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Research paper

Microplastic Pollution in The Marine Ecosystems: A Forensic Approach to Source Identification and Mitigation

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Abstract

Microplastics (MPs) pose growing ecological and economic risks in marine ecosystems, particularly due to their persistence, bioaccumulation, and impact on fisheries and tourism. This study presents a forensic investigation framework for identifying MP sources and proposes economically viable mitigation strategies. Emphasis is placed on cost-benefit analyses of MP control interventions such as pellet-capturing systems, periodic beach cleanup drives, and recycling incentives for fishing gear. The economic burden of inaction, ranging from seafood contamination to public health risks, is discussed about ecosystem service losses and coastal productivity declines. Using FTIR spectroscopy and morphological classification, the study systematically traces pollution patterns along India's southern coastline. Further, the paper explores regulatory mechanisms and policy incentives, including extended producer responsibility (EPR), ESG-aligned investments, and polluter-pays frameworks, to promote compliance and governance transparency. The integration of environmental forensics with financial accountability tools strengthens the case for stakeholder-driven marine plastic governance. By incorporating economic reasoning and governance frameworks, this paper aligns microplastic mitigation with broader goals of sustainable blue economy development. The proposed framework supports both scientific inquiry and policy reform, offering scalable models for pollution management in emerging coastal economies.

Keywords: *Environmental; Pollution; Microplastics; Marine Environment, Nature.*

1. Introduction

Plastics are in a never-ending process of disintegrating into smaller particles. Early in the 1970s, reports of tiny plastic particles floating on the ocean surface appeared in scientific journals(Tao et al., 2024; Sumaila ET AL., 2020). These particles were identified as spherules (of the Polystyrene type), a raw material used in the production of plastics (Prata, 2024). Subsequently, researchers began to look for evidence concerning the plastic pollution of aquatic ecosystems(Maghsoodi, 2014; Jassim, 2023). During the initial stages of research, the focus was more on larger plastic (macro-plastics) debris and its impacts (Hassan et al., 2024), although some studies were conducted on the floating plastic pellets also (Verma et al., 2024). Because of this, even after its first detection in the natural environment, the term "microplastics" did not come into popular use for a long time. Concerns about MP are mounting due to its persistent nature, owing to a lack of mineralisation. Over time, MP formed from the larger plastics increases exponentially. One of the biggest environmental threats facing the world today is global MP pollution, and maintaining environmental security depends critically on its proper regulation and management. In an attempt, this section focuses on documenting the spread of MP in different components of the environment across the globe(Guo et al., 2024). The bibliometric network analysis is a useful tool to quantitatively assess trends and patterns of academic literature. The global scientific literature on marine MP was explored to quantify MP research conducted in countries around the globe(Arellano et al., 2024). A large amount of MP in the marine waters and sediments raised the obvious speculation of detecting MP in common salt, which is processed by evaporating seawater(Balasubramanian et al., 2021). Commercial salts consumed daily all around the world are contaminated with MP. In a study, MP particles larger than 149 μm were extracted from 17 salt brands originating from eight different countries (Jambeck & Law 2020).

2. Sources of MP in the Marine Environment

The MP observed in the marine environment can be of local origin or transported from distant sources. As mentioned, "Strandline is one of the first deposition habitats of microplastics before they are integrated into the beach as a standing stock". Strandline, also called wreck line, is the mark left by the accumulation of the washed-up debris on the beach. Strandline is subjected to change with the tidal variation. The fresh wreck line formed by the waves on the shore during the time of sampling is chosen for collecting samples. MP in strandline can be mainly from three origins: MP from distant terrestrial environment, MP formed at the site due to beach activities (Alpizar et al., 2020), and MP originated from the activities on sea surface. The MP originating from the land reaches the marine environment through river discharge joining the sea, rainfall fall or flood runoff, which gets deposited in the strandline. Similarly, it is hypothesised that in the case of MP formed due to the activities on the beach, they are carried away by waves during high tide and deposited back on the strandline. Otherwise, it could be carried from a distant location on land by the strong wind to the marine water and later be deposited on the strandline after its degradation. Thus, one of the reasons why sampling was carried out in the strandline is to have an estimate of freshly deposited MP. The ship wreck, accidental spill of pellets in the sea, dumping of waste, discarding of fishing gear, etc., are among the activities responsible for the deposition of MP in the strandline (Abimbola et al., 2024). There are different transport routes by which the MP reaches the marine environment, among which land-based pathways are more prominent. River discharge is one of the major carriers of MP to the marine environment. Natural calamities like cyclones and floods also increase MP pollution (Gouin et al., 2019). Identifying the major ports/harbours, plastic manufacturing units, and cosmetic/personal care products manufacturing units near the study area would give a satisfactory explanation of the source of primary MP reaching the marine environment. For the secondary MP, more detailed studies will be required.

