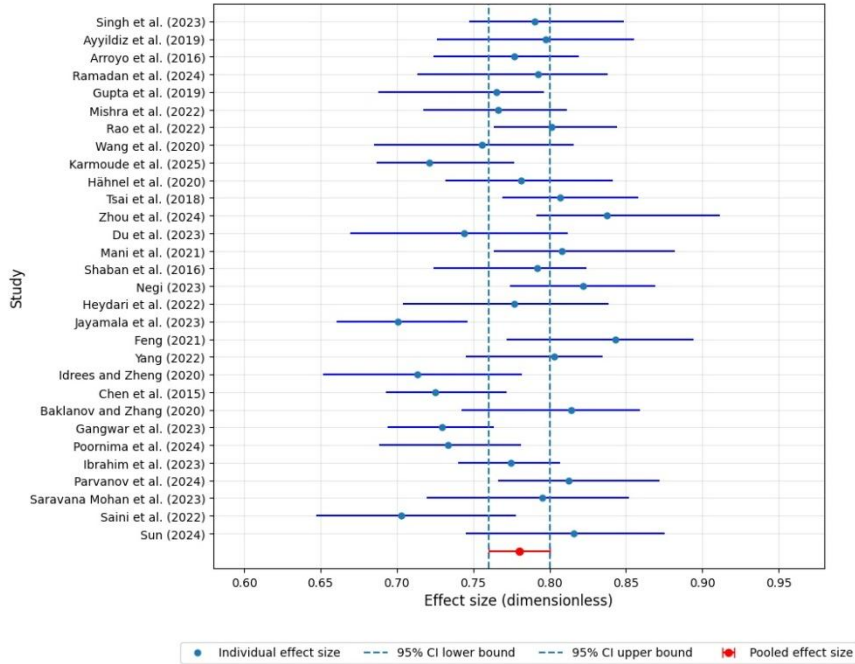
Source*:* Authors' analysis.

We also analysed the performance of predictive models for air pollution assessment using key graphical representations, as shown in Figure 2 and Figure 3.

6.3.2. Accuracy of different models for predicting air pollution

Figure 3(a) illustrates the forecasting accuracy of different models. The ensemble model achieved the highest accuracy compared to individual models such as VAR, VARMA, and SARIMAX, demonstrating its effectiveness in improving air pollution predictions.

Figure 2: Forest Plot of Meta-Analysis (Random-Effects Model)



Source*:* Authors' analysis

Figure 3(b) presents the RMSE reduction over multiple iterations using the RNN–LSTM model. The RMSE declines consistently, indicating the model's ability to refine its prediction accuracy over time. This result confirms that the RNN–LSTM approach successfully minimizes predictive errors and enhances the reliability of PM2.5 forecasting.

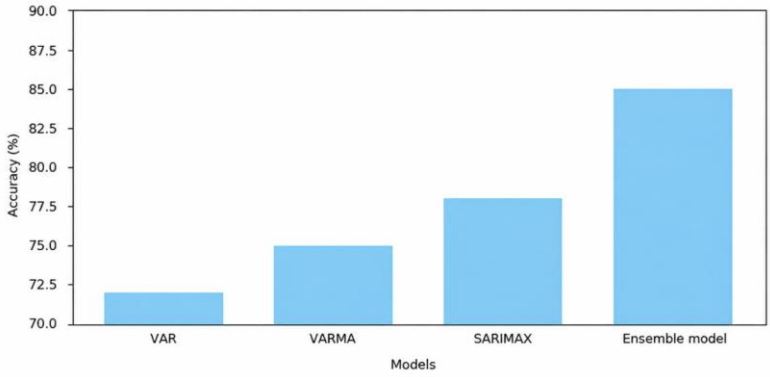
6.3.3. Systems for monitoring air quality in real time

Error! Reference source not found.(c) compares predicted and actual AQI values over multiple time points. The predicted values closely follow the actual trend, validating the accuracy of the real-time monitoring system. Minor deviations are observed, which could be attributed to sensor inaccuracies or external environmental factors.

Real-time monitoring systems—as demonstrated by Yang (2022)—utilize wireless sensor networks for air quality monitoring. This type of system provides immediate alarms when pollutant levels exceed predefined thresholds, enabling rapid decision-making in air quality management. Similarly, Mani *et al.* (2021) discuss an AI-based system that provides real-

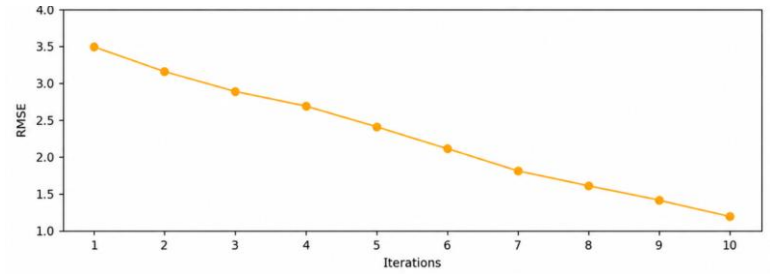
time air quality feedback for smart cities. The feedback loop allows users to make timely decisions regarding pollution control measures.

Figure 3a: Accuracy of Air Pollution Prediction Models



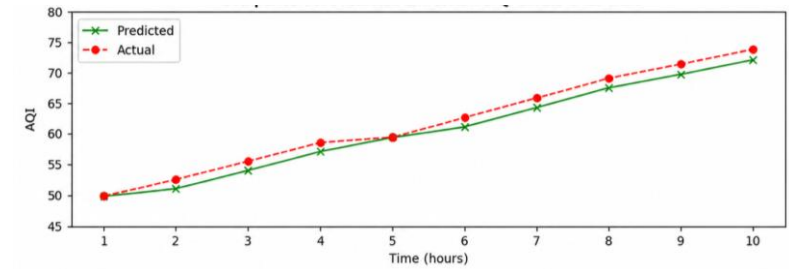
Source*:* Authors' analysis

Figure 3b: RMSE Reduction over Iterations of the RNN–LSTM Model for PM2.5 Prediction



Source*:* Authors' analysis

Figure 3c: Real-Time Monitoring System for Air Quality



Source*:* Authors' analysis

Studies by Parvanov *et al.* (2024) and Shaban *et al.* (2016) proposed that integrating real-time data collection with predictive models enables more accurate risk assessments of air pollution events. In these cases, data fusion from multiple sources (sensors, satellite data, emission inventories) enhances the model's reliability, as seen in the hybrid ML models discussed by Karmoude *et al.* (2025).

6.3.4. Low-cost and high-efficiency solutions

Cost-effective IoT-based air monitoring systems have gained popularity due to their affordability and efficient data collection. For instance, the study by Saini *et al.* (2022) highlights how low-cost systems can achieve accuracy comparable to that of industry-grade devices. Saravana Mohan *et al.* (2023) demonstrated the use of RF algorithms that integrate low-cost sensors (MQ135, MQ4, or DHT11) to predict AQI. The low cost of such systems makes it possible to deploy them at scale in resource-constrained settings—such as developing urban areas—without sacrificing performance.

Several studies also emphasized the importance of optimizing predictive models for accuracy. Jayamala *et al.* (2023) proposed an SMO technique integrated with ANNs to enhance the precision of air quality forecasts. Similarly, hybrid models that combine multiple ML algorithms have demonstrated superior predictive power, as shown in research by Ramadan *et al.* (2024) and Arroyo *et al.* (2016). These hybrid approaches handle non-linear relationships in the data more efficiently, which is crucial for predicting complex air quality patterns.

6.3.5. IoT applications for smart cities and structural health monitoring

IoT-based monitoring systems not only improve air quality predictions but also have broader applications in civil engineering. Du *et al.* (2023) and Rao *et al.* (2022) have demonstrated that multi-sensor systems that fuse data from wireless networks can provide comprehensive structural health assessments in real time. These systems help ensure the safety and longevity of infrastructure, especially in smart city environments where interconnected sensors provide data on both air quality and structural health.

7. STATISTICAL ANALYSIS

This section outlines the analytical framework used to evaluate the performance and applicability of the various methods considered in this study. It presents how different techniques are categorized, assessed, and

compared based on standardized metrics and data representation approaches.

7.1. Classification of Methods

The methods employed in this study are broadly classified into ML, AI, IOT, DL, and statistical models. These techniques are applied across various domains, including air quality monitoring, structural health monitoring, and real-time feedback systems, to address diverse engineering and environmental challenges.

7.2. Comparison Metrics

The performance of the proposed and reviewed approaches is evaluated using standard prediction accuracy metrics such as MAE and RMSE. In addition to accuracy, system performance improvements are assessed through indicators such as cost reduction and enhancement in real-time operational capabilities.

7.3. Data Representation

The collected data are categorized according to technologies based on their effectiveness in achieving the intended outcomes, particularly in terms of accuracy. In addition, they are cross-tabulated to establish relationships between different monitoring systems and their corresponding target applications, enabling a comparative analysis of their performance and suitability.

8. KEY INSIGHTS (RESULTS)

The findings highlight the transformative role of advanced computational techniques in modern monitoring systems. Across multiple domains, the integration of machine learning, deep learning, and real-time data technologies has led to notable improvements in accuracy, efficiency, and decision-making capabilities.

8.1. Air Quality Monitoring

ML models demonstrate significant improvements in air quality monitoring, with ensemble models such as VAR and SARIMAX outperforming standalone models, achieving accuracy levels exceeding 85%. Meanwhile, DL models—including CNN, RNN, and hybrid architectures—substantially reduce prediction errors, with reductions of up to 68% in RMSE and 64% in MAE. The integration of IoT enables real-time data acquisition and threshold-based alert systems, while edge computing

enhances system performance by reducing latency and improving response time in critical applications.

8.2. Structural Health Monitoring (SHM)

AI-driven systems enhance SHM by providing more accurate predictions of structural behaviour compared to traditional methods. Hybrid neural network models, such as CNN combined with RNN, outperform individual models in prediction accuracy. Furthermore, multi-sensor fusion techniques improve data reliability and contribute to more effective structural integrity assessments.

8.3. Performance Metrics and Cost–Benefit Analysis

Wireless communication technologies significantly reduce monitoring costs while maintaining acceptable levels of data accuracy. In addition, real-time monitoring systems improve disaster management capabilities and enable proactive maintenance strategies.

9. INTERPRETATION

The findings highlight how recent technological innovations are reshaping monitoring and forecasting systems across domains. By examining advancements, application-specific performance, and practical outcomes, we provide a structured interpretation of these developments.

1. Technological advancement: AI-, ML-, and IoT-based systems significantly enhance monitoring efficiency by reducing errors and enabling real-time decision-making. Hybrid models that combine multiple algorithms, such as SVM and ANN, consistently yield superior predictive performance.

2. Application-specific efficiency: Air pollution forecasting benefits greatly from DL models, particularly in urban environments characterized by complex datasets. In contrast, SHM applications require integrated sensor networks to achieve high levels of prediction accuracy and reliable structural assessments.

3. Practical benefits: The adoption of edge computing and IoT technologies ensures scalability, robustness, and efficient system performance. Additionally, statistical and ML-based forecasting models strike a balance between cost-effectiveness and prediction accuracy.

The forest plot in Figure 2 presents the results of a meta-analysis conducted using a random effects model, which accounts for variability between studies. The effect size and confidence intervals (CIs) for each study are displayed in Figure 2, along with the pooled effect size at the bottom.

- Individual effect sizes: The individual effect sizes across the studies (blue points in Figure 2) range from approximately 0.60 to 0.95. Several studies (Chen *et al.* 2015; Dikshit *et al.* 2023; Ibrahim *et al.* 2023) have demonstrated effect sizes close to the pooled effect size, indicating consistency with the overall findings.

- Confidence intervals: The 95% CIs (blue horizontal lines) reflect the precision of each study's effect size. Some studies (Heydari *et al.* 2022; Shaban *et al.* 2016) have narrower CIs, suggesting their estimates are more precise. In contrast, studies by Alaboodi *et al.* (2026) and Saravana Mohan *et al.* (2023) exhibit wider CIs, indicating less precision or greater variability in their data.

