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Microplastics in water bodies: Sources, effects, and mitigation

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Abstract

Microplastics, defined as plastic particles ranging from 1 µm to 5 mm in diameter, emerge from the breakdown of larger plastic materials or from industrial production processes. Their prevalence in aquatic environments has raised significant alarms due to their ability to infiltrate various ecosystems. These particles not only pose a risk to aquatic organisms but also can leach harmful substances such as plastic additives and toxic metals. The growing presence of microplastics in oceans, rivers, and lakes underscores the urgent need for continued research and mitigation strategies aimed at addressing this global environmental threat.

Keywords

Microplastics, plastic pollution, aquatic ecosystems, environmental concerns, bioaccumulation, biodiversity.

1. Introduction

Plastic pollution has emerged as a serious environmental concern of the current time, pollution of aquatic environment by plastic waste having the highest impact. It is ironic to see that plastic debris has entered the aquatic ecosystem to such scale that aquatic animals now have to consider it in the same respect as any other resource. A relatively recent addition to the litany of environmental concerns has been microplastics (Wagner et al., 2014). Microplastics are tiny plastic particles, typically 1 µm to 5 mm in diameter, which occur because of fragmentation of larger plastics or through small size manufacturing (Thompson & Napper, 2019). Micro-plastic pollution in aquatic environment is drawing widespread concern owing to their small size that makes them the most abundant type of particles found in surface waters, sediment, and biota, including fish and filter-feeding bivalves. Microplastics can release hazardous substances, such as plastic additives, absorbed hydrophobic organic chemicals, and possibly also toxic metals. Because of their small size, microplastics can be digested by a wide range of organisms, from zooplankton to large predators. Consequently, microplastics are a global concern with increasing scientific, public, and legislator interest. They have been found widely in oceans, as well as in rivers, lakes, and sediments, but the knowledge about microplastics in the aquatic environment is not exhaustive and one can expect that more research with novel approaches will be done and published in the forthcoming years. There is a mounting concern that microplastics could bio-accumulate and bio-magnify in the food web and are an existential threat to the aquatic ecosystem. This has been realized in terms of harvesting of fish and other marine life for human consumption and long-term loss of marine species and biodiversity.

Understanding is evolving about the behavior and distribution of microplastics in both marine and freshwater environments, including the mechanisms of their formation by degradation. The complex narrative is underpinned by an ever more detailed body of scientific work on the form, distribution and impacts of these particles. Observations in the environment, alongside laboratory work and modeling, are steadily expanding knowledge of how and why a broad variety of microplastics have been found in every part of the globe. The unprecedented wealth of the newly established linkages between biotic and abiotic health implications of microplastics are increasingly well-measured, yielding cause for deep-seated concern.

This article is structured as follows. Section 2 describes sources of microplastics and factors affecting its occurrence and fate. Section 3 deals with the ecological impacts of microplastics on freshwater ecosystems. In this section, the effects of microplastics on aquatic organisms and their potential role as vectors for other contaminants and biomagnification at organism and ecosystem level are discussed along with a focus in comparison to marine pollution. Section 4 is dedicated to an attempt to assess and compare issues of microplastics in freshwaters in relation to oceans. Potential future research directions and the need for legislation based on established ecotoxicological effects are also addressed. Section 5 discusses the potential mitigative and preventive strategies of microplastics pollution. The essay concludes with a summary of the key points made within the essay itself.

2. Sources of Microplastics

The literature on the Microplastics subject points to a wide variety of sources contributing to the microplastic contamination of water bodies. These can be divided into two main types, with some debate in the scientific community on the nomenclature of a systematic taxonomy: primary sources and secondary sources. Primary sources refer to direct release into the environment with the intended size distribution of microplastics. These include, for example, the use of microbeads and microspheres in household products like toothpaste, facial cleansers, exfoliants, or industrial blasting. According to an artificial classification of the expected average diameter size, these particles are often defined as ranging from 1μm to fewer than 100μm. Secondary sources are more of a concern and are yet less well understood, describing the degradation of de facto plastic larger items into particles. With varying geographical and industrial scenarios, this type of pollution can trigger and is essential to understand their combined contribution.

