MICROPLASTIC POLLUTION IN COUPLED NATURE–SOCIETY SYSTEMS: SYNTHESIS OF IMPACTS AND CO-MANAGEMENT STRATEGIES

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Abstract
Microplastic pollution has emerged as a defining socio-ecological crisis of the Anthropocene, transcending its initial classification as a marine litter problem to become a complex, global threat embedded in Coupled Nature–Society Systems (CNSS). This review synthesizes current knowledge on the origins, pathways, impacts, and governance of microplastics (MPs), adopting a CNSS framework to highlight dynamic feedbacks between environmental degradation and human activity. MPs originate from both primary and secondary sources and disperse through atmospheric, terrestrial, aquatic, and biological routes, accumulating across trophic levels and global geographies. Their ecological impacts include biodiversity loss, ecosystem disruption, and bioaccumulation, while their socioeconomic consequences span food insecurity, health risks, economic loss, and cultural erosion - especially in low - and middle-income countries (LMICs). The paper advocates co-management as a systemic, adaptive governance strategy, promoting shared responsibility among states, industries, communities, and scientists. By integrating circular economy principles, extended producer responsibility, and One Health approaches, co-management enhances resilience and equity within CNSS. The review concludes with research priorities and policy recommendations, emphasizing the need for interdisciplinary collaboration, context-sensitive governance, and globally binding agreements to mitigate microplastic pollution across the plastic life cycle.

Keywords: microplastic pollution; Coupled Nature–Society Systems (CNSS); co-management; circular economy; environmental governance; socio-ecological systems; trophic transfer; One Health; global plastics crisis; interdisciplinary policy; ecological resilience

1. INTRODUCTION

Microplastics (MPs) are broadly defined as synthetic polymer particles smaller than 5 mm in diameter, while their even smaller counterparts, nanoplastics (NPs), measure below 1 µm (Kumar et al., 2025; Peng et al., 2024). Since the industrial-scale introduction of plastics in the 1950s, global plastic production has grown exponentially, surpassing 400 million metric tons annually by 2022 (OECD, 2022). This unprecedented proliferation, driven by urbanization and consumer culture, has led to the widespread dispersion of MPs

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across all environmental matrices - hydrosphere, atmosphere, lithosphere, and biosphere (UNEP, 2021; Priya et al., 2022).

While traditionally framed as an environmental problem, microplastic pollution is increasingly recognized as a deeply interlinked socio-ecological crisis. It is estimated that only 21% of global plastic waste is either recycled or incinerated, leaving the remaining 79% to accumulate in terrestrial and aquatic environments (Borrelle et al., 2020). If current waste management trajectories persist, approximately 12 billion tons of plastic waste will have accumulated in nature by 2050 (UNEP, 2021). Economically, marine plastic pollution imposes annual costs of US$ 6–19 billion on sectors such as fisheries, aquaculture, and tourism (Wu et al., 2025; Stoett et al., 2024). Socially and medically, the infiltration of MPs into human biological systems - detected in blood, lung, and vascular tissues - raises profound health concerns (Leslie et al., 2022; Jenner et al., 2022; Sun et al., 2023). Moreover, MPs contribute to the formation of a new ecological niche, the plastisphere, serving as habitat for microbial communities, and have been proposed as stratigraphic markers of the Anthropocene (Porta, 2021).

Tackling this phenomenon requires an analytical framework capable of reflecting the mutual interdependence between human activity and ecological systems. The Coupled Nature-Society Systems (CNSS) perspective offers a different approach that focuses on the strong observed link between the effects of uncontrolled human activity - such as plastic overproduction and waste mismanagement - and ecological response pathways, including toxicity, trophic transfer, and bioaccumulation. Microplastics exemplify this entanglement: patterns of human behavior shape ecological stability, while the resulting environmental changes reverberate back into society through effects on health, food security, and economic resilience (Liu et al., 2007; SAPEA, 2018; Evangeliou et al., 2020; Su et al., 2023; Schmidt et al., 2024: Villarrubia-Gómez et al., 2022).

Gradually, with the awareness of the situation, microplastic pollution began to be widely perceived as a “wicked problem”, with a potentially dangerous nature and requiring high interest. This type of pollution is a complex problem, multidimensional by nature, requiring an integrative approach and which cannot be solved by simple and easily accessible solutions (Lalrinfela et al., 2024, Wu et al., 2025). Co-management, an adaptive and participatory governance approach that distributes responsibility across governments, industries, researchers, and communities, rather than technical interventions, is necessary to address it (Onyena et al., 2021; Ramli et al., 2024). In situations with CNSS, co-management can be particularly effective, as it allows for customizable, iterative strategies that address feedback loops that link the social and ecological realms (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021).

The present paper aims to provide a critical synthesis of the microplastic crisis, with the following objectives:

- to trace the historical emergence and intensification of microplastic pollution;
- to identify its effects and clarify how they are situated within the CNSS paradigm;
- to demonstrate that co-management represents a governance approach consistent with CNSS principles;
- to propose integrated, cross-sectoral mitigation pathways, grounded in empirical evidence and adaptive governance.

2. RESEARCH METHODOLOGY

To achieve its objectives, this paper combines peer-reviewed academic studies, policy reports, and empirical case studies in a qualitative synthesis. This approach allows for an integrative understanding of the microplastic crisis, as it considers multiple perspectives: ecological, economic, and socio-cultural. Narrative and qualitative syntheses are particularly well suited to capturing the systemic complexity of interactions between nature and society. They can generate both theoretical contributions and practical guidance for adaptive co-management strategies (Snyder, 2019; Sandelowski & Barroso, 2007; Berrang-Ford et al., 2015).

