Regulating Plastic Rivers: A Study of Microplastic Pollution and Regulatory Deficits in India's Freshwater Systems

Richa Mishra[1], Nidhi Singh[2]

Microplastic pollution in Indian rivers characterises a key, less explored environmental issue with significant public health consequences. The current legislation in India, such as the Water (Prevention and Control of Pollution) Act and the Environment (Protection) Act, does not have specific provisions addressing microplastic pollution. The present study aims to evaluate how scientific knowledge of microplastic behaviour can contribute to shaping the stringent and supportive regulatory systems for India's freshwater ecosystems. The research employs applied policy research methods to examine how scientific knowledge of microplastic breakdown can be used to shape more effective and responsive environmental regulation. The study employs a mixed methodology. The first involves a policy review of a systematic nature that examines Indian river pollution policies, government reports, and monitoring systems to establish gaps in institutions. The second involves the use of interdisciplinary Indo-European collaborations that utilise laboratory experiments and machine learning to simulate emissions from ageing microplastics under different environmental conditions. Third, the research performs machine learning and comparative EU frameworks for adaptive governance against the precautionary governance framework of the EU. The research points to regulatory blind spots in existing pollution legislation, the necessity of pollutant-based monitoring frameworks, and the utility of integrating new environmental science into governance arrangements to frame adaptive, evidence-driven policies. The study further integrates machine-learning-based degradation simulations and machine-learning and comparative EU frameworks for adaptive governance between India and the European Union to develop actionable foresight for evidence-driven governance.

Keywords: microplastic pollution, freshwater governance, environmental risk, green criminology, India, machine learning simulation, comparative policy analysis

1 Introduction

Plastic is one of the most significant ecological challenges of the 21st century. The production of plastic, which exceeds 400 million tons annually, accounts for almost half of this total, with a substantial portion designed for single-use purposes (Organisation for Economic Co-operation and Development [OECD], 2022). The durability and versatile functionality of plastic have reassured its prominent place in the economy; however, the environmental risk it poses now cannot be ignored. Once used, plastic gets repurposed into microplastics, which are particles smaller than 5 mm and have now been classified as one of the most persistent materials in the world. From the bottom-most trenches in the ocean to high altitude clouds in otherwise untouched reserves, microplastics are everywhere (Brahney et al., 2020). Currently, it is estimated that 11 million tons of plastic are dumped in the oceans every year, and if the world continues to function in the same way without attempts to change, that number is expected to increase threefold by 2040 (OECD, 2022; United Nations Environment Programme [UNEP], 2021). In addition to being harmful to the ecosystem, microplastics are a concern to public health because they have been proven to accumulate in various aquatic organisms and are now found in the food people consume as well as in human blood (Babu, 2025; WHO, 2022a). Addressing this challenge directly supports Sustainable Development Goals 6, 12, and 14, aligning India's freshwater governance with global environmental targets. Environmental harm through microplastic pollution represents a form of green crime, echoing the socio-legal analyses by Eman (2013) and Eman et al. (2020), who underline the justice dimensions of environmental neglect in South-Eastern Europe.

---

1   Richa Mishra, Ph.D., Professor, Parul Institute of Engineering and Technology (PIET), Parul University, India. ORCID: 0000-0002-1173-8962. E-mail: richa.mishra31240@paruluniversity.ac.in

2   Nidhi Singh, Ph.D., Professor of Policy Research, Parul Institute of Applied Sciences, Parul University, India. ORCID: 0009-0001-3952-8350. E-mail: nidhi.singh39020@paruluniversity.ac.in

India is grappling with global issues that have emerged since the turn of the century. These issues now include the shortage of water resources in the country. With only 4% of the world's freshwater, the country with 18% of the world's population is deeply mired in water scarcity issues. Although the NITI Aayog (2019) report has categorised 21 of its megacities with the condition of "Day Zero" with infinitesimally low availability of resources, the country still uses 62% of its freshwater resources for irrigation. Groundwater is being overexploited to an unsustainable point. Microplastics, along with sewage, industry effluents, agricultural runoff, and other invisible pollutions, sustain the dereliction of water bodies and other freshwater sources. The Ganga is revered in the country and is considered to be sacred, symbolising spiritual purity. However, it has also been listed amongst the most polluted rivers in the world with respect to plastic (Meijer et al., 2021). This gives an indication of the rising issues of plastic pollution in water bodies.

Indian rivers are more than just water bodies, as they are culturally, ecologically, and economically important. They support agriculture, industry, and livelihoods, and are also sacred lifelines as per Indian customs and religious traditions. The intrusion of microplastics into river systems, however, poses an unprecedented challenge by impairing ecological and cultural harmony. Unlike most forms of pollution, microplastics "slip through the nets" of monitoring and regulation, thus becoming a "hidden pollutant" in water governance. Recent research indicates that microplastics in freshwater systems in India already exist and are affecting aquatic biodiversity, food safety, and public health, and yet they are absent from the legislative agenda (Rillig et al., 2019a).