Geographical and industrial substrate factors influence the prevalence and type of microplastic pollution in aquatic environments. These particles are ubiquitous on a global scale, but they are not uniformly dispersed or present. Roads built as the oceanic trade route now also delves pollution from inland. Coasts are exposed to casually tossed and eroded synthetic fibers from clothing and textiles. Everywhere plastic has reached the geochemical plateau of geophagy. These fibers can also be carried by the wind, as can transport the tires and road wear particles that billow. Weather fibers are also data habitat for persistent organic pollutants (POPs). On discharge, most partially purifying wastewater treatment plants worldwide are close to water courses. Following rain, minutes of airborne fibers end up downstream. This same soil pollution can be recovered and fragmented in agricultural runoff or simply lifted and redeposited in irrigation reservoirs just where the plastic is needed the most.

There seems to be a substantial gap in the geographical and disciplinary specificity of the emerging microplastic crisis. And the solution to emerging microplastic crises may also need to tackle more "emergee" problems. Such complex fractal structure of causal dots is lost consciousness. Reasons of micronicity of macroscopic behavioral counterintuitivity remembrance of these usually unconscious multilayered landscapes (Tursi et al., 2022). The main source of freshly available microplastics is the breakdown of larger plastic items into smaller particles. Part of the public problem awareness has been drawn at the sight of tiny, seeded flowers slowly flooding tiny imperceptible "weed-tide lines", but this is the terminus of outputs of global fibers endemic usage. Lacking better data disposability entrains the proper actions detachment, deep down to spatial-specific water waste streams. Broadening the focus, (although still pioneering) soil particles tracing and air equivalents fractioning highlighting relevant but often overlooked toxic and carcinogenic characteristics.

2.1. Primary Sources

Microplastics are small plastic particles of less than 5 mm in diameter. They were first discovered in the marine environment with their persistent organic pollutant (POP) characteristics and hydrophobic property in the water, which is able to uptake heavy metals and toxic chemicals in a high concentration (Usman et al., 2020). Primary microplastics are materials directly emitted in a microscopic size, like those manufactured intentionally. Also, they are added into routine consumer products, namely personal care products, abrasive cleaners, and some clothing. Throughout the years, the secondary emits first as large objects are turned into the small beads, then break it down to micro size (Thompson & Napper, 2019). In particular, the section begins by outlining instances of consumer products that are purposely manufactured using microplastics, the majority of which are added to personal care and cosmetic products to increase their abrasiveness, including facial and body scrubs, as well as toothpaste. To perform daily personal and healthcare services like swimming, bathing with soap, and applying body lotion, they might utilize wiping equipment containing microplastics in the makeup. Thus, cosmetics with microplastics become the main source of microplastics in the water environment. The production of detergents and abrasive cleaners, microplastics are also used for the impact ingredient for hard surface cleaning to improve their shine. The manufacturing process involving raw materials, intermediate pre-production, and end production stages is a routine technique for many sectors. Furthermore, the industrial sectors include rubber granulate on synthetic sports fields, protective coatings, anti-slip coatings, and sticky films for face and hand protection in some cases, add microplastic particles too directly emitted into the environment. It is well known that during washing with synthetic clothing industrial textiles and fibers, in particular mixed fiber textiles, release microplastic fiber into the wastewater. Moreover, hundreds of billions of new clothes are manufactured each year globally, especially the production of synthetic textiles containing nylon and polyester polymers, is anticipated to quadruple by 2030, compared to 2011. Yet, the textile sector, as well as the other major industrial sectors, lacks professional guidelines for processing, using or otherwise handling microplastic materials. Amidst more substantial regulations, stakeholders in all industries using or delegating microplastic ingredients should become more compliant. Meanwhile, it is important for the assessment of possible measures in regulating pollution and the need for qualitative evaluation of research methods to characterize source-related input of pollution. Hence, errands and resolutions to improve this defense have to center upon minimization and the processes or procedures themselves, namely the rejection of microplastic equipment through suction or magnetic filtering. Broadly so, the increased attention, also through expressed concerns compliance from stakeholders both regional and worldwide, is essential. The unique properties of microplastics and the unsuspecting effects they cause compel a different array of measures, including regulatory, technological, and behavioral. Effort should be intensified at the primary sources of microplastics previously highlighted; consumer products containing modified or fiber solid plastics, the industrial processes using them, and the textiles shedding fibers throughout the washing cycle, are fundamental links from the chain of the whole microplastics contamination. Due to the relation of certain impacts of a certain sector, the approach must, naturally, be joint and coordinate between national government, industrial corporations, cities and counties, academic researchers, environmentalist organizations, and the global community. However, it is the hope that this sub-section will foster recognition and promote the adoption of measures to combat such pollutions, as success in this area seems likely to reduce the size of microplastic emissions generally and is perhaps a necessary precursory to other efforts. A culturally diverse variety of solutions, including the complete life cycle of such products, are inevitably required. Such awareness must be accompanied by an addressed ameliorative strategy in the form of stopping addition of microplastics to consumer and industrial products, and appropriate quality filtration after washing evidence is ceasing to be a crucial mechanism. Evidently the primary routes of entry must be targeted first and foremost and is necessary to curb the wider implications from personal exposure, food chain ingress, and the onward chemical load in the environment. As dangerous as the already made pollution is, containment greatly exacerbates the matter. Especially large concentrations in air, drinking water, and food must be treated, and they mostly call for extraordinary measures, many of which are not currently feasible. Finally, more intense methodological and often interdisciplinary research is required to bring about the understanding of all possible effects concerning the observations in the affected areas discontinuously.