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3. CONCEPTUALIZING COUPLED NATURE–SOCIETY SYSTEMS (CNSS)

The deep connections and feedback dynamics between the evolution of human societies and the state of natural ecosystems can be more easily observed and analyzed in an integrative framework such as that offered by Coupled Nature-Society Systems (CNSS) (Liu et al., 2007). From this perspective, elements previously viewed as external pressures, such as industrial development, land-use change, and pollution, are now considered as integral parts of ecological systems, influencing and being influenced by ongoing environmental processes (Evangeliou et al., 2020; Su et al., 2023; Schmidt et al., 2024: Villarrubia-Gómez et al., 2022). In CNSS, feedback loops play a key role: human-caused disturbances (such as pollution and resource exploitation) alter the functioning of ecosystems, with consequent effects on health, economy and social behavior (Liu et al., 2007; Su et al., 2022; SAPEA, 2018). A crucial concept in this paradigm is resilience, defined as the ability of systems to withstand shocks, adapt and recover, without losing their essential structure and functions (Oliveira et al., 2024). When certain ecological limits are exceeded within a CNSS, critical points can be reached that produce irreversible effects in both nature and society (Wu et al., 2025; Stoett et al., 2024; Priya et al., 2022).

3.1. Microplastic Pollution: A Crisis of Nature-Society Systems

Meanwhile, microplastic pollution (MP) is a distinct problem for Nature-Society Systems (NSS), due to its complex origin, the many types of impacts it generates, and its defining transboundary nature. The increasing societal needs for cheap and sustainable plastics have led to a rapid increase in production, which is expected to exceed 400 million metric tons in 2022 (OECD, 2022). However, due to limited recycling infrastructure and linear economic models, microplastics have become widely dispersed in the environment. Only 9% of plastic waste is effectively recycled globally, while the rest accumulates in landfills, rivers, oceans, soils, and even atmospheric compartments (UNEP, 2021; Borrelle et al., 2020).

MPs are now present in virtually all environmental media - from deep ocean trenches to alpine snow and agricultural soils (Tian et al., 2022; Evangeliou et al., 2020; Su et al., 2023; Ding et al., 2022). Due to their trans-media mobility, microplastics travel through air, water and soil, often reaching far from where they originated. Their transboundary nature makes management more difficult, as pollution in one country can affect ecosystems and communities globally (Wu et al., 2025; Stoett et al., 2024; Porta, 2021).

Moreover, MPs interact with biota at multiple trophic levels, leading to ecosystem dysfunctions and bioaccumulation across food chains. These ecological disruptions circle back to human health: MPs have been identified in seafood (Jangid et al., 2025), drinking water (Gambino et al., 2022), human blood (Leslie et al., 2022), lungs (Jenner et al., 2022), and even placental tissue.

Microplastics can also act as carriers for other environmental contaminants, thereby amplifying their overall toxicity potential (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020).

3.2. Historical Context of the Microplastic Crisis

The historical development of the microplastic crisis reveals its deep integration into the dynamics of Coupled Nature-Society Systems (CNSS). The production of plastics began on a large scale in the 1940s, registering a spectacular increase from 1.5 million tonnes in 1950 to over 390 million tonnes by 2021 (UNEP, 2021; OECD, 2022). Although the term “microplastic” was only introduced in 2004 by Richard Thompson to describe particles with dimensions below 5 mm (Thompson et al., 2004), their first reports on the surface of the oceans date back to 1972. Since then, numerous studies have confirmed their widespread distribution in rivers, lakes, soils and even in polar regions (Su et al., 2022; Van Cauwenberghe et al., 2015; Schmidt et al., 2024).

The real awakening of global awareness regarding plastic pollution occurred in 1997, with the discovery of the “Great Pacific Garbage Patch” – a huge accumulation of floating waste, made up of large and small fragments of plastic, carried by ocean currents. While discussions initially focused on marine ecosystems, today it is becoming increasingly evident that plastic pollution also affects terrestrial, freshwater, and even atmospheric environments (Yang et al., 2021; Onyena et al., 2021, Qiu et al.; Su et al., 2022). Microplastics have been redefined not only as marine debris, but as ubiquitous contaminants in all ecological domains through this expanded perspective. Stratigraphic indicators of the Anthropocene can be traced through their substrates for microbial colonization, which is known as the plastisphere (Porta, 2021).

Microplastics have become a major international policy concern due to the growing body of scientific evidence and media exposure. The characteristics of microplastics – their widespread presence, persistence and ability to move across borders – give them the status of a typical example of a "wicked problem" in the CNSS. Such problems are marked by multiple causes, difficult-to-define thresholds and controversial governance solutions (SAPEA, 2018; Porta, 2021; Ghosh et al., 2023).

3.3. Co-Management as an Adaptive CNSS-Aligned Strategy

The adoption of flexible and collaborative governance models is necessary to address problems that are both complex and deeply rooted in socio-economic systems. Co-management has been recognized as a viable paradigm. A range of actors - government agencies, local communities, scientific institutions, industry representatives, and non-governmental organizations - share responsibility and make decisions jointly (Medupir et al., 2025; Ramli et al., 2024; de Azevedo et al., 2018). Unlike traditional hierarchical approaches, co-management emphasizes inclusion, cooperation, and adaptability across different levels of governance.

Regarding microplastics, the main strategies promoted within co-management include (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021):

- reducing dependence on plastic production,
- encouraging the adoption of biodegradable and reusable materials,
- strengthening circular economy practices such as collection, sorting, and recycling,
- fostering public education and awareness, and
- supporting technological innovation for detection, removal, and remediation.

Conceptually, co-management aligns with the CNSS framework by acknowledging the socio-ecological complexity of the microplastic challenge. While CNSS illustrates the systemic feedback loops linking society and the environment, co-management offers the institutional means to address these interactions in a collective and adaptive manner. It enables multi-level, cross-sectoral collaboration to monitor, prevent, and mitigate pollution, while fostering long-term resilience and equity (Liu et al., 2007; Oliveira et al., 2024).

4. SOURCES AND PATHWAYS OF MICROPLASTICS IN CNSS

Microplastic (MP) pollution emerges not only from material degradation but also from deeply embedded social practices, economic systems, and institutional gaps. Within the Coupled Nature–Society Systems (CNSS) framework, understanding the origin and movement of MPs requires analyzing both environmental flows and social drivers, since plastic particles move through and across physical and institutional boundaries, affecting ecosystems and societies at multiple scales (SAPEA, 2018; Liu et al., 2007, Villarrubia-Gómez et al., 2022).