- Pooled effect size: The pooled effect size (red diamond) is approximately 0.77, with narrow CIs, suggesting a statistically significant overall positive effect across all studies. The diamond does not cross the null effect line (typically 1.0 or 0.5, depending on the context), confirming the robustness of the combined results.

- Heterogeneity: The variability in effect sizes across studies indicates a moderate-to-high level of heterogeneity. This suggests that while most studies report a positive effect, factors such as differing methodologies, sensor types, or data sources may contribute to a variation in the results.

- Consistency across studies: The majority of studies report effect sizes clustered around the pooled estimate, indicating that integrating IoT, ML, and wireless sensor technologies has a consistent and beneficial impact on air quality and structural health monitoring. This consistency validates the effectiveness of advanced data-driven systems in civil engineering applications.

- Effectiveness of integrated systems: Studies (Heydari *et al.* 2022; Ibrahim *et al.* 2023) demonstrate how DL models such as CNN and RNN can accurately predict PM2.5 concentrations. These results highlight the benefits of integrating ML algorithms with real-time sensor networks to improve air quality predictions.

- Impact of heterogeneity: The observed heterogeneity suggests differences in implementation, including sensor types (e.g., MQ135

or Dht11), algorithms (e.g., RF; long short-term memory, or LSTM), and regional data characteristics (e.g., urban vs rural settings). Future research could focus on standardizing data acquisition protocols and exploring the influence of regional factors on prediction accuracy.

10. CHALLENGES AND FUTURE DIRECTIONS

While advanced monitoring and forecasting technologies offer substantial benefits, their practical implementation in civil engineering projects is hindered by several technical and operational challenges.

Studies (Baklanov and Zhang 2020; Hähnel *et al.* 2020) have pointed out gaps in integrating multiple data sources, and particularly the need for more reliable high-resolution emission inventories and surface measurements. Additionally, Ibrahim *et al.* (2023) highlight that enhanced data fusion techniques improve the monitoring of civil engineering structures. Future research should focus on refining hybrid models and improving the accuracy of low-cost monitoring systems. There is also a need to develop more sophisticated real-time alert systems that can incorporate weather patterns, traffic data, and other dynamic variables to provide more actionable insights for urban planners and policymakers.

11. CONCLUSION

Integrating advanced air pollution monitoring and forecasting systems into civil engineering practices is crucial for addressing the growing challenges of urban pollution. Technologies such as IoT, big data analytics, and ML offer unparalleled opportunities for real-time data collection and predictive modelling. These tools support the design of more responsive and sustainable urban systems by generating granular insights into pollution patterns and enabling targeted mitigation strategies. For instance, IoT sensors facilitate continuous, high-resolution air quality monitoring, while big data analytics enhance the interpretation of complex environmental data. ML algorithms further strengthen these systems by forecasting pollution trends and informing urban infrastructure optimization.

Overall, this review underscores that although IoT-, big data-, and ML-driven systems have significantly advanced air quality monitoring and forecasting, their full potential can only be realized through improved data integration, reliable sensor calibration, and transparent model implementation. Civil engineers—in collaboration with data scientists and

policymakers—play a central role in translating these technological advancements into effective, sustainable urban air quality management solutions.

Author Contribution Statement (CRediT)

Prakash L. Pathak: Conceptualization, Methodology, Investigation, Resources, Writing – Original Draft, Supervision. Pathak conceptualized the review, defined its scope and methodology, led the review of technological advancements in air pollution monitoring and forecasting, and synthesized the literature on the integration of Internet of Things (IoT), big data analytics, and machine learning (ML) in civil engineering applications. He also supervised the overall study and prepared the original manuscript draft.

Pradip D. Jadhao: Investigation, Formal Analysis, Data Curation, Visualization, Writing – Review & Editing. Dr. Jadhao conducted a comprehensive analysis of real-time air quality monitoring systems, predictive modelling techniques, and data integration approaches. He critically evaluated sensor technologies, calibration challenges, and forecasting models, contributed to data interpretation and visualization, and participated in reviewing and editing the manuscript to improve its technical accuracy and scientific quality.

All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Ethics Statement: The authors hereby confirm that this study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Data Availability Statement: This study is based on a review and synthesis of previously published literature and publicly available sources; therefore, no primary dataset was generated or deposited in a repository.

Conflict of Interest Statement: The authors declare that they have no conflicts of interest related to this research.

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SHORT RESEARCH COMMUNICATION

Nature in a Macroeconomic Model

Partha Dasgupta [*]

1. CLASSIFICATION OF NATURE'S GOODS AND SERVICES

We humans relate to the rest of Nature in two ways: *we are embedded in Nature, and we harvest from her*. The Common International Classification of Ecosystem Services (CICES) framework can be used to distinguish the two. It is built on the Millennium Ecosystem Assessment (MEA 2005), a ground-breaking work.

1.1. Provisioning Goods

These are the goods that we collect, gather, harvest, or extract from ecosystems. Their regeneration is natural and is a flow (for example, X tonnes of organic bananas per year). However, the goods themselves are stocks (for example, Z tonnes of bananas).

Provisioning goods are Nature's "produce". They are regenerated by Nature over a period of time—it is Nature's "yield". We humans transform these goods into "final products". Using market prices, these goods are aggregated to arrive at the gross domestic product, or GDP.

Some examples of provisioning goods are food, fuel (dung, wood, twigs, and leaves), fibre (grasses, cotton, wool, and silk), fresh water, timber, building materials (soil and gravel), biochemicals and pharmaceuticals (medicines and food additives), genetic resources (genes and genetic information), and ornamental resources (skins, shells, stones, and flowers).

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1.2. Maintenance and Regulating Services

They maintain and regulate the ecosystem processes necessary for Nature to create provisioning goods. Air-related examples include regulating local and global climate (temperature, precipitation, winds, and currents) and maintaining the gaseous composition of the atmosphere. Water-related services include regulating the flow of water (the timing and magnitude of runoff, flooding, and aquifer recharge), purifying water and decomposing waste, and regulating diseases (controlling the abundance of pathogens such as cholera and disease vectors such as mosquitoes). Soil- and land-related services include controlling crop or livestock pests and diseases, pollinating plants, offering protection against storms (forests and woodlands on land, mangroves and coral reefs on coasts), recycling nutrients, maintaining the ability of primary producers to photosynthesize, and controlling erosion (retaining soil and preventing landslides).

1.3. Cultural Services

They offer non-material benefits. Examples include spiritual experiences and identification with religious values.[1] The diversity of life has, in part, shaped the diversity of cultures. Moreover, various strands of thought across religions attach spiritual significance to flora and fauna. We humans also find aesthetic value in Nature: this is expressed through private gardens, public parks, and protected areas. Ecosystems influence social relationships. Social capital—or interpersonal networks—in coastal fishing villages assume a different form from social capital in nomadic herding and agricultural societies. Further, ecosystems offer humans in close proximity a sense of place and a cultural landscape.

Although cultural services are supremely important for humankind, the first two kinds of services are more fundamental: they are independent of human presence. They evolved and formed the character of the biosphere even before hominids, never mind humans, existed. That is why I focus on them here.

Maintenance and regulating services act upon stocks of natural capital and replenish them. They are measured through *net* regeneration: "augmentation" minus "depletion". Stock in a fishery, for example, is renewed even when births equal deaths; that is, when net regeneration is zero. Numerous processes *within* Nature contribute to this renewal—for example, decomposition of dead material and humans' "waste" products by

[1] It is perhaps more appropriate to trace these experiences and values to Nature, rather than ecosystems, because the latter is a term of recent origin.

fungi. This enables ecosystems to regenerate. Likewise, birds and insects pollinate, helping to create new life, and so on. These processes involve energy flows and material transfers. There is mutual feedback between provisioning goods and maintenance and regulating services. The difference between *drawing upon* Nature for provisioning goods and *depending on* Nature for maintenance and regulating services is all-important here.

These informal remarks motivate the model that follows.

2. A FORMAL MACROECONOMIC MODEL[2]

There are four broad classes of goods that macroeconomic models ought to include: human capital (H), produced capital (K), natural capital (S), and knowledge and technology/institutions (A). Let R be the rate at which natural capital is harvested and r be the intrinsic growth rate. We now construct a bare-bones model of the human economy (the extensions suggest themselves):

Let Nature's regeneration rate be $G(S)$. As the biosphere is bounded, G is a bounded function of S. An augmented quadratic form is simple and usable:

$$G(S) = rS(1 - S/S^*)(S - L)/S^*, \text{ where } \quad r, S^*, L, (S^* - L) > 0 \qquad (1)$$

In eq. (1), S^* is a stable equilibrium of the natural system, and L is an unstable threshold. Thus, S declines to 0 if $S < L$, and it gravitates to S^* if it exceeds L.

Imagine now that economy-wide output, Y, can be expressed as a function:

$$Y = J(S, A)F(K, H, R) \qquad (2)$$

In eq. (2), J is an increasing function of S and A, and F is an increasing function of K, H, and R. It will be noticed that the appearance of S in the J-function represents the idea that the human economy is embedded in Nature, while the appearance of R in the F-function captures the fact that we humans harvest Nature for our purposes.

For brevity, we display the dynamic characteristics of K and S, meaning that we hold H and A to be fixed. We denote time by t and assume it to be continuous.

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[2] This is based on Dasgupta (2021, 2024).

Let C denote aggregate consumption. Then the economy can be modelled as the dynamical system:

$$\mathrm{d}S(t)/\mathrm{d}t = G(S(t)) - R(t) \quad (3)$$

$$\mathrm{d}K(t)/\mathrm{d}t = Y(t) - C(t) \quad (4)$$

$$Y(t) = J(S(t), A)F(K(t), H, R(t)) \quad (5)$$

In the dynamical system described by equations (1) and (3)–(5), K and S are state variables, whereas R and C are control variables. Positive economics would ask us to study the system under specific behavioural rules regarding the control variables. Alternatively, we could study an optimizing system, in which the control variables are chosen by a decision-maker in light of their objectives.

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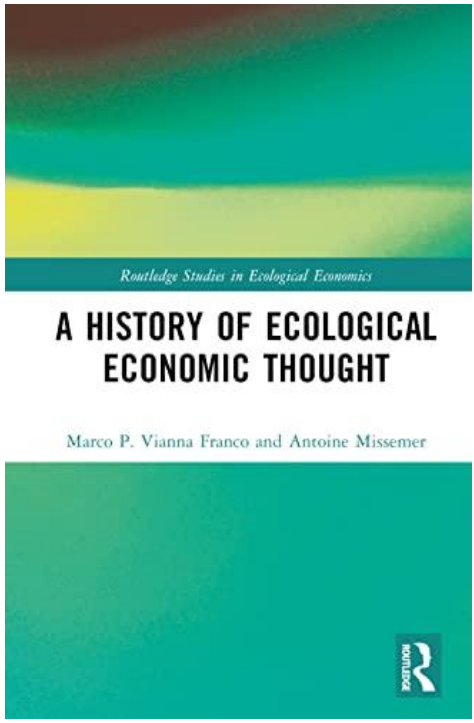
BOOK REVIEW

A Deep Look Back into Early Eco-Economics

Venkatachalam Lingappan *

Marco P Vianna Franco and Antoine Missemer. 2023. *A History of Ecological Economic Thought*. Oxfordshire: Routledge. 200. ISBN (ebook): 978-1000624618. ISBN (hardcover): 978-0367363925.



The title of the book under review is a bit of a misnomer, as Marco Franco and Antoine Missemer's volume is a historiographical study rather than a history of ecological economics, given its examination of economic–environmental conceptualizations going back to the sixteenth century.