2.2. Secondary Sources

Microplastics have attracted global attention as emerging environmental pollutants. They mainly enter water environments by primary sources, and few studies have focused on their secondary sources. Secondary microplastics are from direct weathering processes, including physical abrasion and photodegradation, of large plastic items, including plastic bottles, foam boxes, and bags. They are reported to release from plastic products, but there is not necessarily a dynamic at every relevant particle size for a given product. As such most conclusions must be generalized, such as stating lightweight plastic products release more primary microplastics. Moreover, the proposed term is treated in the context of particulate release from other sources, like laundering textiles and tire wear. This accounts for about 75% of all primary microplastics entering the environment. Conversely, the weathering processes of macroplastics have been somewhat under addressed in literature, with even primary scholars observing this. A broader approach is needed, from government policy and industry intervention to reduce macroplastics and introduce longer-lasting materials to consumer education and altered behavioral practices. It will contribute to the lack of an empirical investigation of secondary microplastic sources concerning a variety of plastic products open to environmental weathering (Thompson & Napper, 2019).

Research and policy regarding microplastic pollution to date have focused on primary microplastics, but macroplastics containing toxic additives and compromising data integrity are a more serious problem. The rapid fragmentation of three common macroplastic products results of the human rights framework against pollution being weighed down by the pervasiveness of toxic pollution forms. This has weakened environmental legislation internationally and existing data on (micro) plastics has underpinned a narrow focus on marine sources. Less attention has been devoted to the faster weathering of macroplastics and consequent secondary microplastic production. The breakdown of secondary microplastics will be complex given the diversity of materials and weathering means of primary inputs. It will take 20–500 years for plastics to fully degrade, but for most people this is harder to conceptualize than, say, to know not to drink waters downstream from a tannery. Therefore, tackling macroplastics is preferable to managing flip- floplastics. The techniques employed by some microplastics scholars would seem of little use in identifying larger particles in a complex sample (Porter, 2019). It is the result of primary products that have caused the rapid breakdown of large items and the release of secondary ones.

3. Effects of Microplastics in Water Bodies

The management of resources should be focused on maintaining sustainable systems in order to ensure benefits for future generations. Aquatic ecosystems should be managed with the utmost care, as these systems are the main support of modern civilisation. Growing global and local environmental issues threaten aquatic environment quality, and an example of this trend can be assumed from the occurrence of microplastics.