This research, therefore, attempts to fill an important policy gap. All of India's major environmental legislation, from the Water (Prevention and Control of Pollution) Act of 1974 ("The Water (Prevention and Control of Pollution) Act", 1974) and the Environment (Protection) Act of 1986 ("The Environment (Protection) Act", 1986) to the 2016 Plastic Waste Management Rules (amended 2021) ("Plastic Waste Management Rules", 2021) and the 2022 prohibition on certain single-use plastics, does not include any provisions for microplastic pollution in freshwater ecosystems (Comptroller and Auditor General [CAG], 2021; Ministry of Environment, Forest and Climate Change [MoEFCC], 2022). Insufficient monitoring of exposure, as well as a lack of precautionary measures for exposure, pose significant governance deficits. Unlike this, the European Union (EU) is an innovator of precautionary policies that assimilate emerging science into policy frameworks, thus serving as a useful counterpart (European Commission, 2021b).

1.1 Microplastics as an Emerging Global Pollutant

Microplastics are defined as plastic particles less than 5 mm, either intentionally manufactured (primary microplastics such as pellets or microbeads) or formed through the breakdown of larger debris (secondary microplastics) (OECD, 2022). There are diverse sources for microplastics, including packaging waste, industrial leakage, synthetic textile fibres, and tyre abrasion. For example, studies show that a single load of synthetic laundry can release over 700,000 microfibres into wastewater systems, many of which eventually reach rivers and lakes (Napper & Thompson, 2016). Similarly, tyre abrasion contributes a large yet frequently overlooked share of microplastics to urban runoff and river systems (Kole et al., 2017).

A growing body of global evidence reveals how deeply microplastics have infiltrated natural ecosystems. They have been detected not only in oceans but also in rivers, soils, and even the atmosphere (UNEP, 2021). Brahney et al. (2020) identified microplastic particles in rainfall, showing that these pollutants can travel long distances through atmospheric circulation. Within aquatic environments, they accumulate in river mouths and oceanic gyres, entangling marine species and disrupting biodiversity (UNEP, 2017). Their presence in soils has also been shown to alter soil structure, hinder plant growth, and threaten food security (Rillig et al., 2019b). Addressing these impacts is central to achieving global sustainability commitments, particularly Sustainable Development Goals 6, 12, and 14, which focus on clean water, responsible production, and life below water.

Microplastics are not only an ecological problem; they also pose potential health risks. People are exposed through multiple pathways, including contaminated food, water, air, and even table salt. The World Health Organisation (WHO, 2022b) has identified drinking water and seafood as major dietary sources. In India, the discovery of microplastic fibres in municipal tap water has raised public concern about daily exposure. Laboratory studies have linked microplastic ingestion and inhalation to oxidative stress, DNA damage, and inflammatory responses, while additives like BPA and phthalates are known to disrupt hormonal and reproductive systems (Rochman et al., 2014). Inhalation of airborne fibres may also contribute to respiratory and cardiovascular complications (Prata, 2018).

From an economic perspective, the consequences of plastic and microplastic pollution are equally alarming. The OECD (2022) estimated that environmental degradation, fisheries collapse, reduced tourism, and cleanup costs could together impose an annual global loss of nearly USD 600

billion by 2040 (UNEP, 2021; World Wide Fund for Nature [WWF], 2022). Developing economies, including India, are likely to bear a disproportionate share of this burden since their rivers and freshwater systems are deeply interwoven with agriculture, livelihoods, and cultural heritage.

1.2 India's Critical Freshwater Crisis

India, home to nearly 18% of the world's population but only about 4% of its freshwater resources (Food and Agriculture Organization of the United Nations, 2022), faces an increasingly fragile water situation. Most Indian rivers are already under immense pressure from untreated sewage, of which only around 30% is processed alongside industrial effluents and agricultural runoff (Central Pollution Control Board [CPCB], 2020). Against this backdrop, the infiltration of microplastics adds a new, largely invisible layer to the country's freshwater crisis (Meijer et al., 2021).

The Ganga River, for instance, often celebrated for its spiritual significance, has been identified among the ten most plastic-polluted rivers in the world (Meijer et al., 2021). Yet India's principal environmental laws, the Water (Prevention and Control of Pollution) Act ("The Water (Prevention and Control of Pollution) Act", 1974) and the Environment (Protection) Act ("The Environment (Protection) Act", 1986), do not explicitly recognise microplastic contamination (CPCB, 2020; MoEFCC, 2022). While the Plastic Waste Management Rules ("Plastic Waste Management Rules", 2021) introduced the concept of extended producer responsibility and certain single-use plastic bans, enforcement remains inconsistent and weak, as observed by the Comptroller and Auditor General (2021).

This absence of robust implementation has created a regulatory blind spot: microplastics remain outside national monitoring systems even as scientific evidence of their spread grows. Domestic studies have already detected microplastic particles in Ganga Basin sediments (CPCB, 2022) and Delhi's tap water (Babu, 2025), reinforcing the need for an integrated monitoring and regulatory framework. Similar governance gaps have been discussed by Meško and Eman (2020), who noted that institutional inertia and fragmented policies often leave emerging environmental risks insufficiently addressed.