4.1. Primary and Secondary Sources of Microplastics

MPs originate from two major source types:

- Primary microplastics are intentionally manufactured small-sized particles used in cosmetics (e.g., exfoliants), industrial abrasives, and pre-production plastic pellets. These are often directly released into wastewater and urban runoff (UNEP, 2021; Qiu et al., 2020).
- Secondary microplastics result from the fragmentation of larger plastic items due to physical, chemical, and biological processes. Common sources include plastic bags, bottles, fishing gear, textiles, tires, and agricultural films (Borrelle et al., 2020; Priya et al., 2022).

In CNSS, these sources are tightly coupled with human behavior - fast fashion trends, reliance on synthetic materials, weak regulatory frameworks, and unsustainable consumption patterns all contribute to ongoing MP generation (Liu et al., 2007; Oliveira et al., 2024; Priya et al., 2022).

4.2. Terrestrial Inputs and Soil Pathways

Contrary to the earlier marine-centric view, recent studies show that terrestrial environments serve as major reservoirs and conduits of microplastics. MPs enter soils via:

- Application of sewage sludge as fertilizer (Campanale at al., 2024; Ghosh et al., 2023; Sa'adu & Farsang, 2023);
- Plastic mulching films in agriculture (Sa'adu & Farsang, 2023; Campanale et al., 2024);
- Atmospheric deposition (Evangeliou et al., 2020; Su et al., 2023);
- Waste mismanagement, illegal dumping, and open landfills (Machado et al., 2018).

Soils act both as sinks and sources - trapping MPs in aggregates or releasing them through erosion and surface runoff (Li et al., 2018). MPs in soil disturb microbial communities and nutrient cycles, disrupt water retention, and impact root-soil interactions critical for plant growth and food security (Priya et al., 2022; Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020; Porta, 2021).

4.3. Freshwater Systems as Transport Corridors

Rivers and streams act as linear transport systems within CNSS, transferring MPs from land to oceans. MPs accumulate in river sediments, float in surface water, or are ingested by aquatic organisms (Xia et al., 2025; Van Cauwenberghe et al., 2015). Urban runoff, combined sewer overflows, industrial discharges, and improper waste disposal exacerbate MP loads in freshwater bodies (Wang et al., 2021; Onyena et al., 2021).

These systems are highly sensitive to human population density, infrastructure quality, and land use patterns, making them ideal indicators of coupled human–environment interactions (SAPEA, 2018; Ghosh et al., 2023).

4.4. Marine Environments and Ocean Currents

Once MPs reach marine systems, they are widely dispersed by ocean currents, wind, and waves, contributing to massive accumulation zones such as the Great Pacific Garbage Patch (Porta, 2021; Ghosh et al., 2023; Grattagliano et al., 2025). MPs in oceans originate from both direct sources (shipping, fishing, offshore platforms) and indirect land-based inputs (via rivers and coastal erosion) (UNEP, 2021).

They are found in all ocean layers - from the surface to deep-sea sediments - and are ingested by a wide range of marine organisms, leading to trophic transfer (Jangid et al., 2025). Climate change exacerbates this through increased ocean stratification and storm frequency, enhancing MP dispersion and bioavailability (Li et al., 2024).

4.5. Atmospheric Transport and Deposition

Atmospheric pathways are increasingly recognized as critical vectors for MP dispersion. MPs become airborne via road abrasion, synthetic textile shedding during drying, construction activities, and agricultural dust (Gambino et al., 2025). These particles can travel hundreds to thousands of kilometers, contaminating remote regions including alpine snow, glaciers, and uninhabited islands (Evangeliou et al., 2020; Su et al., 2023).

Atmospheric deposition contributes to the cycling of MPs between air, land, and water, particularly during precipitation events. Airborne MPs are also inhaled by humans and animals, creating public health risks (Evangeliou et al., 2020; Sun et al., 2023).

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4.6. Biological Vectors and Trophic Transfer

MPs move not only through abiotic pathways but also via biological vectors. Aquatic and terrestrial organisms ingest MPs and redistribute them through excretion or mortality. For example, seabirds and fish can transport MPs over long distances, while filter feeders like mussels concentrate particles that later enter the human food chain (Jangid et al., 2025; Wu et al., 2023).

Trophic transfer is well-documented, with MPs being transferred from primary producers and zooplankton up to top predators. This process not only spreads contamination but also increases ecological and physiological risks at each level (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020).

4.7. Socioeconomic and Institutional Pathways

Beyond physical flows, MPs also travel through socioeconomic and institutional pathways in CNSS. These include:

- Trade and globalization, which distribute plastic goods and associated waste across continents (OECD, 2022);
- Urbanization, leading to concentrated MP emissions in megacities (Qiu et al., 2020);
- Tourism, contributing seasonal surges in litter in coastal and protected areas (Dauvergne, 2023; de Azevedo et al., 2018);
- Regulatory disparities, where weak environmental enforcement allows for unchecked plastic waste generation (Wu et al., 2025; Stoett et al., 2024).

Institutions often fail to internalize the true costs of plastic production and disposal, perpetuating systemic leakage and accumulation. Without integrated, cross-border frameworks for waste governance, microplastic pollution remains inadequately addressed at the global scale (Medupin et al., 2025).

5. ECOLOGICAL AND SOCIOECONOMIC IMPACTS

Microplastic (MP) pollution exerts wide-ranging impacts across both natural ecosystems and human societies, with many effects emerging from the interdependent and dynamic relationships typical of Coupled Nature–Society Systems (CNSS) (SAPEA, 2018; Villarrubia-Gómez et al. 2022; Su et al., 2023*)*. The ecological and socioeconomic consequences of MPs are not isolated events, but part of a reinforcing system of feedbacks, trade-offs, and vulnerabilities that require systemic analysis and response (Lalrinfela et al., 2024; Evangeliou et al., 2020; Kumar et al., 2025).

5.1. Disruption of Ecosystem Structure and Function

MPs and nanoplastics (NPs) are now ubiquitous in freshwater, marine, terrestrial, and atmospheric ecosystems, causing measurable disruptions to biodiversity, trophic interactions, and biogeochemical cycles (Priya et al., 2022; Sun et al., 2023).