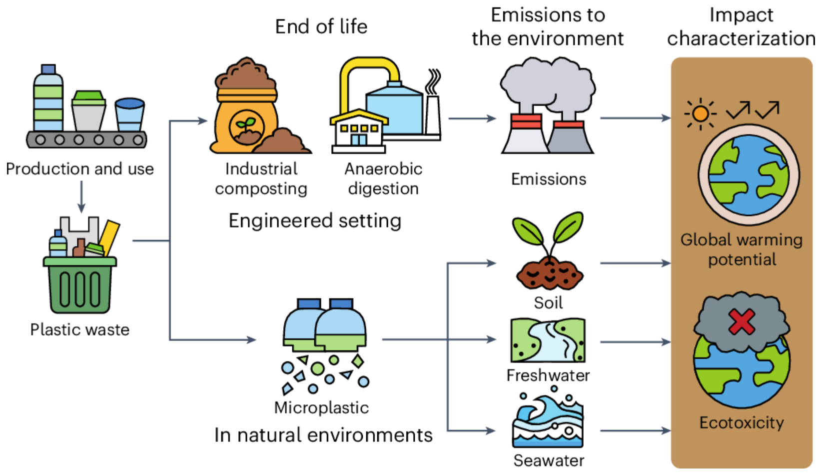


Fig. 1: Impacts of MP

MP pollution is a conundrum because, despite its ill impacts, there is an increase in the production of plastics due to their appealing benefits like cost efficiency, long life, amenability to engineering for specific needs, etc. MP qualifies to be a pollutant due to its affinity to accumulate hydrophobic organic compounds and other harmful compounds, the capability of fragmenting into nano-scale particles, making it ubiquitous, the presence of cancerous additives and heavy metals in its production phase, etc. Once the presence of harmful materials in MP got established, the focus of research shifted to the bioaccumulation and ecotoxicological effects of MPs on marine biota, further highlighting their potential deleterious impacts on human health via dietary exposure(Onyena et al., 2021).

3. Study Design

It is noteworthy that “spherules”- one of the classifications under MP were detected in surface water even before the term “microplastic” got introduced in the scientific community. Starting from there, the scale of research spiralled after it was identified as an emerging contaminant. When it comes to the distribution of MP, many studies in the last couple of decades have reported the presence of MP in different environmental spheres. Further, many studies presented the possible impacts of MP on human health and the environment. In short, the scientific literature so far has established MP pollution as a concern demanding regulatory intervention. Hence, moving beyond, an important requirement is methods to identify the sources of the MP to tackle the MP pollution problem. The conventional methods to determine the concentration of known compounds released in the environment can be used for monitoring purposes; however, for source identification, one needs to build on this. It is important to recognise that MP presents a complex problem- with diverse use of a single type of polymer, multiple manufacturing techniques, use of different additives in the same type of polymer, etc(King &Locock, 2022). Therefore, comprehensive and systematic sampling and analysis techniques are essential to address the MP pollution issue. Even though the abundance of MP is well documented in the case of the marine environment, its distribution across time and space is not constant in terms of abundance, type of polymer, shape, etc. This can be attributed to the dynamic nature of the ocean. FTIR analysis not only aids in pollution source identification but also enables economic risk zoning for targeted mitigation investments. This allows cost-prioritized remediation planning and stakeholder-specific budget allocation. Therefore, from the regulatory perspective, it is essential to capture the spatiotemporal variations in MP pollution. The specific research objectives were

1. To assess the economic impacts of microplastic pollution on marine-based livelihoods (e.g., fisheries, tourism).
2. To propose cost-effective management strategies supported by economic modeling and policy incentives.
3. To integrate forensic data (e.g., polymer type, morphology) with governance frameworks for plastic mitigation.