1.3 Advances in Scientific and Technological Insights

Scientific laboratory-based simulations that replicate environmental stressors, such as UV radiation, salinity, and microbial activity, have explored how microplastics degrade and release toxic additives (Gewert et al., 2015; Lambert & Wagner, 2016). Such studies showed that even biodegradable plastics fragment into persistent pollutants. Ivleva et al. (2016) further show that degradation patterns differ by hydrological context, which highlights the need for localised studies in this area.

At the scientific and technology frontier, AI and machine learning are being deployed to model microplastic distribution and predict emissions from ageing plastics. Chassignet et al. (2021) showed the potential of global flow models, while Indo-European collaborations like the PANIWATER project integrate laboratory simulations with real-time detection technologies (FTIR, LDIR spectroscopy) to inform governance (OECD, 2022; Yin et al., 2024).

1.4 Research Gap and Problem Statement

While going through studies on microplastic pollution in India, we noticed that much of the discussion still leaves important questions unanswered. Our review revealed three main gaps that continue to hinder real progress: 1) missing data and monitoring, 2) weak and outdated rules, and 3) a poor link between science and policy. Most global research focuses on the ocean. In India, freshwater systems have been studied in a largely unstructured manner. The few reports we have, such as those on the Ganga or Delhi's tap water, give only small pieces of the picture. There is still no steady or national effort to monitor microplastics in our rivers and lakes. Our main environmental laws, including the The Water (Prevention and Control of Pollution) Act ("The Water (Prevention and Control of Pollution) Act", 1974) the Environment Protection Act ("The Environment (Protection) Act", 1986), and the Plastic Waste Management Rules ("Plastic Waste Management Rules", 2021), do not actually mention microplastics. Because of this, there is no clear legal route to control or penalise microplastic pollution. Even the existing laws are not well enforced, as official reviews often point out gaps in capacity and action. New research and AI-based studies now explain how microplastics form, move, and affect health. But in India, these findings rarely shape policy or regulation. We usually respond only after visible damage appears, instead of preventing it early. This reactive style of governance keeps us behind countries that already follow a precautionary approach. These three gaps show a wider problem: our scientific understanding of microplastics is growing fast, but our policies have not caught up. This distance threatens the safety of our water, the well-being of people who depend on it, and the cultural ties many communities share with rivers. In this study, we have tried to bridge that space by reviewing policies, learning from India–Europe collaborations, and suggesting a more flexible and forward-looking way to manage microplastic pollution.

2 Theoretical Framework

To study the regulatory deficits concerning microplastic pollution in India, this study has attempted to use two complementary theoretical perspectives: 1) Green Criminology and 2) Risk Governance Theory. These two theoretical perspectives will allow us to interrogate both the justice dimensions of ecological harm and the institutional responses to scientific uncertainty. Below, we will explore them in some detail. As noted by Eman (2013), environmental crime transcends national borders and often persists due to governance inertia and limited cross-institutional accountability. Comparative studies in transnational criminology (Meško, 2024) further validate the importance of adaptive policy frameworks in contexts where uncertainty and diffuse accountability prevail.

In this study, we turn to Green Criminology as a way of understanding environmental harm through a broader, justice-oriented lens. Rather than limiting our analysis to what is legally defined as crime, this approach invites us to examine actions that, while not technically unlawful, still cause serious ecological and social damage (White, 2013). Within this perspective, we regard microplastic pollution as a green crime – a form of environmental harm that remains largely unregulated yet produces tangible impacts on rivers, ecosystems, and public health. Although a growing body of scientific work identifies clear risks associated with microplastics, India's current laws-the Water (Prevention and Control of Pollution) Act ("The Water (Prevention and Control of Pollution) Act", 1974), and the Environment (Protection) Act ("The Environment (Protection) Act", 1986) do not recognise them as pollutants or hazardous materials. Consequently, releasing these particles into freshwater systems remains beyond the reach of legal accountability. This gap demonstrates a serious weakness in how we define and address environmental wrongdoing. From this standpoint, we also look at the underlying systems that enable such harm. The continued loss of industrial pellets, insufficient effluent control, and minimal enforcement reveal how corporate and institutional practices externalise environmental costs. Treating microplastic contamination as a green crime thus helps surface the ethical dimensions of this neglect. We argue that stronger accountability is essential through disclosure obligations for industries, liability mechanisms grounded in the polluter-pays principle, and the strategic use of public-interest litigation to ensure that environmental damage translates into enforceable responsibility.

We also apply Risk Governance Theory to understand how policy frameworks respond to uncertainty. Ulrich Beck's (1992) idea of the "risk society" reminds us that many contemporary threats, such as microplastics, are manufactured risks: products of industrial processes that are global in scope, invisible in nature, and difficult to predict. Unlike traditional hazards, these are sustained by everyday human activity and persist across boundaries of geography and time. Their tiny size and ability to accumulate in living organisms make them an especially challenging category of risk (Renn et al., 2011). Risk Governance Theory proposes that when risks are uncertain but potentially severe, policy should lean toward precaution and adaptability. The European Union's Plastics Strategy and its REACH regulations are good illustrations of this approach, setting precautionary limits and discharge thresholds for microplastics (European Commission, 2021a; van Asselt & Vos, 2008). In contrast, India's environmental governance remains mostly reactive. The focus stays on visible or conventional pollutants such as sewage, organic waste, or heavy metals, while less tangible threats like microplastics receive little policy or monitoring attention. This reveals an institutional culture that responds to proven harm rather than anticipating emerging risks.