Biodiversity and Physiology. Aquatic organisms exposed to MPs experience gastrointestinal damage, oxidative stress, reproductive decline, altered metabolic activity, and neurotoxic effects (Jangid et al., 2025; Sun et al., 2023). In Daphnia magna, for example, exposure to MPs led to reduced filtration rates and altered predator avoidance behaviors (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020). Soil biodiversity is also affected: MPs reduce microbial richness, alter microbial community composition, and modify root–microbe interactions essential for nutrient cycling and plant growth (Li et al., 2018; Ihenetu et. al, 2024; Ghosh et al., 2023).

Ecosystem Processes. MPs interfere with key ecosystem services. In aquatic systems, they impair photosynthesis in phytoplankton, disrupt primary production, and hinder nutrient cycling through the plastisphere's influence on microbial functions (Lalrinfela et al., 2024). In soil, MPs disturb water retention and aggregation, while atmospheric deposition extends their impact to remote areas. These disruptions reduce the ecological resilience of systems already vulnerable to stressors such as climate change, pollution, and land-use transformation (Li et al., 2024; Ihenetu et al., 2024: Tian et al., 2022).

Trophic Transfer and Bioaccumulation. MPs accumulate in food webs, with particles moving from plankton to invertebrates, fish, and top predators (Grattagliano et al., 2025; Wu et al., 2023, 2022; Jangid et al., 2025). The bioaccumulation of MPs and their associated contaminants (e.g., heavy metals, antibiotics, endocrine disruptors) amplifies their toxic effects at higher trophic levels (Sadique et al., 2025; Abel. & Coates, 2025; Waaijers-van der Loop et al., 2022). Microplastics function as carriers for both chemical pollutants and pathogens, creating layered risks that threaten the health and stability of ecosystems (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020).

5.2. Public Health and Human Exposure

Microplastics have been detected in diverse human tissues and samples, including the lungs, blood, placenta, saphenous veins, and stool (Leslie et al., 2022; Jenner et al., 2022). Human exposure occurs mainly through ingestion and inhalation, with dermal absorption playing a comparatively minor role.

Health effects. Both microplastics (MPs) and nanoplastics (NPs) have been shown to trigger oxidative stress, inflammation, immune dysfunction, and metabolic alterations. Because of their extremely small size, NPs are capable of crossing cellular membranes and even the blood–brain barrier, raising concerns about potential neurotoxic effects and apoptosis (Sadique et al., 2025; Sun et al., 2023). Recent findings also point to possible associations between MP exposure and cancer development, particularly in the gastrointestinal and respiratory systems (Sun et al., 2023; Ghosh et al., 2023).

Routes of exposure. MPs have been identified in a wide range of commonly consumed food items, including vegetables, salt, bottled water, seafood, dairy products, and meat (Gambino et al., 2022). Bottled water has shown higher concentrations of MPs than tap water, often due to packaging and processing methods (UNEP, 2021). Seafood is a notable dietary pathway—particularly in regions dependent on aquaculture and coastal fisheries (Wu et al., 2023). MPs also enter the body via airborne fibers and dust particles, especially in urban environments with poor air quality or near industrial activity (Evangeliou et al., 2020).

Synergistic Toxicity. MPs often carry adsorbed pollutants such as heavy metals, pharmaceuticals, and persistent organic compounds. This „cocktail effect” leads to complex and sometimes greater toxicological impacts than individual components would produce alone (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020). The long-term, cumulative health effects of chronic exposure remain poorly understood, indicating a major research gap (Lalrinfela et al., 2024).

5.3. Food Security and Cultural Disruption

MP pollution threatens global food security by contaminating key agricultural and aquaculture systems.

Aquaculture and Fisheries. Fish and shellfish farming systems are particularly vulnerable to MP contamination through polluted water and feed. Studies indicate near-universal contamination of commercial fish feed with MPs and farmed European seabass have been found with MPs in multiple organs organs (Wu et al., 2023; Jangid et al., 2025). This affects not only food safety but also consumer trust and market stability in affected regions.

Cultural Practices. Coastal and Indigenous communities often rely on traditional fishing, shellfish gathering, and mangrove stewardship for subsistence and identity. MP contamination of these environments disrupts food access, undermines spiritual and cultural ties to place, and contributes to the erosion of traditional ecological knowledge (Ding et al., 2022; Dauvergne, 2023; de Azevedo et al., 2018).

One Health Implications. The „One Health” approach emphasizes the interconnectedness of environmental, animal, and human health. MP pollution violates this principle by threatening food quality, ecosystem health, and ultimately, human well-being in a feedback loop of compounded vulnerability (Li & Meng, 2025; Grattagliano et al., 2025).

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5.4. Economic Costs and Inequities

The economic burden of MP pollution is multifactorial, affecting waste management, fisheries, tourism, and public health.

Direct and Indirect Costs. Global economic losses from marine plastic pollution are estimated between US$6–19 billion annually, impacting fisheries, aquaculture, and coastal tourism (Wu et al., 2025; Stoett et al., 2024). Waste cleanup and infrastructure upgrades also demand considerable financial resources, especially in urban and coastal regions (Qiu et al., 2020; Wang et al., 2021). MP-induced health effects could impose future costs on healthcare systems, though these are currently difficult to quantify.

Inequities in Exposure. MP pollution reflects and reinforces environmental injustices. Developing countries, often with limited waste management infrastructure, face disproportionate burdens of exposure and cleanup responsibility (UNEP, 2021; Medupin et al., 2025). Within countries, low-income populations are more likely to live near pollution hotspots and rely on contaminated food and water sources. Small-scale fishers and subsistence farmers, particularly in the Global South, are highly vulnerable to both ecological degradation and loss of livelihoods (Wu et al., 2025; Stoett et al., 2024).

Governance Gaps. Existing regulatory frameworks remain fragmented, and international cooperation is limited. Many policies lack enforceable targets, monitoring mechanisms, or inclusive participation, allowing pollution to persist unchecked across borders (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021; Medupin et al., 2025). The absence of global extended producer responsibility schemes further contributes to economic externalization of plastic pollution costs.