4. System Implementation

The ingestion of MP by marine fauna exposes seafood consumers to the risk of accumulating MP in their bodies, which could have significant health impacts. This calls for immediate attention to assess the MP abundance in the Kerala coastline and take regulatory measures to control the health impacts it may carry. MP, which was only considered aesthetically distasteful, has turned out to be an emerging pollutant with high-risk potential to humans. Even though it is complex to track the source of MP in the environment, regulatory actions were taken wherever the source could be established, for example, the regulation of microbeads in cosmetics. Likewise, if sources are identified for MP at a polluted site, regulatory measures can be enforced, and violators can be punished. But, to get the polluters punished, evidence is required to be presented and the violations established in a court of law. Environmental forensic investigations can be used as a tool for this. This study proposes a forensic investigation framework to systematically collect evidence from the site and the analysis results to be presented before the court. MP pollution can be location-specific and time-varying. Hence, determining the type and abundance of particles on a beach at a specific time and identifying how the type or number of MP varies over time (trend assessment) plays an important role in gathering information on MP pollution. Identifying and understanding the factors influencing MP accumulation will help in implementing effective control strategies.

Using the Attenuated Total Reflectance (ATR) assembly and the FTIR-Perkin Elmer Spectrum 2 model, MPs were chemically identified. The L60002 Polymer & Polymer additives Database of S.T. Japan-Europe GmbH, a supporting polymer data library, was used to identify the developed infrared spectrum. The criteria used to categorize MP according to polymer type were establishing a match with a polymer in the library of greater than 75% (Munhoz et al., 2022). Characteristic peaks are used to determine the type of polymer for manual spectrum interpretation. Because of the degradation the marine samples had experienced, some of these peaks were not captured. However, the resulting spectrum showed most of the characteristic peaks. When examining marine MP that are exposed to chemicals, biological contaminants, and foreign materials found in the environment, the surface technique known as ATR provides rapid results but necessitates sample preparation. To create an appropriate infrared spectrum, these contaminants must be carefully eliminated.

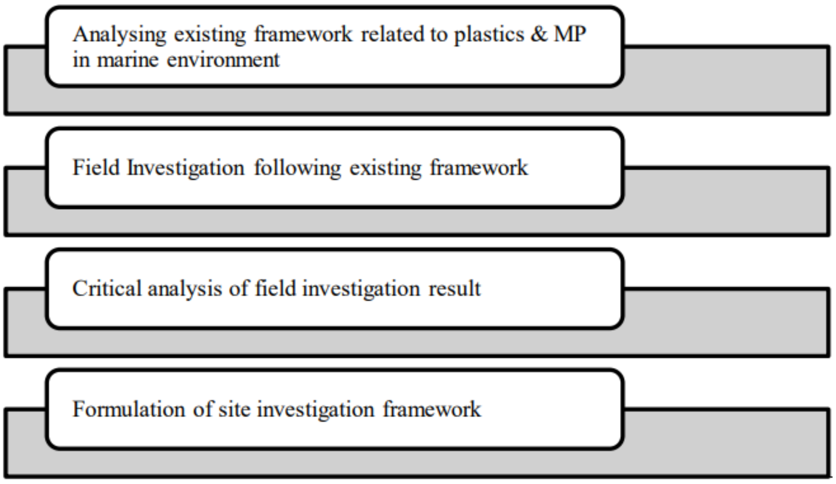


Fig. 2: Methodology

Classifying MP based on different criteria helps in arriving at generalized conclusions regarding a particular type. Four criteria—primary and secondary MP nature of origin, polymer type, morphology, and color—were used to categorize the MPs that were analyzed. Primary MP are special-purpose plastics, such as microbeads and pellets (plastic raw materials), that are produced in sizes smaller than 5 mm. As the name implies, secondary microplastics are created when macroplastics break down. Using the FTIR result, MP are categorized according to the type of polymer, such as PE, PP, PET, etc (Mehinto et al., 2022). Based on morphology, the classes identified in this study are fragments, fibre, film, beads, and pellets. The beads are spherical MPs, different from pellets, as beads do not form a raw material for plastic products, unlike pellets. Such classification is adopted to distinguish between primary and secondary MPs. Moreover, in some cases, pellets are seen in a cylindrical shape as well. Therefore, beads and pellets together cannot be categorised as spherical.