Bringing together Green Criminology and Risk Governance Theory enables a fuller understanding of the dual challenges within India's freshwater governance: the moral and the institutional. The first framework sensitises us to issues of environmental justice and responsibility, while the second reveals procedural and structural gaps that hinder proactive regulation. Through this integrative lens, we aim to connect the ethical and the administrative dimensions of environmental management. Green Criminology exposes how regulatory silence allows harm to persist without accountability, whereas Risk Governance Theory highlights the need for anticipatory, evidence-based policymaking. Taken together, they offer a way to rethink how we govern emerging contaminants. Our argument, therefore, is that addressing microplastic pollution in India requires more than incremental reform; it calls for a deliberate shift toward a precautionary, justice-driven, and adaptive policy model. By doing so, we can move from reactive clean-up efforts to preventive governance that aligns environmental protection with equity and long-term sustainability.

3 Methodology

The study undertakes policy research analysis and incorporates both qualitative and interdisciplinary approaches to analyse the governance of microplastic pollution in India's freshwater systems. The methodology has been designed in three parts: A review of India's freshwater governance system has been conducted to identify regulatory gaps related to microplastic pollution within India's water governance frameworks. The review firstly examines the legislation, such as the Water (Prevention and Control of Pollution) Act, the

Environment (Protection) Act, Plastic Waste Management Rules, the Plastic Waste Management (Amendment) Rules, and National Water Policy. Secondly, it examines programs and missions like Namami Gange, Ganga Action Plan, and Swachh Bharat Abhiyan. Thirdly, it undertook the analysis of institutional reports, including those from the Central Pollution Control Board (CPCB), the CAG, and the NITI Aayog assessments. The review mechanism used a systematic framework, classifying policies into categories of recognition (explicit mention of microplastics), monitoring (pollutant-specific tracking), and regulation (standards, bans, or enforcement mechanisms). This helped in identifying the policy loopholes in India's current legislative landscape.

point for comparison, like Regulatory definitions and standards (whether microplastics are legally recognised pollutants); Monitoring and enforcement mechanisms (national pollutant inventories, water quality directives); Governance principles (precautionary approach, circular economy, extended producer responsibility). This comparative analysis highlights how India could adapt elements of the EU's precautionary governance to its own legal and institutional systems. The analytical framework in Table 1 summarises datasets, analytical tools, and comparative parameters between the Indian and EU frameworks.

The findings extracted from the three methodological components are analysed through the lens of Green

Table 1: Overview of data sources, analytical tools, and comparative parameters

Component	Data Sources/ Literature Base	Analytical Tools and Approach	Comparative Parameters (India vs. EU)	Selection Criteria for Studies
Policy and Legislative Review	Government notifications, Environmental (Protection) Act, Plastic Waste Management Rules, CPCB and MoEFCC reports	Qualitative policy mapping; legal text analysis; thematic coding of regulatory gaps	Existence of microplastic definitions, monitoring provisions, and enforcement mechanisms	Inclusion of primary legal frameworks published between 2015 and 2024
Science-Policy Interface	Peer-reviewed studies on microplastic detection and degradation; Indo-EU research collaborations; UNEP and OECD datasets	Content synthesis, cross-referencing of scientific and regulatory evidence	Integration of scientific findings into environmental decision-making	Studies focusing on freshwater systems and published between 2018 and 2024
Comparative Governance Analysis	EU Water Framework Directive (2000/60/EC), Marine Strategy Framework Directive (2008/56/EC), Circular Economy Action Plan (2020)	Comparative policy benchmarking; matrix analysis of institutional structures	Precautionary principle adoption, inter-agency coordination, and transparency mechanisms	EU directives and progress reports from 2000–2023
Analytical and Theoretical Framework	Academic works in Green Criminology and Risk Governance Theory	Thematic interpretation; cross-disciplinary triangulation	Accountability mechanisms; risk anticipation; institutional responsiveness	Inclusion of peer-reviewed theoretical sources from 2008 to 2025, relevant to environmental governance

Releasing that scientific uncertainty surrounding microplastics, the study has incorporated some findings from Indo-European interdisciplinary collaborations that simulate the environmental behaviour of microplastics. The Indo-EU studies considered were peer-reviewed publications from 2018 to 2024 that modelled polymer ageing under hydrological or climatic conditions comparable to Indian rivers.

Comparative analysis has been done for India's water governance frameworks and the European Union's precautionary policy models with the aim of identifying lessons for India. The EU's integration of microplastic science into adaptive and anticipatory regulation serves as a key reference

Criminology and Risk Governance Theory. This allows the study to assess the persisting lacunae in the legislative and institutional systems that would help in formulating sustainable precautionary dimensions of India's regulatory deficit on microplastics. The interdisciplinary approach aligns with Meško's (2024) cross-cultural research paradigm, integrating criminology, sociology, and policy studies.