6. GOVERNANCE AND CO-MANAGEMENT STRATEGIES

The persistent and complex nature of microplastic (MP) pollution - characterized by multisectoral origins, diffuse dispersion pathways, and systemic ecological and social impacts - requires more than technical solutions. It demands integrated, adaptive, and collaborative governance rooted in the Coupled Nature–Society Systems (CNSS) framework (SAPEA, 2018; de Azevedo et al., 2018). Effective co-management provides a means of addressing these interlinked challenges by engaging diverse actors, sharing responsibility, and incorporating local knowledge, institutional innovation, and scientific expertise (Herizal et al., 2024; Lalrinfela et al., 2024; UNEP, 2021).

6.1. Governance Challenges

Fragmented Responsibilities. Governance of microplastics is currently marked by institutional fragmentation across local, national, and international levels. Despite microplastic pollution being a transboundary issue, no globally binding treaty yet governs its monitoring, prevention, or mitigation (Medupin et al., 2025). While the 2022 UNEA resolution to negotiate an international legally binding agreement on plastic pollution is a milestone, its implementation details remain undefined (UNEP, 2022).

At national levels, policy heterogeneity prevails. Some countries, like Rwanda and India, have enacted bans on single-use plastics (SUPs) and adopted Extended Producer Responsibility (EPR) frameworks, while others rely on voluntary initiatives or lack formal policies altogether (Nøklebye et al., 2023; Behuria, 2021). Local governments often fill policy gaps through waste collection, beach cleanups, and educational campaigns - but such efforts require integration with higher-level strategies to be effective (Jane, 2025; Li & Meng, 2025; Grattagliano et al., 2025).

Scientific Uncertainty and Risk Gaps. A major barrier to coordinated action is scientific uncertainty, particularly concerning human health effects, thresholds for safe exposure, and mixture toxicity involving plastics and associated pollutants (Sun et al., 2023; Sadique et al., 2025, 2023). Methodological inconsistencies in sampling, extraction, and analysis of MPs complicate comparability and hinder global risk assessment (Lalrinfela et al., 2024; Li et al., 2018).

Key knowledge gaps include: MPs in groundwater; long-term and multigenerational effects; and their role as vectors for pathogens or heavy metals (Sun et al., 2023; Menéndez-Pedriza & Jaumot 2020; Sa'adu & Farsang, 2023; Campanale et al., 2024). These uncertainties impair evidence-based policymaking and foster uneven risk perceptions across stakeholders.

Lack of Stakeholder Participation. Effective mitigation depends on multi-stakeholder participation, yet community engagement remains limited. Few programs integrate citizen science, local surveillance, or co-management mechanisms. Studies show that public awareness campaigns increase willingness to adopt sustainable behaviors (Li & Meng, 2025; Grattagliano et al., 2025; Folke, 2007), and behavioral change is most likely when supported by education, financial incentives, and visible policy action (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021).

Need for Adaptive and Inclusive Approaches. Governance must be adaptive, inclusive, and systemic, incorporating principles from the circular economy, environmental justice, and green chemistry. Prioritizing prevention and reuse over recycling, redesigning products for biodegradability, and improving infrastructure are all essential (Abel. & Coates, 2025; Waaijers-van der Loop et al., 2022). Innovations like Safe and Sustainable by Design (SSbD) seek to mitigate MP risks at the source by embedding environmental safety in materials and product lifecycles (OECD, 2022).

6.2. Co-management as a Strategic Response

Co-management frameworks bridge governance gaps by distributing responsibilities across actors and levels, facilitating shared decision-making and local ownership of environmental interventions (Dauvergne, 2023; de Azevedo et al., 2018).

a) Community-Driven Initiatives

Local interventions often take the form of beach clean-ups, SUP bans, education campaigns, and deposit-return schemes. For example, Rwanda's nationwide plastic bag ban has been complemented by community-level enforcement and awareness, resulting in one of the world's most effective SUP interventions (UNEP, 2021; Behuria, 2021).

In the U.S., over 270 municipalities adopted plastic bag regulations by 2017, while Ireland's plastic bag tax - supported by a national information campaign - achieved a dramatic 90% reduction in use, with high public approval (Wu et al., 2025; Stoett et al., 2024).

Citizen science programs, such as those monitoring marine litter or tracking waste flows, enhance surveillance and foster a sense of ownership. However, the lack of funding and institutional support limits their scalability (Villarrubia-Gómez et al., 2022; Li & Meng, 2025; Grattagliano et al., 2025; de Azevedo et al., 2018).

b) Government–Industry Partnerships

EPR frameworks have gained traction in the EU and Asia, requiring producers to internalize waste management costs and stimulate eco-design (Kripalani et al., 2025; Lalrinfela et al., 2024; Villarrubia-Gómez et al., 2022). India's 2016 Plastic Waste Management Rules and 2022 ban on SUPs illustrate the move toward producer accountability, though implementation remains inconsistent (Nøklebye et al, 2023; Wu et al., 2025; Stoett et al., 2024).

Innovative practices include:

- Biodegradable materials (e.g., Polymateria's biotransformation technology);
- Use of recycled plastics in construction;
- Circular packaging design, as in UK and Scandinavian markets;
- SSbD strategies in material innovation and product engineering (OECD, 2022).

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c) Cross-sector Collaborations

Collaborations across government, academia, NGOs, and the private sector generate systemic insights and policy innovation. Examples include:

- The Global Partnership on Marine Litter (GPML): a UN-supported platform that consolidates data and connects stakeholders across sectors (UNEP, 2021);
- The EU's REACH regulation, which integrates microplastic restrictions and calls for safer alternatives (Abel. & Coates, 2025 ; Waaijers-van der Loop et al., 2022);
- Science-policy interfaces, which facilitate risk communication, standard-setting, and regulatory development (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021).
- The „One Health” framework is increasingly recognized in these initiatives, highlighting interconnections between environmental, animal, and human health.

6.3. Case-Based Synthesis of Co-management Models

TABLE 1 - EXAMPLES OF CO-MANAGEMENT STRATEGIES ADDRESSING MICROPLASTIC POLLUTION.