Although microplastics are considered emergent pollutants, they are widespread contaminants, while the sources are mainly derived from inadequate waste management practices, insufficiently treated textile fibres, industrial usage of plastic materials, as well as cosmetics and personal care products, with these last two ones falling under the category of primary microplastics. Both aquatic ecosystem and human health are subjects of a wide range of effects caused by microplastics (G.A. Barboza et al., 2018). Biota ingestion of microplastics leads to a range of health effects on marine organisms, whereby the unclear risks of contaminated seafood consumption are raised. Moreover, since most toxic substances tend to attach on polluted particles, and considering the bioaccumulation in food chains, there is also a risk for humans after consumption of marine biota. Pervasiveness and resistance of plastic materials clearly reveal that the more the studies are conducted, the more its wide ranging negative effects are being comprehended. Already, these hazardous lateral impacts are examined in many experimental settings. All of the coherences predict that there should be impacts visible at ecosystem level, in terms of services and biodiversity. However, there is still insufficient long-term related research, except simulations or reviews. This is the point that creates a big gap on the understanding of the threat posed, although from the beginning as an alert has been voiced about the seriousness of potential impacts on ecosystem integrity.

3.1. On Aquatic Life

There is a growing body of evidence on the potential effects of microplastics on aquatic life. This issue mainly relates to various species, including fish and other marine organisms, as well as related ecosystems such as freshwater, salt marsh, and estuarine habitats. A range of methodologies are involved in this respect, examining the ingestion, toxicological, biological, and ecological effects of microplastics (Usman et al., 2020). Microplastics primarily affect marine organisms in terms of ingestion, potentially leading to harm to their health. Many studies confirm that fish species, as well as various trophic levels, can consume microplastics. The ingestion of microplastics has shown multiple effects on fish, including biochemical responses, digestive system function disorders, oxidative stress, disturbance of homeostasis, inflammation, and modulation of the immune system. Additionally, fish exposed to different contents of microplastics present physiological stress with potential consequences. In other marine species, exposure to microplastics causes changes in behavioral and reproductive parameters, including feeding behaviors, heart rate, free swimming activity, energetic requirements, as well as alterations in feeding habits and dietary preferences.

Microplastics not only accumulate toxic chemicals on their surfaces but also release toxic chemicals themselves, making the combined toxic effects with chemicals increased as the time of exposure increases. Moreover, many studies have shown that smaller microplastic particles are significantly more toxic than larger microplastics, but at a relatively higher concentration, the proportion of larger microplastics that caused toxicity exceeded the smaller size groups. Microplastics can not only be ingested by lower trophic level organisms but also by middle trophic level and higher trophic level organisms, resulting in ingestion of microplastics by big animals that can have potential impacts on biodiversity and ecosystem stability. Additionally, microplastics are found not only in individuals at the top of the food web but also in a variety of higher trophic levels. It is known that the higher trophic levels of the food web, such as whales, have the potential to bioaccumulate toxic substances. After entering the ecosystem, microplastics accumulate heat and a variety of thoroughly studied harmful pollutants that increase the toxicity and bioavailability of the combined pollutants present in microplastics. The bulk of the reviewed literature draws attention to both the potential harmful effects of microplastics on the health of aquatic life and glass eel as a suitable model for studying the impact of microplastics, while many critical uncertainties and the need for additional research are emphasized. The health of aquatic species is of great importance in understanding the potential and ultimate outcomes of broader impacts revolving around the issue of microplastics, serving as an excellent indicator of weather and how aquatic ecosystems are affected by these emerging contaminants.

3.2. On Human Health

Exposure to microplastics is currently a rising concern, not least due to the potential risks for humans (G.A. Barboza et al., 2018). Considering this, a better understanding and scientific basis of the consequences of micro- and nanoplastic contamination on human health would benefit the further evaluation and public health assessments of the associated emerging risks to society (Alberghini et al., 2022). Yet, microplastics can be absorbed by fish gills and consequently be translocated and accumulated in the muscle tissue, which may result in consumption of contaminated fishery products and further cause potential risks for consumers. Another possible pathway for human exposure is drinking water since tap and bottled/spring water can contain microplastics as a result of the release of fibers and polymer particles from the purification and conditioning processes. Other possible pathways for microplastic ingestion by humans are various fresh and processed foods adding exposure. For instance, they have been detected in honey, mollusks, beer, and table salt, as well as in the particulate matter in the air, so, possible inhalation of airborne micro and nanoplastics. Studies are ongoing concerning the toxicity and possible long-term impacts of microplastic intake, which however, are still in their infancy for humans, and hence the actual health implications of micro- and nanoplastic exposure for human health are not well understood. Alongside compositional concerns, the ingestion of microplastics loaded with chemicals, biota and/or pathogens should be regarded with caution due to the potential transfer of these additives from the plastic material to the human body. Considering these alarming signals, the scientific community has initiated research work on human health aspects related to the exposure to micro- and nanoplastics, while the food safety-related agencies are following this trend.