Prior historiographies in this field generally identify the systematic development of environmental economics as beginning in the 1930s, with Pigou's seminal work (1932), while positioning ecological economics as a distinct movement emerging in the 1990s, rooted in Kenneth Boulding's foundational contributions from the 1960s. In contrast, Franco and Missemer

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establish that the conceptual underpinnings of economy–environment relationships possess considerably older historical roots, extending through multiple centuries of intellectual discourse. The authors argue that longitudinal analysis of economics–environment interactions yields substantially richer insights than the focus on temporally circumscribed investigations of recent developments alone.

Where the existing historiographical literature on economy–environment dynamics predominantly emphasizes neoclassical environmental economics, Franco and Missemer throughout this book illuminate previously marginalized strands of ecological economic thought, such as the role of chemistry and soil science in agriculture. Their work evaluates how earlier scholars investigated the interdisciplinary nexus between economic systems and natural sciences, chronicling conceptual frameworks characterized by shared ontological and epistemological understandings of societal functioning and natural world dynamics. The authors reconstruct the intellectual genealogy of Western ecological economic thought from the Renaissance and Enlightenment periods—spanning the sixteenth, seventeenth, and eighteenth centuries—through the 1940s. The book's periodization reflects both the relative scholarly inattention to pre-1940s intellectual contributions and the substantial existing literature documenting post-1940s developments in the field.

The book then traces the deep and recurring entanglement of natural science with economic thought across multiple intellectual traditions, geographies, and centuries. At its core, the work argues that economic thinking has never developed independently of our understanding of the natural sciences—from the botanical and zoological inquiries of early modern natural history to the energetics movement, ecological utopianism, and conservation science of the nineteenth and twentieth centuries.

A central theme running through the book is how specific scientific disciplines—chemistry, physiology, ecology, and evolutionary biology—shaped not only economic theory, but also the institutional and policy frameworks governing land use, agriculture, and natural resource management. The authors discuss, for instance, the transformative role of soil chemistry and plant nutrition science in agrarian governance, illustrating how laboratory advances translate directly to territorial economic policy. The book also highlights the geographical diversity of these intellectual exchanges: German Naturphilosophie, Russian and Soviet ecological scholarship, Austro–Hungarian social energetics, and North American conservation traditions. Each produced distinct but related frameworks to understand the economy, as embedded within natural systems. Particularly notable is the book's recovery of underexamined traditions—such as the

"Other Austrian" (91) school's engagement with nature's incommensurability and Stanchinsky's work (1930) on natural reserves as instruments of ecologically informed economic planning. In this examination, the authors anticipate the central concerns of contemporary ecological economics.

Franco and Missemer's analysis demonstrates that concerns regarding sustainability, resource depletion, and biophysical limitations on economic growth represent persistent themes in economic theorizing across several centuries. Far from constituting a uniquely twentieth-century development, these preoccupations possess deep genealogical roots spanning multiple centuries, they suggest. Through the recovery of these earlier intellectual traditions, the authors transform contemporary scholars' understanding of the historical evolution of economic engagement with environmental questions.

The volume underscores the considerable influence of the natural sciences—natural history, including chemistry, biology, ecology, and physics—on the formation of ecological economic thought. These interdisciplinary engagements were not peripheral considerations but frequently served as foundational elements in the theoretical architectures that address economic phenomena, particularly those concerning agricultural systems, resource extraction, energy flows, and the material bases of production and consumption.

Although predominantly historiographical in orientation, the monograph carries significant implications for contemporary environmental and sustainability challenges. By retrieving neglected or marginalized intellectual currents, Franco and Missemer equip contemporary scholars and policymakers with an expanded conceptual toolkit with which to analyse human–nature relations. This historical lens enables readers to recognize that ongoing debates surrounding sustainability, resource constraints, and ecological limits are built upon deep intellectual foundations, having been continuously shaped through centuries of scholarly discourse and contestation. This will deepen our understanding of the economy–ecology nexus and enhance appropriate policies to change the behaviour of people to take care of our environment seriously.

As such, it represents an indispensable pedagogical and research tool for graduate students and faculty engaged in the fields of economic thought historiography, environmental economics, and ecological economics.

The interdisciplinary approach advocated by the authors, while valuable, raises some important concerns. It is largely suited to empirical questions: for instance, evaluating the economic impact of water pollution on

agriculture draws on economics, soil science, agronomy, toxicology, and statistics. Yet several critical questions remain unresolved: Which disciplines are truly necessary, in what proportion should each contribute, and should the scope extend to fields such as history, anthropology, and sociology? More fundamentally, who determines this, and does the bounded rationality of researchers not risk making such an approach inherently incomplete? Without adequately addressing these questions, disciplinary coherence cannot be assured—and this is precisely where the book falls short.

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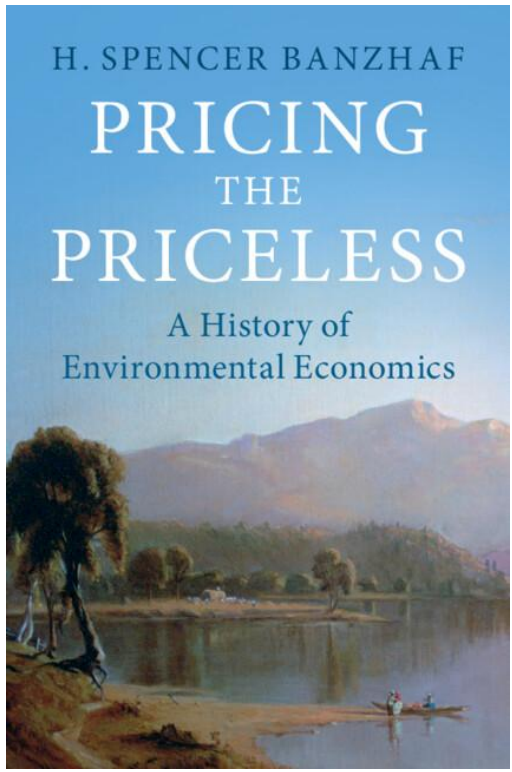
BOOK REVIEW

Quest to Quantify the Unquantifiable

Praharsh M Patel *

Banzhaf, H Spencer. 2023. *Pricing the Priceless: A History of Environmental Economics*. Cambridge University Press. 298. ISBN: 9781108867184.



My interest in environmental economics was shaped by growing up in a small town in Gujarat, where I had access to green spaces and clean air and water, and then moving to New Delhi for my higher education and work, where the environmental degradation is hard to ignore. This lived paradox of high income but low environmental quality drew me to the subject. However, for a long time, I struggled, like many, with a curious question: What does it actually mean to be an environmental economist?

The book *Pricing the Priceless* by Spencer Banzhaf engages with this question and shows how the field has expanded

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to include not only policy issues but also moral debates about nature and the environment. More importantly, it examines the challenge of utilizing natural resources while preserving environmental quality. The book delves deep into the intellectual history of environmental economics in the context of the United States (US). It provides rich critical context that is often missing from the classroom teaching of environmental economics.

As historians often put it, "the near history is messier than the rosy distant past". Similarly, the book engages with turbulent debates and contested ideas that continue to evolve. It confronts one of the most enduring paradoxes of modern development: how societies can reconcile material progress with the preservation of nature and the environment, and how economic reasoning has become central to navigating this trade-off. Scholars trained in science, technology, engineering, or mathematics often treat nature as a physical system rather than a social one. This book offers a powerful reframing of what it means to study the environment through an economics and policy lens. Banzhaf also offers an impressive intellectual genealogy of the field, situating environmental economics within broader economic thought.

Comprising nine chapters and an epilogue, the book introduces the key figures and institutions that have guided the discourse on environmental economics. The opening chapter, "Introduction: Environmental Economics in Context", should be mandatory reading for students of environmental economics, as it explains why the field was founded. Banzhaf revisits early conservation debates amongst well-known figures in US environmental history, such as Gifford Pinchot and John Muir, who were committed to conservation but divided in philosophy. Pinchot's utilitarian, scientific approach to resource management stood in contrast to Muir's ethical and aesthetic admiration for the wilderness. These debates were not merely ideological; they shaped the institutional and analytical foundations of modern environmental policy. The historical excavation of how economic thinking came to be applied to environmental and natural resource issues in the chapter "Do Economists Know about Lupines? Economics versus the Environment" lays a strong foundation for the rest of the book.

One of the book's major strengths is its attention to institutions. Environmental economics did not develop in academic isolation; it evolved through close engagement with policymaking bodies and public agencies. Banzhaf provides a comprehensive account of how institutions such as the US Army Corps of Engineers, Bureau of Reclamation, US Forest Service, National Park Service, and Fish and Wildlife Service helped create the demand for a systematic cost–benefit analysis. These agencies faced

pressing investment challenges related to large-scale infrastructure projects across the country, and the expertise of economists became integral for conducting the rigorous cost–benefit analyses required to pass the federal government's litmus test.

Equally important is Banzhaf's discussion of the intellectual ecosystems that nurtured environmental economics. Institutions such as Resources for the Future, the RAND (Research and Development) Corporation, and the Harvard Water Program played a pivotal role in fostering mathematically robust and interdisciplinary research and methodological innovation. Foundations such as Ford and Sloan provided critical early financial support, enabling economists to engage in long-term, policy-relevant research. The book carefully documents how these networks sustained debates both within and beyond academia on public goods, externalities, and valuation methods.

The book's focus on US environmental policy is both a strength and a limitation. On the one hand, the US provides a uniquely well-documented case of environmental governance that views nature through a rational utilitarian lens. On the other hand, the book largely treats the US experience as analytically self-contained, offering limited engagement with environmental economic thought in the Global South and other regions. While Europe's contributions to early forestry and resource management are acknowledged briefly, readers from the Global South may notice the absence of parallel histories from their countries. This book may not be a global history of the field, but it provides a template for how such stories can be written by incorporating local agents and institutions.

The epilogue brings the book to a full circle. It connects the founding understanding of consumption and economics to contemporary challenges such as climate change, biodiversity loss, and sustainable development. It emphasizes that valuing nature is not about commodification for its own sake but about enabling informed, transparent, and accountable decision-making.

In conclusion, Banzhaf suggests that environmental economists bear a heavy responsibility to translate ecological complexity into analytical frameworks that policymakers can use, without losing sight of ethical concerns and distributional consequences. *Pricing the Priceless* helped me better understand what it means to be an environmental economist: not to place a price tag on nature as if it were for sale but to recognize that economic decisions are inevitable, trade-offs are real, and ignoring value does not make it disappear.

Banzhaf quotes Lord Kelvin, who we all know invented the absolute temperature scale:

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science. (2023, 225–226)

As the modern-day discourses for environmental conservation evolve to be scientific, this "quest to quantify the unquantifiable" can be a guiding principle for collaborative science for a better environment for all. For students, researchers, and policymakers alike, this book is a timely reminder that the future of environmental governance depends as much on sound rational reasoning as it does on scientific understanding and moral imagination.

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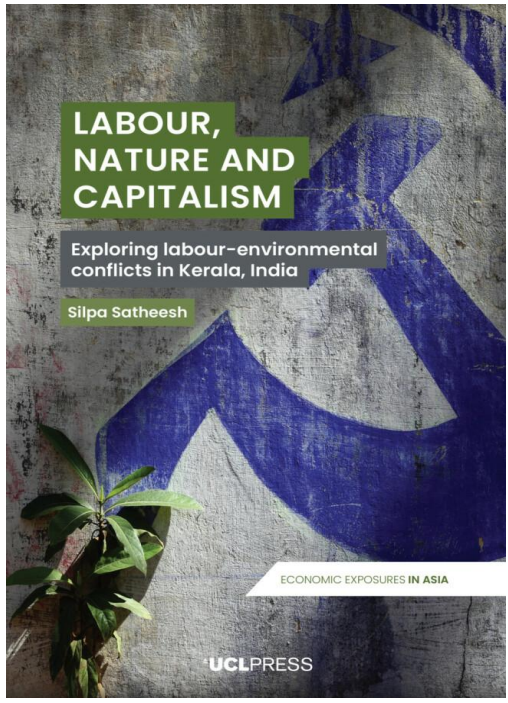
BOOK REVIEW

Environmental Justice and the Working Class: Labour, Nature, and the Contradictions of Capitalism

Adithya Kumar *

Silpa Satheesh. 2025. *Labour, Nature and Capitalism: Exploring Labour-environmental Conflicts in Kerala, India*. University College of London Press. 252. ISBN (online): 9781800088054.