Case	Key Stakeholders Involved	Governance Structures and Processes	Social and Ecological Outcomes	Tensions / Limitations
Rwanda – Plastic bag ban and community management	National and local government, local communities	National and local policy measures, supported by community-led management; strict bans and regulations	Regulatory success with significant plastic bag consumption reduction; increased sense of shared responsibility	Limited scalability; need for durable alternatives
European Union – Marine Strategy Framework Directive	Member states, transboundary actors, multi-stakeholder groups (public, private, NGOs, researchers)	Framework directive promoting cross-border, multi-stakeholder objective setting for plastic pollution reduction	Support for establishing transboundary goals and planning	Uneven implementation; ambiguous mandates
Greece – Co-management systems for fisheries and ecotourism	Fishers, local public and private actors, non-fishers	Co-management systems in coastal/small island areas with inclusive development plans; EU Fisheries Fund support	Sustainable coastal development, ecotourism, enhanced local quality of life, private investment stimulation	Institutional fragmentation, discontinuity in co-management renewal
Sri Lanka – Mangrove co-management networks	Multiple stakeholders, but with insufficient engagement	Management networks with weak communication and coordination	Limited mangrove conservation outcomes	Low stakeholder engagement, weak collaboration, inconsistent policy support

Source: Adapted from UNEP (2021), Behuria (2021), Nøklebye et al. (2023), Nijamdeen (2023). Li & Meng (2025); Grattagliano et al. (2025), Wu et al. (2025,; Stoett et al. (2024), Dauvergne (2023), de Azevedo et al. (2018), Folke (2007), Herizal et al. (2024), Onyena et al. (2021) and Medupin et al. (2025).

These cases underscore the importance of context-specific design, institutional support, and community inclusion (Table1). As highlighted in Figure 1, co-management is not a panacea - it demands political will, sustained investment, and iterative learning (Dauvergne, 2023; de Azevedo et al., 2018).
In conclusion, microplastic governance must shift from fragmented, reactive measures to proactive, multi-level, and systemic strategies. Co-management, grounded in the principles of CNSS, provides a valuable pathway that bridges ecological dynamics with social responsibility, fostering resilience, equity, and long-term sustainability.

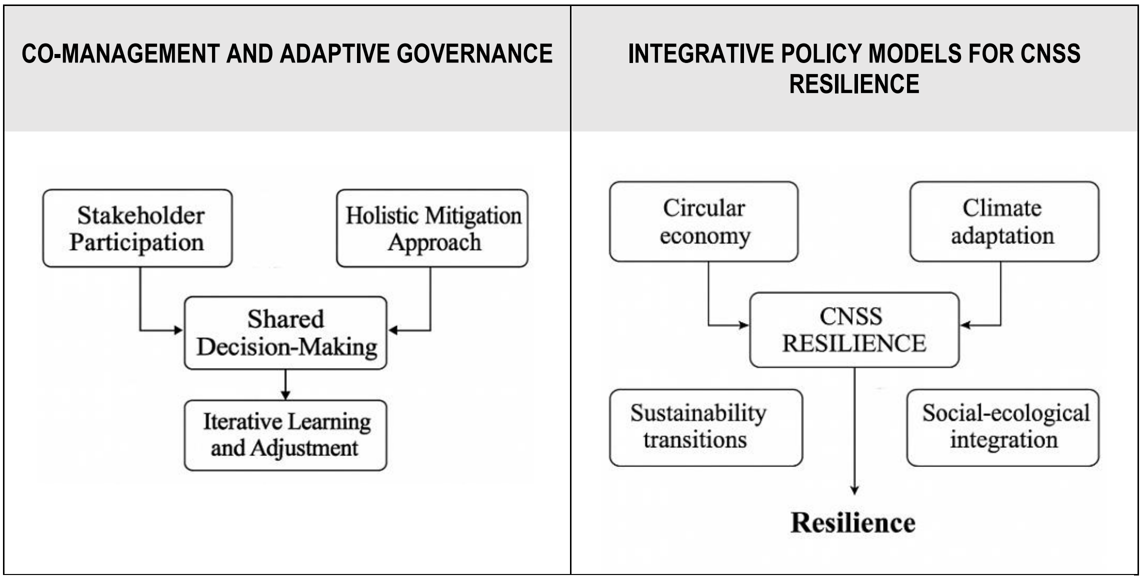

FIGURE 1 - SCHEMATIC REPRESENTATION OF ADAPTIVE GOVERNANCE AND POLICY INTEGRATION IN COUPLED NATURE–SOCIETY SYSTEMS (CNSS)

7. SYNTHESIS AND RESEARCH GAPS

7.1. Bridging Science, Society, and Governance

The management of microplastic pollution illustrates a classic “wicked problem,” marked by systemic complexity, knowledge gaps, and divergent stakeholder interests (UNEA, 2022; Medupin et al., 2025; Li & Meng, 2025; Grattagliano et al., 2025). The incorporation of science, public policy, and community engagement under the umbrella of Nature-Society Systems (NSS) has led to the growth of co-management as a potential governance model in this context. Transparency is enhanced, integrated planning is supported, and context-specific solutions are developed by co-management, which fosters shared responsibility between governments, industries, academia, and civil society (Ramli et al., 2024; Wu et al., 2025; Stoett et al., 2024).

The progress is hampered by significant obstacles such as lack of scientific certainty and fragmented policy action. Although public concern is growing, there is a lack of long-term toxicological evidence and sampling methods vary. This makes it difficult to establish a direct causal link between microplastics and health problems (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021; WHO, 2019). Approaches such as citizen science, participatory research or community-based monitoring can help bridge the gap between science and the society (Dauvergne, 2023; de Azevedo et al., 2018; UNEP, 2021; UNEA, 2022).

7.2. Equity, Trust, and Adaptive Capacity in CNSS Responses

The effectiveness co-management depends on proper participation, trust-building and good governance capacity. Examples such as the plastic bag ban in Rwanda show how local knowledge and a sense of community responsibility can improve compliance and resilience by directly involving communities in enforcing the rules (UNEP, 2021; OECD, 2022; UNEA, 2022, Behuria, 2021). On the other hand, experiences such as those in Sri Lanka, where co-management of mangrove ecosystems was attempted, demonstrate that results can be compromised by lack of stakeholder involvement, poor coordination between institutions and poor communication (Nijamdeen et al, 2023; Medupin et al., 2025; UNEP, 2021).