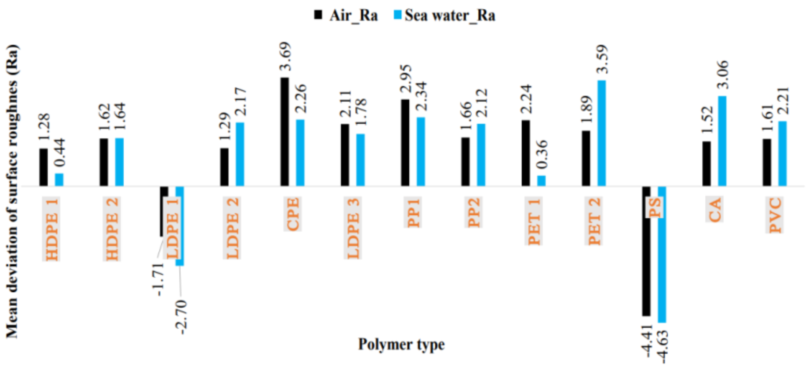


Fig.3: Average Change of Rate Every Half Year

A polymer that has a high degradation rate will develop signs of degradation, such as crack lines, loss of material, discoloration, etc., in a short span after it enters the marine environment. Conversely, a polymer with a lower degradation rate will take a longer duration to develop the degradation features. Therefore, for any type of polymer, it is possible to separate the relatively new MPs from the older MPs in a mix of MPs sampled from a site. Due to its extensive use in packaging, PS degrades the fastest and is therefore likely to form MP more quickly than other materials. It is also abundant in marine environments. Compared to other polymer types, high-density polymers degrade at a slower rate.

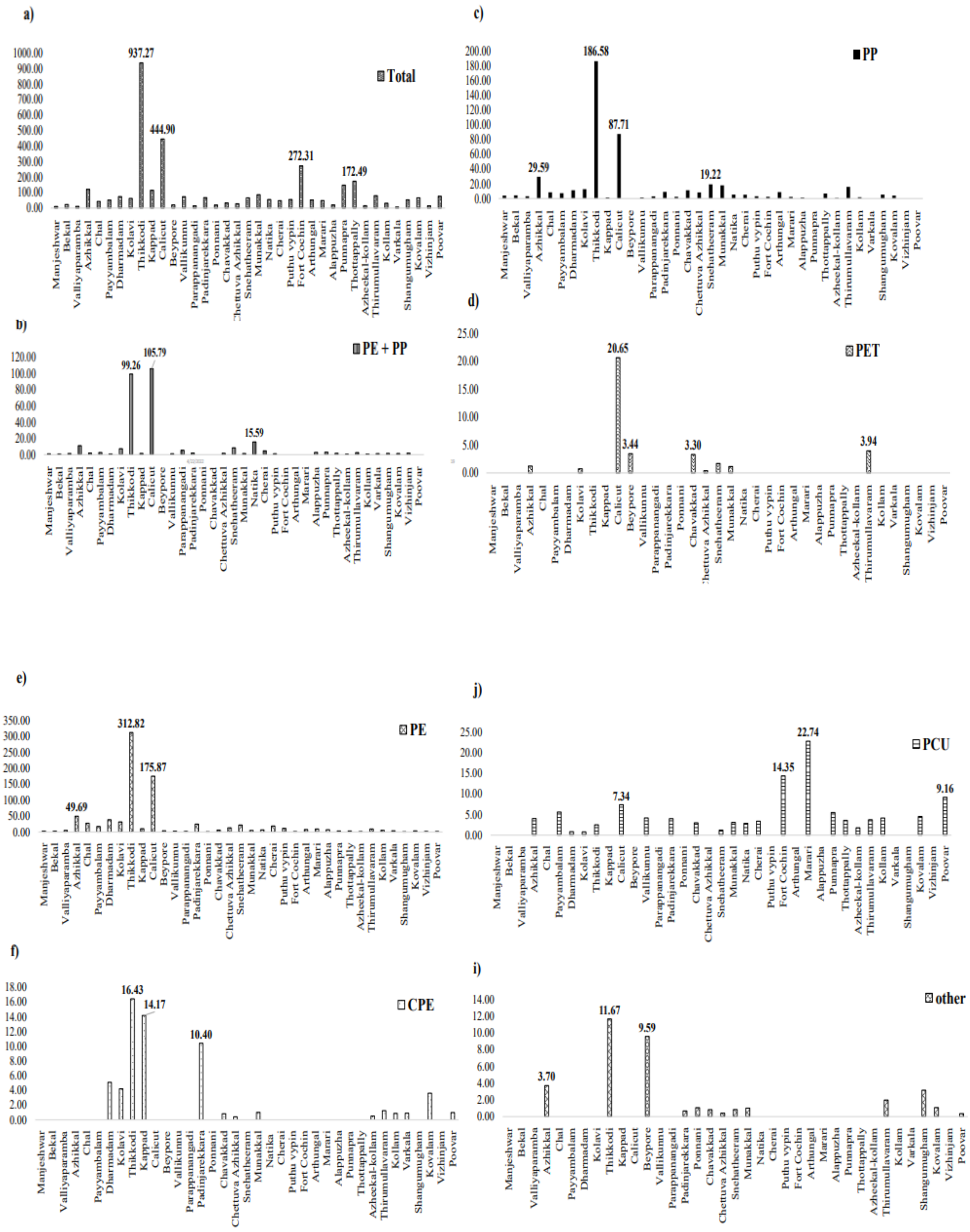
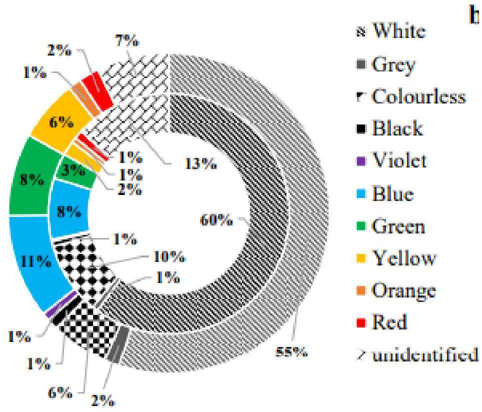
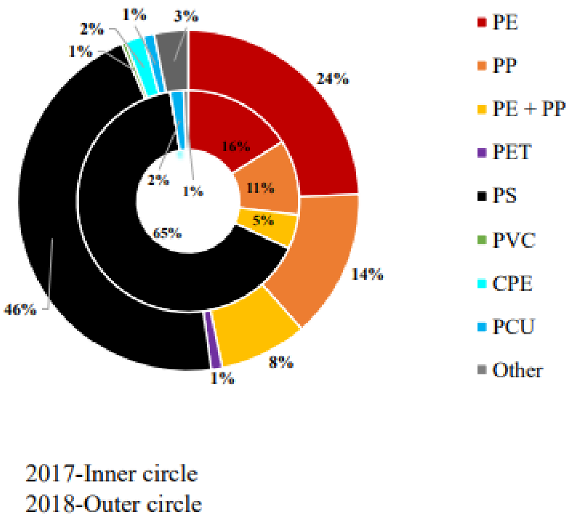