4 Results

In this section, we present our findings in two parts. First, we discuss the empirical evidence on microplastic degradation

and emission potential based on Indo-European collaborative studies. We then examine the regulatory and institutional gaps identified in India's freshwater governance system.

Several Indo-European interdisciplinary research efforts (Lin et al., 2018; Schrank et al., 2019; Wagner et al., 2024; Zhang et al., 2021) have used laboratory simulations and machine learning (ML) models to study how common plastic polymers degrade and release microplastics under typical Indian river conditions. These simulations accounted for variations in ultraviolet exposure, temperature, and microbial activity. Collectively, the studies found a significant and accelerating source of secondary microplastic contamination within India's freshwater ecosystems. Other experimental studies confirmed that plastic polymers tend to fragment much faster under tropical climatic conditions than previously assumed in temperate-region models (Alimi et al., 2022; Binda et al., 2024; Sun et al., 2016). Notably, polyethylene (PE) and polypropylene (PP)-the main components of single-use plastic items-exhibited the fastest rates of degradation (Alimi et al., 2022; Binda et al., 2024; He et al., 2023). The ML-based degradation models predicted approximately a 65% increase in secondary microplastic generation under simulated Indian summer conditions, where solar radiation and temperature remain consistently high. These models, trained on Indo-EU empirical datasets and validated through ten-fold cross-testing, also projected a chronic, non-point source of microplastic emissions resulting from ageing plastic debris. Such findings suggest that existing litter itself has become a continuous and internal source of microplastic pollution, raising long-term ecological and human health risks through potential bioaccumulation and tissue translocation.

Our systematic policy review of India's central environmental statutes, the Water (Prevention and Control of Pollution) Act ("The Water (Prevention and Control of Pollution) Act", 1974), and the Environment (Protection) Act ("The Environment (Protection) Act", 1986), along with relevant government documents, revealed a significant regulatory lag in addressing microplastic contamination. We found that microplastics are completely absent from the current legal framework, and there is no institutional mechanism to manage or monitor them. Neither of the two major Acts defines microplastics as a pollutant, a hazardous substance, or a trade effluent. Consequently, the Central and State Pollution Control Boards do not have a statutory mandate to regulate their discharge. This definitional vacuum means that microplastic emissions fall entirely outside the "Consent to Establish" or "Consent to Operate" frameworks, creating a major legislative gap that allows unrestricted discharge into aquatic environments.

Our analysis of national water quality monitoring programs further confirms that the existing protocols remain pollutant-specific rather than effect-based, rendering them incapable of detecting or tracking emerging contaminants like microplastics. Current monitoring parameters prescribed by the CPCB continue to focus on conventional metrics such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), pH, and heavy metals. After reviewing 22 CPCB Annual Reports on Water Quality (2018–2023), we found no evidence of any dedicated microplastic monitoring stations or guidelines for emerging contaminants.

We also identified a significant infrastructure gap. Most state-level environmental laboratories still lack the instruments necessary for accurate microplastic identification and quantification, such as Fourier-Transform Infrared Spectroscopy (FTIR) or Laser Direct Infrared systems. This lack of equipment further limits the ability of pollution control agencies to implement effective monitoring or regulatory action.

When we synthesised the empirical and policy findings, a clear disconnect emerged. The scientific evidence points to an accelerating risk, yet India's legal and regulatory systems remain unresponsive to it. In contrast, the European Union's precautionary governance model provides a proactive framework that could serve as a valuable reference. Our analysis suggests that India must adopt a similar paradigm shift-one that recognises microplastics as an emerging environmental hazard and integrates both scientific risk modelling and policy reform to establish a sustainable, forward-looking governance structure.

5   Discussion

Our study reflects upon the serious environmental risks posed by microplastic pollution in India's freshwater systems and highlights the limited capacity of the current regulatory framework to respond effectively. In this section, we interpret our findings in light of the literature review and through the lenses of the Precautionary Principle and Green Criminology. Based on the empirical evidence we examined, it is clear that microplastic pollution is no longer a marginal concern; it is an escalating threat whose severity is increasing over time. Unlike episodic pollution events, we observe that the source of microplastics in Indian rivers is largely internal and chronic, resulting from the gradual breakdown of existing plastic waste within aquatic ecosystems. Addressing this issue requires us to think beyond simple discharge limits and focus on product design, lifecycle management, and proactive pollution prevention. Our review of existing policies further

reveals that India's regulatory framework is not yet equipped to manage emerging contaminants like microplastics. The absence of a clear legal definition of whether as a 'pollutant' or a 'hazardous substance' is more than an oversight; we interpret this as a systemic institutional weakness that contributes to ongoing environmental degradation. This resonates with Meško and Eman (2020), who emphasise the criminogenic potential of environmental neglect when regulatory systems fail to anticipate structural harm. These findings align strongly with the perspectives of Green Criminology, which identify governance gaps where regulators lack the legal mandate, monitoring protocols, and infrastructural capacity to prevent foreseeable harm. In this context, we note that unregulated plastic production and disposal continue unchecked, allowing environmentally damaging practices to persist. Without legal recognition of microplastics as a pollutant, State Pollution Control Boards are effectively shielded from accountability, resulting in a form of environmental injustice by failing to protect the public's right to clean water.