A key principle of Nature-Society Systems (NSS) is adaptive capacity, which emphasizes the importance of understanding feedback loops, resilience thresholds and managing uncertainty (Liu et al., 2007). To maintain this capacity, it is crucial to invest in education, intersectoral dialogue and training programmes. These allow communities and institutions to continuously test and adjust their strategies. It cannot be stressed enough how important trust — both within institutions and among all participants — is to building sustainable plastic management strategies.

7.3. Rethinking Systemic Responses through the CNSS Lens

Microplastics are not merely environmental contaminants; they are socio-material products embedded in global economies, consumption habits, and technological infrastructures. As such, their governance must reflect this multidimensionality. The CNSS lens invites a shift from narrowly framed ecological or health risks to a systems view, recognizing how plastic pollution affects and is affected by social, economic, and ecological subsystems (Ramli et al., 2024; Liu et al., 2007).

Key elements of such systemic responses include:

- Embracing ecological complexity beyond simplified toxicity thresholds (Folke, 2007; Menéndez-Pedriza, A. & Jaumot, J. (2020);
- Mainstreaming circular economy principles to reduce plastic production and increase material recovery (Oliveira et al, 2023; Ramli et al., 2024);
- Promoting green chemistry and Safe and Sustainable by Design (SSbD) approaches for material innovation (Wu et al., 2025; Stoett et al., 2024);
- Advancing standardized methodologies for detection, monitoring, and risk assessment (Yang et al., 2021; Li et al., 2018; Kumar et al., 2025);
- Supporting interdisciplinary science–policy interfaces to translate evidence into effective legislation (UNEA, 2022; Suazo et al, 2025).

7.4. Scaling Co-management across Diverse Governance Landscapes

Applying co-management principles in multi-level, transboundary contexts - such as the Danube Delta Biosphere Reserve - requires coordination mechanisms that can reconcile ecological interdependencies with political and administrative boundaries. While no specific examples of co-management of microplastics in the Danube region are provided, similar lessons apply:

- Cross-border data harmonization is essential for integrated risk assessment;
- Shared targets and legally binding regional agreements can align fragmented policies;
- Local authorities are instrumental in implementing Sustainable Development Goals, especially regarding water quality, marine litter, and ecosystem restoration (EU MSFD, 2008).

Digital platforms such as the Global Partnership on Marine Litter (GPML) facilitate multi-stakeholder coordination and data sharing, offering models for scaling co-management in other regions (UNEP, 2021).

7.5. Addressing Global Disparities in Microplastic Governance

Disparities between high-income countries (HICs) and low- and middle-income countries (LMICs) are stark in terms of exposure risk, infrastructure capacity, and policy implementation. Low- and Middle-Income Countries (LMICs) often suffer disproportionately from microplastic pollution. The majority of this is caused by informal recycling practices, unreliable waste treatment infrastructure, and reliance on food and water sources that may already be contaminated (Dauvergne, 2023; de Azevedo et al., 2018; Folke, 2007; Herizal et al., 2024; Onyena et al., 2021). Developing inclusive global policies is difficult due to a lack of data and scientific knowledge, and in particular the lack of literature on monitoring efforts in low- and middle-income countries (LMICs) (Suazo et al., 2025; Gallo et al., 2018). To address this issue, it is essential to adapt standard monitoring protocols to local conditions, based on practical criteria such as cost, resource availability and local expertise. At the same time, public policy initiatives such as Extended Producer Responsibility (EPR) programmes and plastic taxes need to be carefully designed to avoid creating disproportionate financial burdens on vulnerable groups (OECD, 2022). Achieving environmental justice in plastics governance therefore requires a redistribution of responsibility at the global level and increased investment in local capacity building, especially where communities are facing high levels of pollution (Stoett et al., 2024; Borrelle et al., 2020).

7.6. Research Gaps and Future Directions

Although research on microplastics has expanded considerably, important knowledge gaps remain.

- Longitudinal CNSS studies: There is an urgent need for long-term investigations that examine how microplastic exposure interacts with climate change, nutrient cycling, biodiversity decline, and human health across multiple scales (Ramli et al., 2024). Such studies should integrate socio-economic factors alongside ecological and health indicators.
- Digital tools and detection technologies: Innovative approaches, including deep learning, spectral imaging, and environmental DNA (eDNA), hold significant promise for identifying microplastics, but they still require harmonization and validation to ensure consistent use across different contexts (Khanam et al., 2025).
- Community inclusion in co-design: Co-management must center local voices and knowledge systems, especially in LMICs. This includes incorporating indigenous and traditional ecological knowledge in monitoring, restoration, and waste reduction strategies (UNEP, 2018).
- Systemic risk and planetary boundaries: Research should better quantify how microplastics contribute to tipping points in Earth system processes, including feedback loops in climate, ocean acidification, and nutrient cycling (Rockström et al., 2009, Cottrell, 2022).
- Interdisciplinary synthesis: Connecting field data, lab studies, and social science insights remains a methodological challenge. CNSS-aligned studies must adopt multi-scalar, multi-domain approaches that reflect real-world complexity (Moller et al., 2004).

8. CONCLUSIONS AND POLICY IMPLICATIONS

8.1. Microplastic Pollution: A Multi-Scalar, Systemic Challenge

(Microplastics (MP) and nanoplastics (NP) have become a symbol of human-caused pollution. Due to their small size and high resistance, they present everywhere: in the air, in soil, in freshwater and in the oceans (Wu et al., 2025; Stoett et al., 2024; Gallo et al., 2018; Ding et al., 2022; Evangeliou et al., 2020). They are released into the environment through various pathways, from industrial production and product fragmentation, to poor waste management and daily consumption habits. Once in nature, these particles can travel long distances, accumulate in food chains and easily cross borders, whether ecological or geopolitical (Menéndez-Pedriza et al., 2020; UNEP, 2021).

Microplastic pollution is a problem with deep roots, linked to overproduction, excessive consumption and weak governance systems, thus having a complex impact. The effects are felt in multiple areas, affecting people's health, economic stability, biodiversity and even cultural practices, at local, national and global levels (Ramli et al., 2024; Sun et al., 2023; WHO, 2019).