The tension between pro-environmental movements and development initiatives has shaped public debates since industrialization (Drews *et al.* 2019). In emerging economies such as India, this conflict is especially significant, given the pursuit of rapid economic growth and the country's continued dependence on energy-intensive development (Pappas and Chalvatzis 2017). Labour movements—often supported by industry and political actors—frequently oppose civil society–led environmental movements that seek to address pollution, resource depletion, and

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ecological vulnerability. While environmental movements in the Global North gained prominence through campaigns such as Just Stop Oil and the Silent Spring movement, those in the Global South are often initiated and sustained by local communities. Corporate and governmental involvement generally emerges later. Another defining feature is their limited visibility, as they rarely receive sustained media or institutional attention. Consequently, many such movements disappear before their concerns are addressed, while others continue without wider societal support. Only a few enter school textbooks or become subjects of sustained academic enquiry.

A similar pattern is reflected in the Eloor–Edayar region of Ernakulam district in Kerala, where green movements coexist with counter-movements supported by labour organizations and corporations. These struggles receive little public recognition and have attracted limited scholarly attention. In *Labour, Nature and Capitalism: Exploring Labour–Environmental Conflicts in Kerala, India*, Silpa Satheesh documents environmental movements and the tensions between them and labour-led counter-movements. As the author notes, the book does not seek to determine which movement is more necessary or successful; rather, it explores the dynamics of labour–environment conflicts in an industrial region in a rapidly developing country. The book consists of eight chapters and an epilogue explaining how the Periyar River became central to the research. Each chapter combines theoretical, empirical, and methodological concerns, while integrating field narratives with a nuanced discussion of existing literature. Chapter-end discussions aid comprehension, and the language remains clear and accessible.

The introductory chapter outlines the region's history, industrialization, and the emergence of green movements and their counter-movements. It situates labour–environment conflicts within the broader contexts of the world and the Global South, highlighting the limited scholarly attention given to similar movements. The second chapter details the methodology—a multi-method qualitative approach that includes interviews, document analysis, and both theory-driven and field-based frameworks. The author's engagement with subjectivity, positionality, postcolonial perspectives, and decolonizing research practices strengthens the study's methodological rigour. Drawing on interviews, the author captures local communities' emotional and economic ties to the Periyar River. The book examines how industrial growth, while improving infrastructure and amenities, also produces severe environmental degradation, especially river pollution. The documentation of protests—including a human chain organized along the river—and the role of inland fisher workers demonstrates how local economies and social life remain rooted in ecological systems. Through oral

histories and document analysis, the book traces the trajectory of environmental movements in the region and proposes a periodization of their development.

The book also examines the unequal power dynamics between grassroots environmental movements and corporate-backed counter-movements. Community-led initiatives often struggle for resources, while corporate-backed movements benefit from institutional and political support. The author shows how corporations use economic and political influence to suppress dissent among workers, state actors, and regulatory bodies. Importantly, the book challenges simplistic notions of a protest's success, arguing that the scale of participation should not be equated with effectiveness. A major contribution of the work is its analysis of how class identity shapes both environmental movements and their opposition, revealing tensions within the working class itself. Trade unions and labour organizations frequently align with industrial interests, portraying environmental activism as "anti-developmental" or "anti-national", whereas green movements prioritize long-term ecological sustainability. The author links these differences to broader ideological debates, including communist and pro-capitalist discourse within the state. The observation that "a clear divide exists between the unions and the environmental movement in their approaches" (p. 149) highlights the fragmentation of working-class politics. Environmental activism is often delegitimized through narratives that portray activists as extremists, foreign-influenced actors, or affiliates of insurgent groups such as Naxalites and Maoists. Such framing demonstrates how ideological narratives are mobilized to weaken environmental resistance. In the concluding chapter, the author synthesizes these themes, arguing that conflicts between green movements and their counter-movements arise from complex interactions between power, money, and politics, particularly in working-class contexts. Throughout the book, the author explores how individuals and communities negotiate the tension between environmental protection and economic survival. Both industrial expansion and ecological preservation demand attention, and the book effectively captures this dilemma. It succeeds in showing how class-centred movements in the Global South shape labour–environment conflicts and underscores the importance of considering lived experiences to understand these dynamics.

However, the book has limitations. Its strong focus on the Eloor–Edayar region provides depth but limits engagement with similar movements elsewhere in Kerala, a state with a long history of labour and environmental struggles. A comparative perspective could have strengthened the analysis, particularly given Kerala's strong leftist political tradition. The absence of

discussions on other working-class-driven movements restricts the scope of the study and limits the broader applicability of its findings. Despite these limitations, the book's strengths are considerable. Its rich field anecdotes ground the narrative in legitimate experiences, while the integration of empirical evidence and theory remains effective and accessible. Also, the multi-method research design adds depth and credibility. The book will suit a wide range of readers, from students to professionals and activists who have a keen interest in delving deep into ecological issues in the Global South and social movements wrought by the working class. For academics, the book serves as an example of how to integrate empirical and theoretical insights within a strong methodological framework. Overall, *Labour, Nature and Capitalism* offers a nuanced analysis of development, class politics, governance, and environmental conflict, making a valuable contribution to the study of labour–environment relations in the Global South.

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BOOK REVIEW

A Data-Driven Beacon of Hope

David Sierra-Porta*

Hannah Ritchie. 2024. *Not the End of the World: How We Can Be the First Generation to Build a Sustainable Planet*. Chatto & Windus, Penguin Random House UK. 352 pages. ISBN-10: 031653675X, ISBN-13: 978-0316536752.



In a world where environmental news publications often seem to compete in amplifying climate anxiety, *Not the End of the World* emerges as a timely and much-needed endeavour to restore a sense of balance. Hannah Ritchie offers a refreshing perspective in a debate dominated by catastrophic rhetoric on one side and denialism on the other. Her work charts a middle ground: it acknowledges the scale of today's environmental challenges without succumbing to either fear or indifference.

The book can be read as an invitation to rethink our relationship with environmental information. Ritchie observes that apocalyptic narratives, while initially enable rapid mobilization, have increasingly generated distrust, fatigue, and a sense

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of helplessness. Against this backdrop, she argues for reclaiming the power of data and uses examples from recent history to demonstrate that meaningful progress is not only possible but already underway. Rather than fueling despair, her goal is to build hope grounded in evidence and oriented towards action.

This reframing is particularly relevant in a historical moment marked by polarization in the environmental discourse. On the one hand, there are groups that deny the existence or seriousness of the problem; on the other, there are voices predicting imminent collapse. *Not the End of the World* offers a third path characterized by pragmatic optimism grounded in rigorous data analysis and illuminates both the advances made and the challenges that remain.

The book has eight chapters, each addressing a major environmental challenge. It opens with "Sustainability: A Tale of Two Halves", in which Ritchie frames the central argument: progress and setbacks must be seen together to evaluate our trajectory. The following chapters focus on specific issues—air pollution, climate change, deforestation, food, biodiversity loss, ocean plastics, and overfishing—each introduced by a guiding question and examined through data-driven analysis.

Instead of issuing abstract warnings, Ritchie highlights both problems and successful interventions—from reduced smog in cities to reforestation initiatives and improved fisheries management. The narrative is supported by well-designed data visualizations and diverse sources, such as satellite imagery, official statistics, and case studies.

One of the book's most notable virtues is its ability to situate current problems within a historical framework that highlights the significant progress made in recent decades, without lapsing into complacency. This balance between realism and optimism is persuasive: Ritchie acknowledges the scale of ongoing challenges while documenting improvements driven by technological innovation, better public policies, and shifting social behaviours.

Ritchie's style is rigorous yet accessible. She elucidates complex concepts through clear analogies and graphics, enabling readers without technical training to grasp sophisticated analyses of global systems. Another strength is her emphasis on practical solutions. Rather than simply diagnosing problems, she highlights policies, technologies, and strategies already working in different parts of the world. This makes the book both a guide for informed action and an exercise in critical thinking.

Ritchie applies temporal analysis to uncover long-term trends in CO_2 emissions, deforestation, air quality, and biodiversity, showing how the historical context reveals genuine turning points beyond short-term fluctuations (Mathieu *et al.* 2021). She also uses predictive modelling—demographic projections, climate scenarios, and energy transitions. Data visualizations are another strength of the book. From environmental Kuznets curves to global material-flow graphics, the charts reveal patterns that may be invisible when presented as raw numbers, while the geospatial perspectives highlight regional differences in global problems (Steffen *et al.* 2015).

The book illustrates how heterogeneous data—such as satellite observations, government records, surveys, and scientific measurements—can be combined to create coherent narratives. Ritchie addresses the challenge of distinguishing correlation from causation by pointing to quasi-experiments, regression discontinuity, and instrumental variables. She also provides strong examples of composite environmental indicators and policy evaluations using quantitative methods such as difference-in-differences and impact assessments (Rogelj *et al.* 2018). Her treatment of uncertainty and reproducibility is exemplary. She discusses confidence intervals, sensitivity analyses, and probabilistic communication, while case studies show the value of interdisciplinary methods spanning economics and ecology (Herre *et al.* 2024). Throughout, she models transparency by citing data sources and methods clearly, which allows for replication and critical scrutiny.

While the book's data-driven optimism is refreshing, there are areas where the discussion could have gone further. Ritchie devotes relatively little attention to the structural and political barriers that hinder the implementation of successful policies, particularly in contexts where governance is weak or resources limited. Many of the success stories highlighted in the book come from high-income countries, but they may not fully reflect the realities of developing regions, where environmental progress is hindered by inequality, urbanization, and political instability.

Another limitation lies in the treatment of data sources. Although Ritchie emphasizes transparency, she could have engaged more deeply with the limitations and biases inherent in certain datasets. National statistics, for example, vary in quality and coverage, and in some cases, they may be influenced by political pressures or under-reporting. A more explicit acknowledgement of these gaps would have enabled readers to evaluate evidence more critically, especially in cross-national comparisons.

Moreover, while Ritchie excels in presenting successful case studies, she sometimes underplays examples of failures or unintended consequences. A more balanced discussion of both achievements and shortcomings would enrich the reader's understanding of the systemic obstacles to sustainability. Similarly, her focus leans towards technological and policy solutions, leaving less room for cultural or ethical perspectives, which often determine whether large-scale transitions succeed.

Despite these limitations, the book remains a powerful and hopeful contribution to the discussion on the environment. Recognizing its blind spots does not diminish its value; rather, it highlights the need to complement Ritchie's perspective with broader debates on equity, governance, and the diversity of global experiences.

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Ecology, Economy and Society–the INSEE Journal 9(2): 2176.1-2176.4, July 2026

BOOK REVIEW

Economic, Financial and Institutional Dimensions of Climate Action

Kishore K Dhavala *

Mohanty, M, and Runa Sarkar, eds. 2025. *Financing Climate Action: India in a Global Context*. Routledge India. 440. ISBN: 9781032962641



Climate change is widely regarded as the greatest market failure in modern economic history, reflecting the inability of markets to account for the environmental and social costs of greenhouse gas emissions (Stern 2008). Addressing the challenges of climate change requires not only technological and regulatory reforms but also a restructuring of investment priorities and financial flows, redirecting capital from carbon-intensive development pathways towards mitigation, adaptation, resilience, and sustainable development. In addition, concerns about equity and the role of existing financial mechanisms in realizing a just and effective climate transition are equally

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significant. In this context, *Financing Climate Action: India in a Global Context*, edited by Mritiunjoy Mohanty and Runa Sarkar, is a timely and substantive intervention and provides a valuable contribution to climate finance literature. The open-access edited volume consists of 27 chapters across six thematic sections. The contributors are from a diverse range of disciplines, including economics, finance, public policy, energy systems, environmental science, and development studies, and represent academic institutions, policy think tanks, and practitioner organizations. This interdisciplinary breadth lends the volume a richness that is often lacking in economics-centred research on climate finance. The volume explores the economic, financial, and institutional dimensions of climate action and offers insights relevant to the Global South.