Through our comparative analysis, we highlight a fundamental difference between India's centralised, reactive approach and the European Union's precautionary governance model. In India, regulatory action generally waits for demonstrated harm, delaying intervention until environmental damage has already occurred. By contrast, the EU's application of the Precautionary Principle mandates preventive measures when there is a plausible risk of serious or irreversible damage, even without conclusive scientific proof. The key contribution of our study is that effective regulation requires more than legislative amendments; it requires a shift in governance philosophy. We argue that moving from a reactive, post-crisis model to a precautionary approach, which integrates scientific risk modelling into regulatory decision-making, can help India better anticipate and prevent harm from emerging environmental threats such as microplastics.

6   Conclusion

In this work, we draw on insights from both Indo-EU research collaborations and recent policy reviews to examine why India's environmental governance still struggles to keep pace with emerging pollution challenges. Our analysis shows that microplastic contamination in rivers and lakes is not merely the result of waste being dumped from outside sources; it is increasingly a home-grown problem, worsened by the gradual breakdown of older plastic waste under changing climatic conditions. The findings point out a clear mismatch between the growing, evidence-backed risks of microplastic pollution and the country's current regulatory setup. India's

main environmental laws, the Water (Prevention and Control of Pollution) Act ("The Water (Prevention and Control of Pollution) Act", 1974), and the Environment (Protection) Act ("The Environment (Protection) Act", 1986), do not yet recognise microplastics as a distinct pollutant, creating a serious gap in enforcement. This policy shortcoming is made worse by weak institutional capacity; as CPCB reports reveal, there is no dedicated system for monitoring microplastics, and most state laboratories still lack the basic instruments needed for their analysis. Much of this failure stems from the centralised way environmental control (bureaucratic Control) is exercised in India, which stands in contrast to the European Union's more precautionary approach. The tendency to wait for definitive proof of harm before taking action mirrors what Green Criminology describes as structural or institutional neglect. Taken together, these findings highlight how India's regulatory framework lags in addressing new contaminants, calling for a shift toward proactive and precautionary environmental governance.

The following mandatory policy and regulatory recommendations are the outcomes of the study that would help in dealing with structural challenges persisting in the Indian system:

— There is an urgent need to explicitly define microplastics as a Hazardous Substance and Pollutant. The MoEFCC should urgently amend the Environment (Protection) Act ("The Environment (Protection) Act", 1986). This should be the first and foremost legislative action necessary to provide the Central and State Pollution Control Boards with the statutory mandate to regulate MP discharge;

— Implementation of a "Foresight Analysis" to conduct mandatory life-cycle assessments on new plastic polymers, specifically modelling their fragmentation kinetics under tropical conditions before market entry. This will move regulatory focus upstream to material-stream control;

— The CPCB's National Water Quality Monitoring Programme must immediately integrate microplastic particle count, size distribution, and polymer identification as standard, mandatory parameters alongside traditional metrics;

— A targeted-based national fund must be allocated for equipping regional SPCB laboratories with advanced spectroscopic analysis equipment and training technical personnel in emergent contaminant analysis; and

— Regulatory bodies should integrate scientific tools, such as the machine learning degradation models, into policy risk assessments to guide proactive interventions rather than relying solely on retrospective monitoring data.

References

1. Alimi, O. S., Claveau-Mallet, D., Kurusu, R. S., Lapointe, M., Bayen, S., & Tufenkji, N. (2022). Weathering pathways and protocols for environmentally relevant microplastics and nanoplastics: What are we missing? *Journal of Hazardous Materials, 423,* 126955. https://doi.org/10.1016/j.jhazmat.2021.126955

2. Babu, N. M. (1. 2. 2025). Study finds microplastics in Delhi's groundwater: The study commissioned by the Delhi govt. also found microplastics in the Yamuna's water and soil samples from its banks. *The Hindu.* https://www.thehindu.com/

3. Beck, U. (1992). *Risk society: Towards a new modernity* (Vol. 17). Sage.

4. Binda, G., Kalčíková, G., Allan, I. J., Hurley, R., Rødland, E., Spanu, D., & Nizzetto, L. (2024). Microplastic ageing processes: Environmental relevance and analytical implications. *TrAC Trends in Analytical Chemistry, 172,* 117566. https://doi.org/10.1016/j.trac.2024.117566

5. Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., & Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science, 368*(6496), 1257–1260.

6. Central Pollution Control Board (CPCB). (2020). *Status of sewage treatment plants in India.* Government of India.

7. Central Pollution Control Board (CPCB). (2022). *Draft National Action Plan for Microplastics.* Government of India.

8. Chassignet, E. P., Xu, X., & Zavala-Romero, O. (2021). Tracking marine litter with a global ocean model: Where does it go? Where does it come from? *Frontiers in Marine Science, 8,* 667591. https://doi.org/10.3389/fmars.2021.667591

9. Comptroller and Auditor General (CAG). (2021). *Performance audit of river rejuvenation programmes.* Government of India.