8.2. A CNSS Perspective: Entangled Socio-Ecological Risks

Microplastic pollution, from a Nature-Society Systems (NSS) perspective, is the result of the complex interplay between natural phenomena and human actions, and is influenced by feedback loops and ecological thresholds (Liu et al., 2007; Ramli et al., 2024). This systemic approach highlights the unintended consequences of practices such as the production of polluting chemicals and the disposal of non-biodegradable waste, which diminish both the resilience of ecosystems and the stability of society. The ecological impact of microplastics is vast, complex and only partially documented. They disrupt nutrient cycles, affect species at different levels of the food chain and can serve as transport vectors for a wide range of toxic substances (Folke, 2007; Herizal et al., 2024; Onyena et al., 2021; Gallo et al., 2018). Another aspect that needs to be considered is the social one. Microplastics are risk factors that threaten food security, human health and livelihoods, especially in low- and middle-income countries (LMICs), where regulatory systems are often vague and outdated (Dauvergne, 2023; de Azevedo et al., 2018; OECD, 2022; Su et al., 2022).

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Addressing this interconnected challenge requires integrated solutions that transcend disciplinary and sectoral barriers (Moller et al., 2004).

8.3. Co-management as a Governance Innovation

The analysis carried out in this review highlights that co-management, defined as a form of collaboration between public authorities, the private sector, local communities and researchers, is an effective solution to address the challenge of microplastic pollution. The value of this approach lies in its ability to adapt decisions to change, to encourage community involvement and to share responsibilities among all those involved. Thus, it offers a governance model prepared to deal with the uncertainty, complexity and transboundary nature of plastic pollution (Wu et al., 2025; Stoett et al., 2024; UNEP, 2021).

Effective co-management builds trust, harnesses diverse knowledge systems, and promotes accountability. Community-led bans (e.g., Rwanda), EPR regulations (e.g., EU and India), and circular economy efforts (e.g., Ireland's SUP bag tax) show that when diverse actors align, transformative change is possible (OECD, 2022; UNEP, 2021; Behuria, 2021; Nøklebye et al, 2023).

However, co-management must be adequately resourced, inclusive of marginalized groups, and institutionalized within policy frameworks. It cannot succeed as a volunteer-driven or ad hoc process alone; rather, it must be supported by legal mandates, funding, and capacity development.

8.4. Policy and Practice Recommendations

a) Enable Policy Environments for Full Lifecycle Governance

There is growing consensus that only systemic interventions - targeting the full plastic lifecycle - can meaningfully curb plastic and microplastic pollution (UNEP, 2021; UNEA, 2022). Policies must include:

- Product redesign for reuse and recyclability;
- Bans and taxes on non-essential single-use plastics;
- Investment in green alternatives and biodegradable materials;
- Wastewater treatment upgrades to capture MPs before environmental release;
- National benchmarks and monitoring systems for MP emissions.

The EU Plastics Strategy (2018) and REACH restrictions on intentionally added microplastics are exemplary, though implementation remains uneven globally. A binding international agreement that integrates human rights, planetary boundaries, and environmental justice is urgently needed (UNEP, 2018; Gallo et al., 2018).

b) Invest in Local Infrastructure and Capacity

MP governance cannot be effective without strengthening basic waste management infrastructure, especially in LMICs. Investments in collection, segregation, recycling, and composting systems must be scaled up (ASEAN, 2021). Capacity-building through training and public-private partnerships - as exemplified by Seoul's waste education programs - can accelerate adoption of sustainable waste practices (Dauvergne, 2023; de Azevedo et al., 2018; Medupin et al., 2025).

c) Foster Long-Term, Cross-Sectoral Research Platforms

Tackling the systemic challenges posed by microplastic pollution calls for interdisciplinary research consortia that connect environmental science, toxicology, materials science, public health, and engineering (Wu et al., 2025; Sadique et al., 2025; Waaijers-van der Loop et al., 2022)

Funding programs should give priority to initiatives that (Moller et al., 2024; Cottrell, 2022).

- Integrate Indigenous and local knowledge systems;
- Co-design interventions with community stakeholders;
- Assess multi-pollutant exposures and long-term risks.

International data-sharing platforms and open-access databases can help harmonize knowledge and inform better policy (Cottrell, 2022).

d) Mainstream MPs in Circular Economy and Climate Strategies

Microplastics need to be addressed not only as a waste management challenge but also as a climate-related issue. Plastic manufacturing is heavily dependent on fossil fuels, and plastic pollution is increasingly intersecting with food systems and carbon cycles. As part of climate adaptation and mitigation, circular economy strategies should (Ramli et al., 2024; Li et al., 2024):

- Close material loops through reuse and product redesign;
- Incentivize ecodesign and reduced material intensity;
- Set quantitative MP reduction targets (e.g., EU's 30% target by 2030).

Digital tools and AI models can assist in tracking plastic flows, monitoring pollution hotspots, and optimizing waste logistics (Zhao et al., 2024; Peng et al., 2017).

e) Enhance Education, Engagement, and Public Awareness

Public awareness is a cornerstone of behavioral change. Schools, NGOs, and public institutions should integrate microplastics into educational curricula and campaigns, fostering environmental literacy from a young age (UNEP, 2021). Additionally, corporations and institutions should implement internal awareness programs to shift workplace culture toward sustainability, aligned with Extended Producer Responsibility frameworks (Sánchez-García et al., 2025).

8.5. The Way Forward: A Call for Shared Responsibility

Microplastic pollution represents one of the defining socio-environmental crises of our time (Schmidt et al., 2024). Its successful mitigation requires more than technological innovation - it calls for a paradigm shift in how we produce, consume, and govern plastics (Wu et al., 2025; Onyena et al., 2021). Recognizing the systemic nature of the problem, we must collectively advance toward (SAPEA, 2018; Stoett et al., 2024):

- Integrated, science-informed policies rooted in the CNSS logic;
- Co-managed governance models that institutionalize participation and accountability;
- Equitable burden-sharing and support for vulnerable communities;
- Global agreements with binding commitments and measurable goals.

Only through shared knowledge, shared responsibility, and shared action can we protect ecosystems, health, and future generations from the insidious impacts of microplastics.

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