Part I of the book comprises six chapters that provide a multidimensional perspective on climate action financing in India, from macroeconomic, institutional, and sectoral perspectives. The topics covered in this section include financing requirements and the need to mobilize private investments to support renewable energy policies, decentralized adaptation strategies, grid integration interventions, and fiscal reforms. The section demonstrates how public institutions, private capital, community initiatives, and fiscal frameworks collectively shape pathways towards low-carbon and climate-resilient development. The four chapters of Part II examine the governance and institutional dimensions of climate finance, emphasizing that effective climate action depends not only on the availability of resources but also on how they are regulated, allocated, and implemented. The section also underscores that public finance plays an important role where private finance is unwilling to take on the risks involved in adaptation and other difficult climate projects. Overall, this section suggests that climate finance depends not just on funding, but also on the rules, institutions, and partnerships that guide how that funding is used.

Part III focuses on the instruments and mechanisms that can be deployed to mobilize climate finance. Across four chapters, this section moves from broad policy frameworks to practical tools, discussing mechanisms such as capital recycling, securitization, green state development loans, carbon pricing instruments, and debt-for-climate swaps. The section emphasizes the role of public and private financial institutions in supporting projects and fostering innovation, especially where markets are shallow or risks are high. Part IV consists of six chapters that connect climate finance with the economy and discuss how financial tools can support the decarbonization of the energy sector. Further, this section suggests that climate finance must go beyond broad commitments to include practical instruments that can support firms, workers, and infrastructure in moving towards a low-carbon

economy. The chapters also highlight the need for sustainability-linked green bonds; green finance platforms for micro, small, and medium enterprises; energy-efficiency financing schemes; transition plans and disclosure frameworks for large firms; carbon markets; carbon pricing; transmission financing; and just transition funding models.

Part V of the book focuses on public resources, arguing that long-term capital is needed to support public investment institutions, and the involvement of central banks is required to create an effective and equitable climate financing system. Particularly, the chapter on loss and damages advocates for grants and stronger governance arrangements to make climate funding available to countries that are most vulnerable to the climate crisis. The final part of the edited volume examines the experiences of Brazil, India, and Indonesia and argues for regional cooperation to develop effective climate finance programmes. The chapters highlight the role of public-sector firms in supporting a just energy transition. Examples include the use of carbon taxes and green bonds to finance renewable energy and manage inflation. Other examples include the development of country-level platforms to align international support with national priorities, and models such as the Energy Transition Mechanism and Just Energy Transition Partnership, which illustrate the importance of linking finance, policy, and implementation.

The 27-chapter volume is a commendable achievement in scope and intellectual ambition. The contributors are from diverse backgrounds, so some variation in analytical depth across chapters is perhaps to be expected. Certain chapters offer rigorous original analysis, while others adopt a more descriptive approach, synthesizing insights on existing schemes and from secondary sources. Although the thematic introductions by the editors serve as helpful navigational guides, they could have more explicitly highlighted the linkages and points of divergence across chapters. The edited volume would also have benefited from a more sustained engagement with the political economy of climate finance, including the institutional interests that complicate decarbonization, the distributional implications of carbon pricing, and governance challenges.

In conclusion, *Financing Climate Action: India in a Global Context* is a timely and intellectually valuable contribution to the scholarship on climate finance, offering wide-ranging analyses of the institutional, financial, and policy dimensions of climate action in developing economies. The volume's strength lies in how it brings together diverse perspectives on public finance, private capital, governance, instruments, and international experience, while maintaining a consistent focus on equity, resilience, and the realities of development. As India commits to a net-zero future by 2070

while simultaneously pursuing its development aspirations, the book offers valuable insights into the opportunities and constraints that will shape its transition. It is therefore an important resource for researchers, policymakers, and practitioners interested in the evolving relationship between climate finance and sustainable development.

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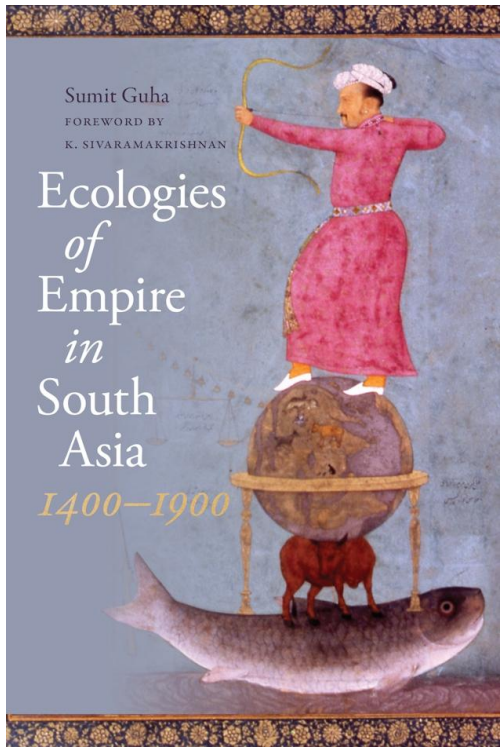
Ecology, Economy and Society–the INSEE Journal 9(2): 2149.1-2149.4, July 2026

BOOK REVIEW

Empires and the Anthropocene

Lavanya Suresh *

Sumit Guha, 2023. *Ecologies of Empire in South Asia, 1400–1900*. 268. University of Washington Press. ISBN (paperback): 978-81-7824-677-2.



Sumit Guha's book, *The Ecologies of Empire in South Asia, 1400–1900*, is an analysis spanning multiple centuries, exploring the relationship between political power, inequality, and the natural world in the Indian subcontinent. Comparing the environmental legacies of the Mughal and British empires, Guha shows that the establishment and administration of these empires were not just about tax revenues or territorial expansion; they also involved a fundamental reshaping of entire landscapes, both their flora and their fauna, to suit the sovereign agenda. This book is a perfect example of a

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study of political ecology that situates the current climate crisis within the context of deep history.

Environmental history has come a long way since Ramachandra Guha (1993) noted that its emergence in India occurred mainly in response to contemporary ecological movements. The departure starts with his seminal work with Gadgil (1993). Sivaramakrishnan's (2008) work added to the growing body of historical research on ecosystems and imperialism in South Asia. Sumit Guha himself has long been a pioneer in engaging with multiple perspectives through his work on the deep history of South Asia (2009). In the book under review, Guha scales the analysis to the level of empires, addressing a critical gap in the literature by foregrounding the inextricable link between technologies of measurement and record-keeping and inequalities of power.

Guha's method relies on a painstaking scrutiny of little-used archival sources, including Persian administrative records, Maratha documents, and British colonial files. He tracks an epistemic shift: the transformation of local knowledge, rooted in sacred cosmologies and hunting ranges, into aggregated information in the service of centralized power. Central to his methodology is the concept of "environing" (p. 5), a term that refers to the knowledge-based representation of the material world in which humans are embedded. Guha argues that humans neither affect nor comprehend the environment equally; hence, the book uses deep historical time to demonstrate the enduring nature of environmental inequity.

The book moves from historiographic critique to how frontiers are established and made concrete. Chapter 1 sets the tone and engages directly with political ecology, focusing on inequality as an ecological driver. Guha establishes his theoretical foundation by critiquing standard climate-change models, such as the History Database of the Global Environment (HYDE). He argues that most environmental datasets that examine deep history oversimplify the matter by making Modernist assumptions—such as the idea that population is a predictor of environmental impact—which fail to account for social inequality, the primary driver of ecological change, as he demonstrates in the book.

The uniqueness of this narrative is that it examines how inequities have historically been perpetuated by state-driven technologies that impact ecosystems at the landscape level, an argument demonstrated in Chapter 2, which showcases the shift from a land-centric Mughal Empire (1526–1600) to the primarily maritime British Raj. He shows how local knowledge remained opaque to the imperial gaze for decades, until the British deployed

novel efforts to map and manage their domains with mathematical precision.

Mapping was a tool that created and perpetuated inequality, with consequent impacts on landscapes. The legibility and dissemination of geographical knowledge also enlarged British power. Further, using evidence from Marathi-speaking West India, Guha documents in Chapter 3 how empire builders needed elite participation. These elites had preferences, such as for white polished rice, spices, and ghee, which shaped land use in favour of specific flora and fauna, profoundly moulding both society and the environment through landlord power.

By focusing on the interlinkage between social and ecological change, Guha rejects the stereotype of the unchanging peasant in a village unaffected by imperial rulers. In Chapter 4, Guha instead draws a mental map of a village, where everything beyond the village is not the "wild", but arrayed in a gradient from fields to grazing land to defecation sites to the forest. The village itself is a sturdy yet specialized socio-ecological entity, and its creation involves replacing forests with fields and vice versa. Village boundaries were dynamic, changing with ecological conditions such as floods, the availability of grazing land, and monsoons—a feature that the empire sought to curb and make more static.

However, this is not just a story of an empire's capacity to change landscapes but also a story of conflict. In Chapter 5, the book shows how human conflict plays a key role in shaping ecosystems. Building an empire had a biotic impact, affecting local characteristics from water to stone, captured elephants, domesticated horses and oxen, and forced human labour. People had to change their farming systems and subsistence strategies in anticipation of warfare. The biotic demands of moving armies and active contestations changed the face of the land.

Guha also explores animal history, particularly its effects on woodland composition, as animals were part of the history of defence, aggression, and leisure by the elite.

The final chapter, Chapter 6, brings together the two key processes tracked throughout the book. The first of these is the transformation of the earth due to the unequal effects of human actions that subordinated the many and empowered a few. Second, the growth in measurement technologies and geographic knowledge paralleled the rise of empires. This impacted land surveys and shaped the role of the industrial–military nexus in enabling deeper market penetration, irrevocably changing flora, fauna, and land by the early twentieth century.

This book is a fine-grained account of the state and ecological evolution in South Asia in the late eras of empire. However, its massive scope of 500 years and multiple empires that ruled in that period occasionally leads it to gloss over regional nuances, as the sheer volume of state records, which are the main source of information, skews the narrative toward a state-centric perspective.

Nevertheless, Guha's work remains highly relevant to contemporary Anthropocene scholarship, which often tends to sever human history from natural history (Gattey 2021). By centring empires in the story of the Anthropocene, Guha provides a necessary corrective to depoliticized climate narratives, arguing that ecological science cannot be conducted in isolation from the examination of human power structures. This book will be of interest to students, policymakers, and academicians who are interested in a nuanced history of climate change in the Indian subcontinent. Ultimately, *Ecologies of Empire in South Asia* is an important contribution not only to the field of environmental history but also to historically embedded climate science.

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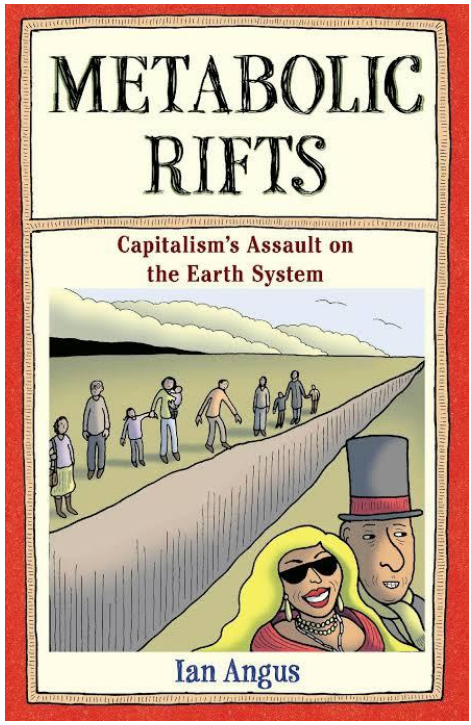
BOOK REVIEW

Severed Universal Metabolism and Predatory Logic: Groundwork for an Ecosocialist Critique of Capitalism

Varun Wighmal [*]

Ian Angus. 2026. *Metabolic Rifts: Capitalism's Assault on the Earth System.* Monthly Review Press. 248. ISBN: 978-1685901622.