Fig.4: Abundance of MP by Morphology

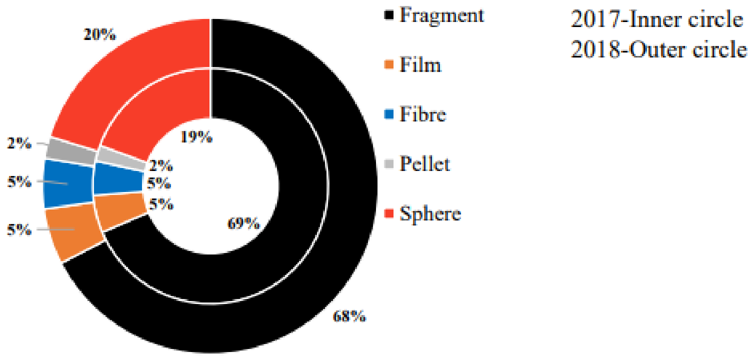
By dividing operating profit by total revenue, one can determine the operating profit margin. EBIT (Earnings before Interest and Tax) Margin is another name for it. Another crucial ratio to monitor in any capital-intensive industry is this one.



(a)



(b)



(c)

Fig.5: Abundance of MP a) Colour, b) Polymer, c) Morphology

As a general trend, excluding some outliers, the Northwest monsoon seems to have a positive relation to MP accumulation. This is due to the less rainfall and lower turbulence at the beach sites. The presence of seaward wind could carry a significant number of bigger plastics to the marine environment from the land, eventually contributing to MP in the marine environment. Even though some pattern of accumulation could be identified, to identify and characterize the factors that dictate these accumulation patterns, detailed studies will be required. Understanding the variables affecting the buildup and distribution of MP at a site can be aided by ongoing monitoring.