10. Eman, K. (2013). Environmental crime trends in Slovenia in the past decade. *Varstvoslovje*, *15*(2), 240-260.

11. Eman, K., Meško, G., Segato, L., & Migliorini, M. (Eds.). (2020). *Water, governance, and crime issues.* Springer.

12. European Commission. (2021a). *EU Action Plan: Towards a circular economy for plastics.* European Commission.

13. European Commission. (2021b). *EU Action Plan: Towards zero pollution for air, water and soil.* European Union. https://environment.ec.europa.eu/publications/zero-pollution-action-plan_en

14. Food and Agriculture Organization of the United Nations. (2022). *AQUASTAT - FAO's global information system on water and agriculture.* https://www.fao.org/aquastat/en/databases/maindatabase

15. Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Science: Processes & Impacts, 17*(9), 1513–1521.

16. He, W., Liu, S., Zhang, W., Yi, K., Zhang, C., Pang, H., Huang, D., Huang, J, & Li, X. (2023). Recent advances on microplastic ageing: Identification, mechanism, influence factors, and additives release. *Science of The Total Environment, 889,* 164035. https://doi.org/10.1016/j.scitotenv.2023.164035

17. Ivleva, N. P., Wiesheu, A. C., & Niessner, R. (2016). Microplastics in aquatic ecosystems. *Angewandte Chemie International Edition, 56*(7), 1720–1739.

18. Kole, P. J., Löhr, A. J., Van Belleghem, F., & Ragas, A. M. (2017). Wear and tear of tyres: A stealthy source of microplastics in the environment. *International Journal of Environmental Research and Public Health, 14*(10), 1265.

19. Lambert, S., & Wagner, M. (2016). Formation of microscopic particles during the degradation of different polymers. *Chemosphere, 161,* 510–517.

20. Lin, L., Zuo, L. Z., Peng, J. P., Cai, L. Q., Fok, L., Yan, Y., Li, H.-X., & Xu, X. R. (2018). Occurrence and distribution of microplastics in an urban river: A case study in the Pearl River along Guangzhou City, China. *Science of the Total Environment, 644,* 375–381.

21. Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science Advances, 7*(18), eaa z5803. https://www.science.org/doi/10.1126/sciadv.aaz5803

22. Meško, G. (2024). Editorial: Comparative, translational, applied and public criminology – A brief reflection. *European Journal of Crime, Criminal Law and Criminal Justice, 32*(4), 273–289.

23. Meško, G., & Eman, K. (2020). *Policing water crimes*. In K. Eman, G. Meško, L. Segato, & M. Migliorini (Eds.), *Water, governance, and crime issues* (pp. 75–91). Springer.

24. Ministry of Environment, Forest and Climate Change (MoEFCC). (2022). *Plastic Waste Management (Amendment) Rules.* Government of India. https://cpcb.nic.in/rules-4/

25. Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine Pollution Bulletin, 112*(1–2), 39–45.

26. NITI Aayog. (2019). *Composite water management index report 2019.* NITI Aayog. https://www.niti.gov.in/reports-research/composite-water-management-index-2019

27. Organisation for Economic Co-operation and Development (OECD). (2022). *Global plastics outlook: Policy scenarios to 2060.* OECD Publishing. https://doi.org/10.1787/aa1edf33-en

28. Plastic Waste Management Rules. (2021). *The Gazette of India*, (33004/99).

29. Prata, J. C. (2018). Airborne microplastics: Consequences to human health? *Environmental Pollution, 234,* 115–126.

30. Renn, O., Klinke, A., & van Asselt, M. (2011). Coping with complexity, uncertainty and ambiguity in risk governance: A synthesis. *Ambio, 40*(2), 231–246.

31. Rillig, M. C., Lehmann, A., de Souza Machado, A. A., & Yang, G. (2019a). Microplastic effects on plants. *New Phytologist, 223*(3), 1066–1070.

32. Rillig, M. C., Lehmann, A., Ryo, M., & Bergmann, J. (2019b). Shaping up: Toward considering the shape and form of pollutants. *Environmental Science & Technology, 53*(14), 7925–7936.

33. Rochman, C. M., Kurobe, T., Flores, I., & Teh, S. J. (2014). Early warning signs of endocrine disruption in adult fish from the ingestion of polyethene with and without sorbed chemical pollutants from the marine environment. *Science of the Total Environment, 493*, 656–661.

34. Schrank, I., Trotter, B., & Laforsch, C. (2019). Effects of microplastic particles and leaching additive on the life history and morphology of Daphnia magna. *Environmental Pollution, 255,* 113233. https://doi.org/10.1016/j.envpol.2019.113233

35. Sun, P., Liu, X., Zhang, M., Li, Z., Cao, C., Shi, H., Yang, Y., & Zhao, Y. (2021). Sorption and leaching behaviours between aged MPs and BPA in water: The role of BPA binding modes within plastic matrix. *Water Research, 195,* 116956. https://doi.org/10.1016/j.watres.2021.116956

36. The Environment (Protection) Act. (1986). *Act no.,* (29/1986).

37. The Water (Prevention and Control of Pollution) Act. (1974). *Act no.,* (6/1974).

38. United Nations Environment Programme (UNEP). (2017). *Marine litter: A global challenge.* UNEP. https://www.unep.org/resources/report/marine-litter-global-challenge

39. United Nations Environment Programme (UNEP). (2021). *From pollution to solution: A global assessment of marine litter and plastic pollution.* UNEP. https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution

40. van Asselt, M. B., & Vos, E. (2008). Wrestling with uncertain risks: EU regulation of GMOs and the uncertainty paradox. *Journal of Risk Research, 11*(1-2), 281–300.