In her critical examination of positivism and constructivism in the philosophy and history of science, philosopher Helena Sheehan argues that the Marxist intellectual tradition has the strongest claim to the sociohistorical and interdisciplinary character of science (Sheehan 2018). Ian Angus' book, *Metabolic Rifts: Capitalism's Assault on the Earth System*, advances the aforementioned interdisciplinary approach to knowledge, transcending parochial positivist and constructivist epistemologies. In addition, the book adopts a realist yet non-reductionist approach to problems afflicting humanity. Angus treats capitalism as an autoimmune condition that

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attacks the Earth system on which it survives.

Until a few decades ago, both Marxists and non-Marxists generally believed that Marxism had very little to contribute to ecology, and that Karl Marx was not deeply concerned about nature or capitalism's assault on the ecosystem. This changed with the seminal work of sociologist John Bellamy Foster, who introduced the concept of "metabolic rift" in his work, *Marx's Ecology* (Foster 2000). Angus builds on the same discourse, apropos of natural science, Marxism, and ecology. By integrating science, philosophy, and political economy to understand the complex reality of capitalism's assault on ecology, Angus situates his work in the Marxist tradition of integrated knowledge.

The book is divided into four parts and has sixteen chapters. The first section presents a detailed account of the discovery and rediscovery of the "metabolic rift" and the eco-socialist tradition. Angus then explores the neglected traditions of key Marxist figures who engaged with science to understand history and the world. According to Angus, although Marx's "metabolic" approach was neglected due to the overt productivism/accelerationism of Marxist thinkers, it survived in the important works of three Marxists: Ferdinand Bebel, Karl Kautsky and Nikolai Bukharin. Angus demonstrates how they individually approached social and scientific questions, similar to the way Marx did.

Kautsky's *The Agrarian Question* was praised by Vladimir Lenin as an important work for its deep insights into agriculture and economics (Kausty 1988). Angus also discusses Bebel's 1879 book, *Woman and Socialism*, which explored ecological issues. Bebel wrote that capitalist agriculture is "soil vandalism" that "cripples the land and decreases the crops". He also bemoaned environmental destruction as "the senseless ravaging of forests, for the sake of profit" (31). Angus elucidates that these works disprove the canard that socialists of the late 1800s and early 1900s did not know or care about the universal metabolism of nature or the ecological catastrophe that is the capitalist onslaught on the universal metabolism.

The second part of the book describes the concept of "organic metabolism" as conceptualized by agricultural chemist, Justus Von Liebeg, and the Communist doctor, Roland Daniels. Marx used this concept to understand the loss of soil fertility and the concurrent rupture between humanity and the Earth, caused by the shipping of nutrients away from the countryside to industrial towns (Foster 1999). Beginning with the primitive accumulation of capital, the process has caused an irreparable breakdown of the organic bond between nature and society.

The bulk of the book is an attempt to explain the core concepts of ecological Marxism and political ecology by detailing the metabolic processes vital to Earth's systems. In Chapter 10, Angus discusses the carbon cycle's breakdown—which is driving climate change—and in Chapter 11, he describes how industrial agriculture is pumping nitrogen into Earth's systems faster than any natural process through fertilizers, disrupting the nitrogen cycle. Angus proposes a radical reduction in the use of nitrogen and chemical fertilizers as a solution to environmental damage, and envisions a time when it will be possible to feed people without them.

These chapters are the strength of Angus' book. They demonstrate how Marxists should use science to understand the complexity of the damage inflicted by capitalism on the Earth's systems and develop viable solutions based on the idea of hope without optimism, i.e., confronting adversity rather than denying it, as promulgated by Marxist literary critic Terry Eagleton (2015). This is explored more prominently in the final chapter of the book, "A Fight for Survival", which explores how scientists often come close to recognizing that the environmental crises we face are systemic ones, but seldom draw radical conclusions that require structural changes. This chapter also demonstrates that although science tells us that we need to take urgent measures, real and substantial change requires a long-term, cooperative approach between scientists, activists, and workers. Angus emphasizes that the reordering of capitalism through investing in green energy is nothing but a smokescreen, obscuring its systemic logic of appropriating nature and labour. He reminds us of the importance of living in tune with the natural world.

One can argue that Angus' work does not delve deeply enough into some important contemporary debates, such as the one between Communist Kohei Saito's "degrowth communism", which draws on Marx's unpublished notebooks, and the left-wing accelerationists and productivists who argue for overpowering nature (Saito, 2023). This can be considered a limitation of the book.

In *Metabolic Rifts,* Angus provides us with great insights into the strong association between revolutionary politics and scientific research, demonstrating how the Marxist idea of an interrelated and emergent knowledge framework is vital to developing real solutions to the climate crisis. This crisis is no longer imminent but is unfolding here and now. It requires not only investment in green energy, but also movements that consider questions of ecology, politics, and economy as interlinked—movements that radically reject the capitalist system's predatory approach to Earth, nature, and human labour. The book will certainly interest

scholars, experts, and lay readers interested in the intersection of progressive politics, ecology, economy, and technology.

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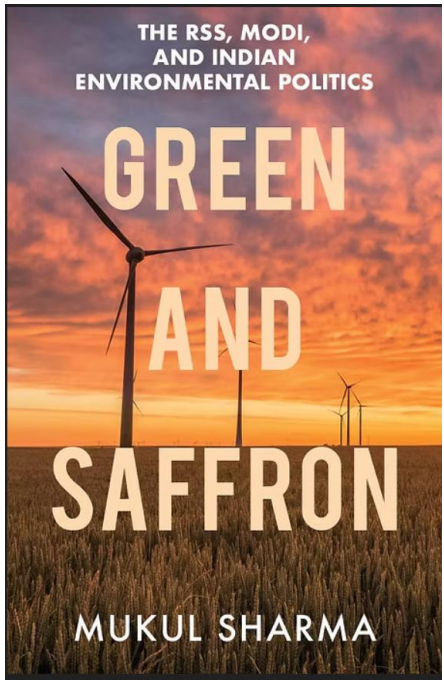
Ecology, Economy and Society–the INSEE Journal 9(2): 2186.1-2186.4, July 2026

BOOK REVIEW

When Green Wears Saffron: Ideology, Authority, and the Politics of Indian Environmentalism

Ankit Mishra *

Mukul Sharma. 2024. *Green and Saffron: The RSS, Modi, and Indian Environmental Politics*. Permanent Black and Ashoka University. 404. ISBN: 9788178246857.



The question of who speaks for the environment, and in whose name, has rarely been more politically charged in India than it is today. Scholarly literature on Indian environmental politics has long celebrated the country's environmental movements as expressions of subaltern ecological wisdom and democratic resistance. This literature optimistically portrays India's ecological conflicts as examples of community-based environmental politics acting as a counterweight to the predatory state. That optimism now requires serious revision. Mukul Sharma undertakes this revision in this substantially expanded and retitled edition of his 2011 work. Where the first edition examined Hindu

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nationalism and Indian environmental politics as parallel trajectories, this edition names the convergence explicitly: the Rashtriya Swayamsevak Sangh (RSS) and Narendra Modi are now directly named in the subtitle. With a new foreword by Jonathan Olsen, a new chapter on climate change and renewable energy, and approximately 50,000 additional words, this edition of the book is the most comprehensive account on its subject available in any language.

Sharma's central argument is straightforward: environmentalism and Hindu nationalism have forged a deep, mutually reinforcing relationship in contemporary India, and this relationship is structural rather than contingent. Sharma draws on threads from across political ecology, environmental history, and discourse analysis, combining textual analysis of RSS publications, particularly the *Organiser*, with extensive fieldwork and historical-ethnographic case studies. The prologue grounds the argument by opening at a Kosi River worship fair in Bihar's Khagaria district, where landless Dalits, dominant-caste organizers, and a community managing floods through goddess worship all appear before a single theoretical claim is made. Environmental meanings—the prologue shows—are never politically innocent. Caste, religion, and power saturate it before any ideologue arrives to put it to use.

Sharma begins by identifying the five axes around which green and saffron converge: ultra-nationalism; the desire to make a Brahminical Hindu tradition the governing ecological framework; the emphasis on authority, discipline, and social order; structural hostility towards Muslims, Dalits, and Christians; and programmatic communal politics. Chapter 2—the most theoretically grounded section—traces these axes by analysing four recurring themes in RSS publications: the construction of a sacred Hindu Motherland embodied by rivers and ancient soil; the feminization of rivers as icons of Hindu purity that are under perpetual threat; the invocation of an ancient "Holy Science" as the source of modern environmentalism; and the projection of Modi as the world's environmental saviour. The chapter's sharpest contribution is its analysis of how the RSS and Bharatiya Janata Party (BJP) approach climate change. Unlike the European far right, which Olsen (1999) has documented as grounded in eco-nationalist and eco-authoritarian ideological formations, the RSS and BJP do not deny climate change. They instrumentalize it, linking Vedic wisdom to solar energy, blaming Muslim invaders and Western colonialism for India's ecological degradation, and positioning a Hindutva civilization as the planetary solution. In addition, India's PARAMPARA document at the United Nations Climate Change Conference 2015 in Paris—which presented air-drying clothes and cycle rickshaws as "ancient Indian practices"—is among

the book's most illuminating examples of the right-wing government's approach to climate mitigation using so-called Indian traditions (MoEFCC 2015: 264).

The following chapters consider three landmark case studies, each analysed against the grain of the celebratory literature surrounding it. Anna Hazare's Ralegan Siddhi watershed programme, Sunderlal Bahuguna's opposition to the Tehri Dam, and the World Wildlife Fund (WWF)-funded Vrindavan Conservation Project each receive sustained scrutiny. Sharma asks: What political formations are these forms of environmentalism associated with and whose interests do they ultimately serve? The Dalit residents of Ralegan Siddhi—who describe their caste-based exclusion from the village's environmental governance—provide the book's most important testimony. The Tehri Dam opposition's entanglement with Vishva Hindu Parishad (VHP) networks demonstrates how legitimate ecological arguments can be taken up by an ideological movement that serves a vastly different politics. The chapter on Vrindavan reveals how an internationally funded conservation scheme was colonized from within by Krishnaite revivalism, producing a conservation that expelled "impure" elements from a sacred landscape while international funders chose to look elsewhere.

The book's most significant and novel contribution is the introduction of the concept of "techno-corporatism" in Chapter 6: a centralized, corporate-driven approach to renewable energy that profits a small number of massive firms, with the Adani Group receiving sustained analytical attention. Sharma traces how the Gujarat model reshaped the state into a hub for corporate investment in renewable energy. The chapter demonstrates that Modi's Yoga diplomacy, the Lifestyle for Environment campaign, and the deployment of godmen as solar energy brand ambassadors are not curiosities but components of a coherent ideological project that ties the Hindu civilizational identity to capital-intensive energy infrastructure. This argument expands scholarship on Indian climate governance in ways that have not been attempted before. The last chapter synthesizes the book's findings into five defining features of Hindu environmentalism: eco-nationalism; the Brahminical tradition as the natural ecological framework; eco-organicism that naturalizes caste hierarchy; a politics of purity and pollution directed at minorities and Dalits; and techno-corporatist climate governance. In the Postscript on RSS *shakhas* conducting nature prayers and Environment Day observances, Sharma shows that the saffronization of Indian environmentalism is not only a state project but also a cultural one, reproduced at the neighbourhood level.