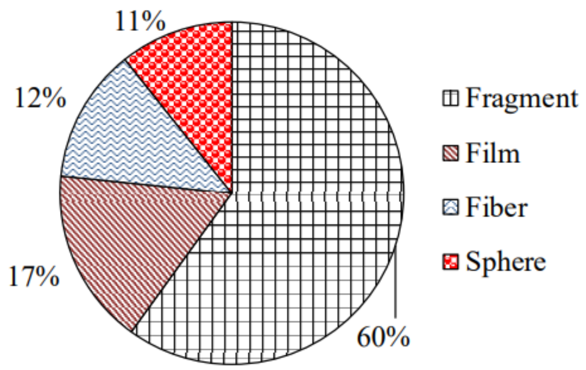


Fig. 6: Abundance of MP by Morphology

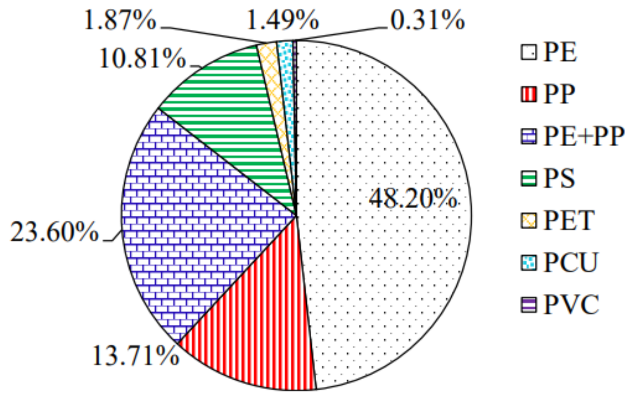


Fig.7: Abundance of MP by Polymer Type

The study's findings suggest that MP pollution of the marine environment may be decreased by implementing straightforward management techniques. Mismanagement in the plastics industry may be the cause of a significant portion of the pellets discovered in Zone 2. Adopting pellet handling and management procedures for the plastics industry can help control this. It may be beneficial to implement measures such as installing pellet-capturing traps at the wastewater discharges of plastic handling and manufacturing facilities. Discarded fishing nets must be disposed of appropriately, and net repair operations must be conducted in approved confined spaces. On recreational beaches, street food vendors can use natural alternatives to PS plates, such as banana leaves or leaf-based plates. To lessen the formation of MP, regular beach cleaning must be done to remove macroplastics.

5. Economic Implications of Microplastic Pollution

Microplastic pollution leads to financial losses in seafood industries, declines in coastal tourism, increased water filtration costs, and public health concerns. Studies estimate that global damage to marine ecosystems from plastic pollution exceeds $13 billion annually. This study calculates potential long-term savings from early intervention via low-cost traps and recycling incentives. Implementing such solutions in hotspot areas yields positive return on investment (ROI), particularly in ecologically sensitive and commercially active coastal zones.

6. Policy and Governance Strategies for MP Management

Effective MP mitigation requires robust governance. This includes mandatory Extended Producer Responsibility (EPR), subsidies for biodegradable alternatives, and enforcement through pollution permits or levies. Aligning with the UN's SDG 14 and national blue economy policies, the framework recommends participatory governance and ESG-aligned investment instruments like blue bonds to fund MP mitigation and restoration activities.

7. Conclusion

The results obtained from this study can be used to control MP pollution. Beach cleaning can be adopted as an important pollution control strategy. Most MPs in the environment are of secondary origin. Therefore, understanding the processes involved in the formation of MP can be useful for MP waste reduction, management, and recovery of the contaminated site. By estimating the residence time of MP, the efficacy of the prevailing management strategies can be checked, and consequently, the existing management strategies can be fine-tuned to produce the desired results. Because they are so common and persistent, microplastics (MP), which are plastics smaller than 5 mm, are a pollutant of growing concern and one of the major challenges of the Anthropocene. This necessitates immediate action to control. Holding the polluter or polluters accountable is essential in every pollution incident to avoid shifting the cost of pollution to the taxpayer. Important steps in pollution management include determining the share of each polluter and allocating the sources of pollutants. However, because a single polymer type has a wide range of applications, pinpointing the source of MP pollution is very difficult. The fact that each polymer type has a wide range of property-tailoring options makes the issue worse. Thus, to determine the source of MP and hold the polluters accountable, methodical data collection and meticulous analysis, as done in environmental forensic investigations, are required.

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