41. Wagner, M., Monclús, L., Arp, H. P. H., Groh, K. J., Løseth, M. E., Muncke, J., Zhanyun, W., Raoul, W., & Zimmermann, L. (2024). *State of the science on plastic chemicals—Identifying and addressing chemicals and polymers of concern.* Zenodo.

42. White, R. (2013). Green criminology and the pursuit of social and ecological justice. *Critical Criminology, 21*, 267–281.

43. World Health Organisation (WHO). (2022a). *Dietary and human exposure to microplastics: What we know and what we need to find out.* WHO. https://www.who.int/publications/i/item/9789240054608

44. World Health Organisation (WHO). (2022b). *Microplastics in drinking water.* WHO. https://www.who.int/publications/i/item/9789240054608

45. World Wide Fund for Nature (WWF). (2022). *Impacts of plastic pollution on fisheries and tourism.* WWF International.

46. Yin, J., Geng, Q., Xiao, X., Wang, S., Meng, L., Deng, N., Xu, J., Su, B., Chen, J., Zhao, W., Jin, L., & Zhao, C. (2024). Mussel-inspired antibacterial sponge for highly efficient water purification and sterilisation. *Journal of Hazardous Materials, 461,* 132598. https://doi.org/10.1016/j.jhazmat.2023.132598

47. Zhang, K., Hamidian, A. H., Tubić, A., Zhang, Y., Fang, J. K. H., Wu, C., & Lam, P. K. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. *Environmental Pollution, 274,* 116554. https://doi.org/10.1016/j.envpol.2021.116554

Reguliranje plastičnih rek: študija onesnaženja z mikroplastiko in regulativnih primanjkljajev v indijskih sladkovodnih sistemih

Dr. Richa Mishra, profesorica, Parul inštitut za inženirstvo (PIET), Parul univerza, Indija. ORCID: 0000-0002-1173-8962. E-pošta: richa.mishra31240@paruluniversity.ac.in

Dr. Nidhi Singh, profesor za politološko raziskovanje, Parul inštitut za aplikativne znanosti, Parul univerza, Indija. ORCID: 0009-0001-3952-8350. E-pošta: singh39020@paruluniversity.ac.in

Onesnaženje z mikroplastiko v indijskih rekah je ključno, manj raziskano okoljsko vprašanje s pomembnimi posledicami za javno zdravje. Veljavna indijska zakonodaja, kot sta Zakon o preprečevanju in nadzoru onesnaževanja z vodo in Zakon o varstvu okolja, nima posebnih določb, ki bi obravnavale onesnaženje z mikroplastiko. Namen te študije je oceniti, kako lahko znanstvena dognanja o vedenju mikroplastike prispeva k oblikovanju strogih in podpornih regulativnih sistemov za indijske sladkovodne ekosisteme. V študiju so uporabljene metode raziskovanja politik, z namenom preučitve, kako se lahko znanstveno znanje o razgradnji mikroplastike uporabi za oblikovanje učinkovitejše in odzivnejše okoljske regulacije. Študija uporablja mešano metodologijo. Prvi pristop vključuje sistematičen pregled politik, ki preučuje indijske politike o onesnaževanju rek, vladna poročila in sisteme spremljanja, s katerim smo identificirali vrzeli v institucijah. Drugi pristop vključuje uporabo interdisciplinarnih indoevropskih sodelovanj, ki uporabljajo laboratorijske poskuse in strojno učenje za simulacijo emisij starajoče se mikroplastike v različnih okoljskih pogojih. Tretji pristop pa temelji na raziskovanju, kjer se izvaja strojno učenje in primerja okvire EU za prilagodljivo upravljanje okvira previdnostnega upravljanja EU. Ugotovitve študije izpostavljajo regulativne slepe pege v obstoječi zakonodaji o onesnaževanju, nujnost okvirov za spremljanje, ki temeljijo na onesnaževalih, in koristnost vključevanja nove okoljske znanosti v ureditve upravljanja za oblikovanje prilagodljivih na dokazih temelječih politik. Študija nadalje združuje simulacije degradacije, ki temeljijo na strojnem učenju, ter strojno učenje in primerjalne okvire EU za prilagodljivo upravljanje med Indijo in Evropsko unijo za razvoj izvedljivega predvidevanja za na dokazih temelječega upravljanja.

Ključne besede: onesnaževanje z mikroplastiko, upravljanje sladke vode, okoljsko tveganje, zelena kriminologija, Indija, simulacija strojnega učenja, primerjalna analiza politik