The book has limitations that deserve serious engagement. The empirical base for the three core case studies remains unchanged from the 2012

publication. Readers seeking post-2014 observations on Ralegan Siddhi, Tehri, or Vrindavan will not find them in this edition. The gender dimension—while observed in the text—does not receive the analytical treatment the subject demands. Sharma notes the position of women in Ralegan Siddhi's ecological order but does not theorize it with comparable rigour. Consequently, the book concentrates overwhelmingly on the saffron side of the convergence. It focuses far less attention on why secular and left-leaning environmental organizations failed to build an effective counter-discourse.

These concerns exist alongside the recognition that this is a work of genuine importance. Sharma's book forces readers to rethink three decades of scholarship that treats Indian environmentalism as inherently progressive. He asks: What happens when certain forms of environmentalism become available for authoritarian capture? The insights provided in the book are uncomfortable, rigorous, and long overdue. Scholars of environmental governance, political ecology, and Indian politics, as well as policymakers working on climate justice, should read this book carefully and critically. What the RSS and Modi have built is not a corruption of a "purer" form of environmentalism; it is a distinct environmental politics, one that fuses ecological care with majoritarian nationalism rather than opposing it. Sharma's book equips us to understand, analyse, and contest it.

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REPORT

A Report on the INSEE–IIT Mandi International Conference on "Ecological Restoration for a Resilient Society: Economics, Policies, and Institutions"

Shyamasree Dasgupta,[*] Seema Purushothaman[**]

The Thirteenth Biennial Conference of the Indian Society for Ecological Economics (INSEE) on "Ecological Restoration for a Resilient Society: Economics, Policies, and Institutions" was held at the Indian Institute of Technology Mandi (IIT Mandi), Himachal Pradesh, India, from 12 to 14 January 2026. The conference brought together relevant stakeholders to engage in thoughtful dialogue over three days. It was preceded by a pre-conference workshop on 11 January 2026, titled "Tools and Methods for Decision-Making on Ecological Restoration", and was followed by a post-conference fieldwork on 15 January 2026. The conference was supported by International Development Research Centre (IDRC Canada), the Foundation for Ecological Security (FES), and the Indian Council for Social Science Research (ICSSR).

The United Nations has declared 2021–2030 as the Decade on Ecosystem Restoration with "aims to prevent, halt and reverse the degradation of ecosystems on every continent and in the ocean" (United Nations n.d.). According to the United Nations Convention to Combat Desertification, a large portion of the world's land is already degraded, and this degradation is worsening rapidly (UNCCD n.d.). India is no exception to the trend, with

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an estimated 96.4 million hectares of land experiencing desertification and degradation (MoEFCC 2023).

Restoring degraded ecosystems to their functional and productive state, while ensuring equitable and sustainable access for the resource-poor, is critical for progressive development. However, many questions about such ecological restoration remain to be tackled before targets can be specified and significant resources are committed. The conference in January 2026 brought together various stakeholders to deliberate on such questions, laying the groundwork for equitable and sustainable land restoration efforts in the country.

Figure 1: Pre-Conference Workshop Session on "Tools and Methods for Decision-Making on Ecological Restoration", 11 January 2026, IIT Mandi



Source*:* Conference Organizing Committee

Figure 2: During the Post-Conference Field Visit on 15 January 2026, Mandi, Himachal Pradesh



Source*:* Conference Organizing Committee

The pre-conference workshop was designed to introduce participants to practical tools, methods, and decision-making frameworks to support inclusive and context-specific ecological restoration. On the post-conference day, the workshop participants were divided into groups for fieldwork in two locations—Chhipanu and Surahan in Mandi district. The fieldwork, organised in collaboration with FES and the Forest Department of Mandi, was designed to enable participants to explore on-the-ground challenges and opportunities when applying the decision-making tools. It concluded with a debriefing session. By combining hands-on field engagement with exposure to decision-making tools, the workshop aimed to strengthen participants' capacity to design context-specific ecological restoration strategies.

Figure 3: Seema Purushothaman's Presidential Address *(left)* and Shyam Masakapalli's Welcome Address *(right)* at the Inaugural Session on 12 January 2026



Source*:* Conference Organizing Committee

In her presidential address at the inaugural session on 12 January 2026, Seema Purushothaman discussed how ecological economics emerged from discontent with the unfulfilled promises of economic growth and the consequent need to reconfigure the system that delivers essentials, conveniences, and intangibles to humanity. While ecological economics acquires different foci in different regions, she contends that a basic tenet remains: the need to push the boundaries of sustainability science to evolve a rigorous trans-disciplinary pathway towards realizing an inclusive, equitable, and resilient society.

The welcome address on behalf of the hosting institute was delivered by Shyam Masakapalli, professor and dean, Sponsored Research and Industrial Consultancy, IIT Mandi, and Manu Devadevan, associate professor, School of Humanities and Social Sciences, IIT Mandi. A video tribute was presented to Madhav Gadgil, who passed away just before the conference,

honouring his immeasurable contributions to the field of ecology and inclusive conservation governance.

This year, INSEE conferred the title of INSEE Fellow on CK Varshney and Jyoti Parikh, founding members of INSEE, in recognition of their outstanding contributions to ecological economics and allied fields. The event was a part of the inaugural session.

Figure 4: Video Tribute to Madhav Gadgil at the Inaugural Session on 12 January 2026

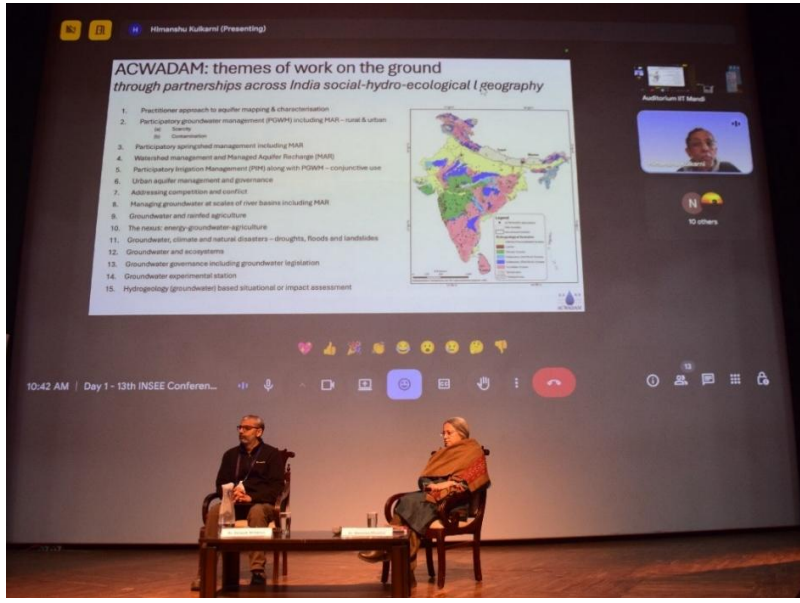


Source*:* Conference Organizing Committee

On the inaugural day, the Second Jayanta Bandyopadhyay Endowment Lecture—set up by the former INSEE president and founding editor of *Ecology, Economy and Society–the INSEE Journal*—was delivered remotely by Himanshu Kulkarni (Advanced Center for Water Resources Development and Management, ACWADAM). Titled "Groundwater, Society, and Ecosystems: Addressing Complex Trade-offs", his lecture emphasized the value of aquifers—an often overlooked but vital resource—and explained why reviving springs is a crucial step in restoring ecosystems, as evidenced by differing groundwater levels beneath forests versus urban land. The lecture also suggested how this priority might be reflected in groundwater governance and policy. Kulkarni's lecture was followed by a panel discussion on water governance and restoration, featuring two speakers working at the interface of gender and water-related issues. Anamika Barua (IIT Guwahati) discussed a case study on Deepor Beel, and Malavika

Chauhan (Centre for Ecology Development and Research, CEDAR) shared insights from her extensive experience in rural development, environmental sustainability, and civil society engagement, particularly in the Himalayan region.

Figure 5: Second Jayanta Bandyopadhyay Endowment Lecture by Himanshu Kulkarni on 12 January 2026



Source*:* Conference Organizing Committee

Figure 6: Release of the Conference Abstract Book at the Inaugural Session on 12 January 2026



Source*:* Conference Organizing Committee

The conference hosted four keynote addresses. The first two addresses were delivered remotely by Pushpam Kumar (United Nations Environment Programme, UNEP), former secretary of INSEE, and Muralee Thummarukudy (UNCCD) on 13 January 2026; they spoke on the economics of restoration, focusing on the integration of ecological concerns into policy frameworks and economic systems.

In his talk on "Mainstreaming Biodiversity into Economics and Finance", Kumar highlighted the need to internalize biodiversity and ecosystem concerns in decision-making on finance and economics, so that harmful subsidies can be avoided across production, distribution, and consumption processes. He emphasized the need for a robust legal and institutional regulatory framework, without which financial mobilization would be challenging.

Speaking on the "Restoration Economy", Thummarukudy noted that although environmental economics has come a long way since its inception as a formal discipline, it is still far from attaining universal application as a tool in decision-making. In his current role as the director of the G20 Global Initiative on Land Restoration at the UNCCD, he emphasized that in peri-urban areas, land restoration can always be left to market forces, and public investment should instead be deployed in areas without a functional market.

On the same day, the third keynote address, titled "Financing Ecological Restoration", was delivered by Rohini Chaturvedi (an independent consultant). She highlighted three non-negotiables for achieving global ecological restoration goals. The first is scale, as small interventions are insufficient to generate meaningful ecological outcomes. The second is the selection of the right place and the use of the right tool, as uniform solutions do not lead to desirable outcomes. And the third is adopting a people-centric approach, with local communities involved at all stages of decision-making.

The final keynote address was on "Regenerative Agriculture and Restoration", delivered by Harpinder Sandhu (Federation University, Australia) on 14 January 2026. Drawing on his decades of experience in agriculture and food systems, he highlighted that agri-food systems cannot be attributed solely to farming but should be understood as integrated networks that link the economy, society, and ecology. He also critiqued the limitations of GDP-centric approaches and commented on the lack of indicators measuring social capital and ecological wealth.

The conference hosted two panel discussions. The discussion on "Resource Use Efficiency and Circular Economy in Ecological Restoration for

Business Action", chaired by Bhim Adhikari (IDRC, Canada), on 12 January 2026, explored the intersection of ecological restoration and business responsibilities. The panellists were Deepak Malghan (IIM Bangalore), Visal Singh (CEDAR), and Aditya Petwal (Centre for Responsible Business, CRB). The panel shared diverse perspectives on the circular economy and on resource-use efficiency.

Figure 7: IDRC-CRB Panel Discussion on 12 January 2026



Source*:* Conference Organizing Committee

The panel on "Forest Restoration and Its Impacts – Evidence from South Asia", on 13 January 2026, was conducted by the IDRC and the South Asian Network for Development and Environmental Economics (SANDEE, instituted by the International Centre for Integrated Mountain Development, ICIMOD). Chaired by Bhim Adhikari, the panel featured Mani Nepal (ICIMOD-SANDEE, Kathmandu), Erandathie Pathiraja (Institute of Policy Studies, Colombo), and Naya Paudel (Forest Action, Nepal), and drew on the ongoing IDRC project on Economics of Forest Restoration in South Asia. The panellists presented facts and figures from restoration activities undertaken across the South Asian countries of Pakistan, Bangladesh, Sri Lanka, and Nepal.

Additionally, on 12 January 2026, there was a dialogue between the representatives of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Forest Department of Himachal Pradesh on "Ecological Restoration in the Indian Himalayan Region". This led to a

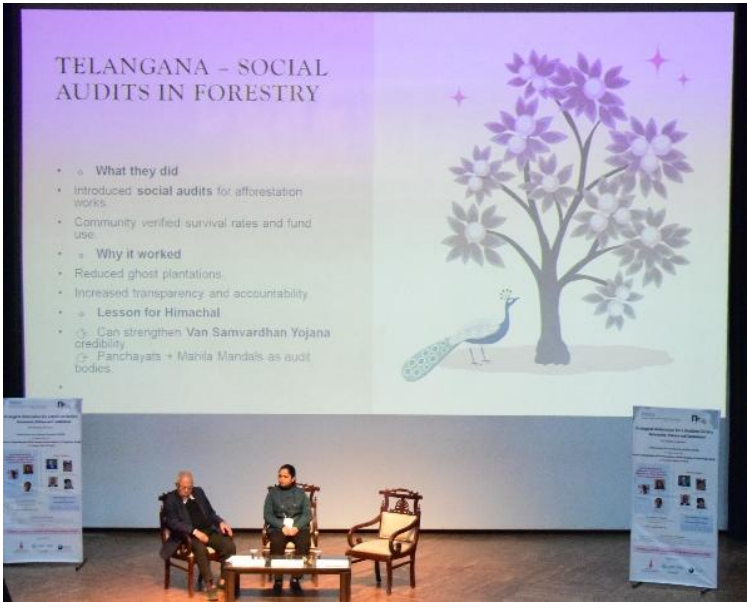
wider discussion on forest restoration and the roles of funding agencies, forest departments, and the community.

Figure 8: IDRC-SANDEE Panel Discussion on 13 January 2026



Source*:* Conference Organizing Committee

Figure 9: Dialogue between GIZ and Forest Department of Himachal Pradesh on 12 January 2026



Source*:* Conference Organizing Committee

A total of 25 oral presentations were delivered across seven thematic sessions on 13 and 14 January 2026. Each presentation was followed by comments from designated discussants and an engaging discussion with the audience. The conference received 126 paper submissions, which were reviewed by a 30-member Scientific Advisory Committee. In addition, the programme also featured two video presentations on 12 January 2026, showcasing innovative approaches to ecological restoration.

In the first video presentation, "Restoring an Urban Lake: Design Principles for a Participatory Socio-Ecological Restoration through a Transdisciplinary Approach", the team from Ashoka Trust for Research in Ecology and the Environment (ATREE) shared a case study of the restoration of a neighbourhood lake in Bengaluru using a participatory and transdisciplinary socio-ecological approach. Drawing on field-based experiences, the presentation highlighted the use of community mapping, biodiversity walks, and storytelling practices to engage residents and inform restoration priorities.

The second presentation was by FES on "Bridging Community Knowledge and Scientific Tools for Landscape Restoration: A Case from the Semi-Arid Kalyanpura Watershed, Rajasthan". It provided a visual representation of the watershed region, which features extensive green spaces, and explained how the local community was introduced to digital instruments for local planning, such as a groundwater monitoring tool. It also featured testimonials from residents who observed the long-term benefits of community engagement in the construction of anicuts and the transfer of other skills.

On 14 January 2026, a discussion on the book *Environmental Studies from India: Engaging with the Planetary Ecological Crisis*), edited by Sudha Vasan (University of Delhi) (Vasan 2025), took place. Saumya Malviya (IIT Mandi) was the reviewer. Nandan Nawn (Jawaharlal Nehru University and Jamia Millia Islamia) offered a summary of his chapter in the book.

A dedicated session on *Ecology, Economy, and Society–the INSEE Journal*—titled "Views from Inside: Making of a Scopus-Indexed COPE Member EES and How the Editorial Process Works"—was conducted by Nandan Nawn (executive editor) and Sudha Vasan (editor) on 13 January 2026.

The final session of the conference was titled "INSEE@25 and Beyond: A Conversation with Past INSEE Presidents" and took place in a hybrid mode on 14 January 2026. Moderated by Seema Purushothaman, the session unfolded as a thoughtful dialogue. The session reminisced on INSEE's origins and its journey so far and also charted possible future paths. Former presidents Jayanta Bandyopadhyay and Gopal Kadekodi

traced the journal's history and offered suggestions for the future. Former INSEE presidents, KN Ninan, Nilanjan Ghosh, and Amita Shah, also shared their thoughts. The younger members of INSEE then shared their expectations from the society.

As the world enters the latter half of the UN Decade on Ecosystem Restoration, the conference emphasised the urgency of translating relevant knowledge into inclusive policies and on-ground action. It reaffirmed INSEE's role as a platform for fostering critical dialogue and collaborative solutions for a more resilient and equitable future.

Figure 10: Participants in the XIII INSEE Biennial Conference at IIT Mandi, 12 January 2026



Source*:* Conference Organizing Committee

Ethics Statement: This study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Data Availability Statement: The work is related to reporting of the 13th INSEE Biennial Conference on "Ecological Restoration for a Resilient Society: Economics, Policies, and Institutions" and hence is not associated to any such data. However, the information on registration, participation and program schedule and other conference-related details are available with the Conference Organizers and could be furnished upon request.

Conflict of Interest Statement: No potential conflict of interest was reported by the author.

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REPORT

A Report on WRI India Workshop Titled "Assessing Distributional Impacts and Advancing Equity in India's Low-Carbon Transition"

Richa,[*] Ashwini Hingne,[**] Varun Jyothiprakash[***] and Arpan Golechha[****]

1. BACKGROUND

As India advances towards its long-term, low-emissions development goals, questions of equity and inclusion become increasingly salient. While decarbonization can generate new jobs, investments, and growth, it can also deepen existing inequalities if distributional impacts are not explicitly addressed.

The WRI India organized a day-long workshop on 29 April 2025 at the Indian Institute of Technology, Delhi, on emerging research, data, and policy approaches to understanding and managing these trade-offs in the Indian context. The workshop brought together over 75 participants—including researchers, policymakers, practitioners, and students—to examine the distributional implications of India's low-carbon transition across regions, sectors, and social groups.

The workshop consisted of a high-level opening session; a methodological masterclass on distributional impact analyses, conducted by researchers;

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thematic World Café discussions on data and methods; and a concluding policy roundtable focused on redistributive policies and institutional responses.

Figure 1. Thematic World Café Session.



Source*:* WRI India; Climate, Economics, and Finance Program

2. SESSION SUMMARY

The central theme of the workshop was that decarbonization is not distributionally neutral. Sectoral discussions covering various industries—such as renewable energy, automotive manufacturing, textiles and apparel, and e-waste processing—highlighted how transition impacts vary across value chains and worker categories. Case studies from different sectors illustrated these dynamics and identified vulnerable groups that require targeted transition support, including women, informal workers, landless labourers, and micro, small, and medium enterprises (MSMEs).

Evidence from large-scale solar projects shows that land-based compensation mechanisms tend to benefit land-owning households, while landless workers experience livelihood losses and limited access to new employment. In the automotive sector, mapping internal combustion engine value chains revealed components and skills that may become redundant in the transition to electric vehicles (EVs), underscoring risks

posed to workers and MSMEs without proactive reskilling and industrial policy measures. Discussions on e-waste emphasized the health and environmental risks borne by informal workers handling hazardous materials, particularly as the deployment of batteries and solar technologies accelerates.

Methodological discussions focused on the limitations of existing analytical frameworks in capturing such impacts. Participants noted that conventional macroeconomic and equilibrium-based models often fail to account for informality, labour heterogeneity, and non-income dimensions of inequality. They emphasized the need to integrate distributive, procedural, and recognition-based equity into climate-economy analysis, and to complement quantitative modelling with qualitative and field-based insights.

Several sessions highlighted the use of environmentally extended social accounting matrices and related tools to assess the effects of climate policies on output, employment, and household incomes across regions and socio-economic groups. These discussions underscored that instruments such as carbon pricing can have regressive effects if implemented in isolation, but that outcomes depend critically on policy design, particularly revenue recycling through targeted transfers, public investment, or employment programmes.

Spatial distribution emerged as a recurring concern. Participants noted that employment gains from renewable energy expansion are likely to be concentrated in western and southern states, while coal-dependent regions in eastern India may face job losses and fiscal pressures. Similarly, while EV adoption may improve urban air quality, upstream environmental burdens from manufacturing and disposal remain unevenly distributed. These patterns raise important questions about regional inequality, migration, and the role of intergovernmental fiscal mechanisms in managing transition-related shocks.

Data availability and governance were identified as binding constraints for robust distributional analysis. Participants highlighted delays in national surveys, limited disaggregation by gender, caste, and employment type, and the lack of panel data to track impacts over time. While private datasets can provide higher-frequency insights, concerns were raised regarding transparency and accessibility. Participants emphasized the need for modular, interoperable, and future-oriented data systems that integrate labour, energy, and consumption data.

The concluding plenary focused on embedding equity within climate policy frameworks by moving beyond compensatory approaches towards anticipatory, justice-oriented planning. Participants stressed the need to

align climate ambition with social protection through progressive fiscal tools, targeted skilling initiatives, and region-specific strategies that account for variations in state capacity and exposure to transition risks. Gender emerged as a cross-cutting priority, with calls to expand the transition discourse to include informal labour, unpaid care work, and intersectional vulnerabilities. Overall, the discussions reinforced the urgency of integrating equity considerations into climate policy design from the outset to ensure that India's low-carbon transition advances social inclusion, regional balance, and long-term development goals.

Figure 2. High-level Plenary Session



Source: WRI India; Climate, Economics, and Finance Program

3. CONCLUSION AND WAY FORWARD

The concluding plenary emphasized the need to move from reactive compensation towards anticipatory, equity-informed climate policy design, aligned with social protection, labour market policies, and regional development planning. Particular attention was given to coal-dependent regions, informal workers, and gender disparities in labour-force participation.

Participants underscored the importance of stronger interdisciplinary research and collaboration to develop reliable methods and robust evidence

on distributional impacts. They identified two critical areas for improving policy relevance: integrating technological pathways into economic modelling, and conducting social impact analysis and field-based research. They made the following recommendations: strengthening analytical frameworks, improving data systems, and fostering closer collaboration between researchers and policymakers to ensure that India's low-carbon transition is inclusive and balanced.

Overall, workshop discussions suggested that aligning climate ambition with social protection and development objectives through anticipatory planning is a priority. Integrating equity *ex ante* into infrastructure, investment, and transition strategies was seen as essential to ensuring that India's low-carbon transition advances inclusion, regional balance, and long-term development goals.

Ethics Statement: We hereby confirm that this study complies with requirements of ethical approvals from the institutional ethics committee for the conduct of this research.

Data Availability Statement: The data comprises workshop discussions and deliberations that are not deposited in a repository but are described within the report.

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About Indian Society for Ecological Economics

INSEE was conceived at a meeting held in New Delhi on 24 September 1998 and within four months it was registered under the Societies Registration Act (1860), as a regional society affiliated to the International Society for Ecological Economics (ISEE).

Its aims and objects include the following:

- To encourage multi-disciplinary, scientific and technological research on the integration of Ecology, Economics and related disciplines and to promote general understanding of the results of that research through education, policy analysis, communication and other appropriate means.
- To promote sustainability at the global, regional, national and local levels.
- To foster inter-disciplinary discourse within and between the social and natural sciences in India and other countries.
- To provide an Indian and South Asian regional focus for activities in Ecological Economics.
- To establish and maintain interaction with the International Society of Ecological Economics and other international organisations working in the same field

It aims to further the cause of sustainable development by providing a forum for dialogue among scholars, practitioners, and policy analysts from various disciplines, particularly economics and ecological sciences on a range of issues of national and international interests, such as climate change, natural resources, energy, waste, ecosystem services and valuation.

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Publications



Climate Change and Disasters: Challenges, Opportunities and Responses. Proceedings of the INSEE-CESS International Conference, edited by Jeena T. Srinivasan and KN Ninan (INSEE, 2020)



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Nature, Economy and Society: Understanding the Linkages, edited by Nilanjan Ghosh, Pranab Mukhopadhyay, Arnita Shah and Manoj Panda (Springe r, 2015)



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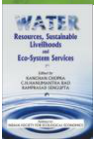

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Interdisciplinarity in Environmental Research: Concepts, Barriers and Possibilities, edited by Sharachchandra Lele, Gopal Kadekodi and Bina Agrawal (INSEE, 2002)









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