It is expected that most of the information presently available is insufficient for a complete risk assessment program of microplastics in drinking water, since human exposure via ingestion or inhalation remains unknown. Thus, scientific research is urged concerning the generation, dissemination, and uptake of nanoplastics, as well as their distribution in tissues and bioaccumulation in organs. Moreover, since understanding the bio-persistency and potential biodegradation of the biopolymer fraction of plastic products is timely, research efforts are meritoriously supported in this direction. Attempts to curb the above- mentioned up-and-coming public health threats are not addressed nicely by existing regulatory framework, itself lacking a relevant risk assessment and management toolset. Therefore, comprehensive scientific research should find a suitable environment to address the lack of knowledge by elaborating proper means for the comprehensive assessment of the risks associated with micro-and nanoplastics in the human ecosystem, including regulatory gap filling. From a societal standpoint, it is suggested that urgent considerations should be considered regarding these wide-ranging potential impacts on personal welfare. In this regard, the welfare of society would be greatly promoted through continuous public awareness campaigns, encouraging educational efforts and increasing the involvement of the general public in decision-making. On the societal front, urgent considerations are advised to be made regarding the wide- ranging impacts on human well-being, as this would greatly further the benefit of society through ongoing public awareness efforts, educational encouragement and enhanced involvement of the public in decision- making processes.

4. Mitigation Strategies

Polymer-based plastics are ubiquitous, and due to their almost indefinite persistence, these materials accumulate and generate a diverse group of substances, called microplastics. The impact of microplastics in aquatic life systems and the human chain has recently been recognized, although details are still emerging regarding their occurrence, monitoring, and control. Prevention from sources combined with removal procedures from water bodies and purification systems constitute the major weapons to fight against these pollutants. The effect of these actions is expected to reduce, however, not to eliminate the level of contamination. The source of polymer-based plastic is of a completely different complexity than common hazardous chemicals, and a continuous increase in their production is observed, especially due to the proportion of bio-persistent, slow-degrading plastic products. In addition, the complexity of their waste consisting of a wide variety of goods, plastics, and additives has been introduced to their mixtures, reservations and incompatibility stipulated in advance attacks. Prevention from sources is composed of set of actions to reduce the amount of particles from reaching aquatic systems. In the forefront the drop in production of plastic products is listed as the main actual reason, as this would indirectly reduce several particles from reach aquatic environments. This strategy, however, remains in the realm of the future as there is no pointer for the reduction, rather an increase. In the absence of it, the change of design of plastic products may decrease the number of used goods slowly degraded, hence release microplastic particles. Designed goods should be more prone to be reused, recycled or composted (Tursi et al., 2022). An impressive change is voluntary (with certain success) or coercive (including implementation of special laws) efforts to limit the use of intended single use and to promote biodegradable products.

4.1. Prevention at Source

Microplastics are an increasing global environmental concern due to their wide distribution and potential health risk. Around 400 million metric tons of new plastic are produced globally and 2.5 million tons of them enter the oceans every year. Microplastics are difficult or even impossible to degrade completely due to their high resilience to UV radiation, chemical or physical wear.

Prevention is the best strategy to address the problem of microplastics in water bodies. The most effective way is to work towards systemic changes in industries that produce plastic goods to prevent this persistent material from being needlessly released to the environment. It suggests a focus on reducing the plastic waste generated, particularly in the sectors where the larger types of polymers are used. It is suggested to replace the polymers of those certain plastic items made of polymers that can easily fragment to some specific biodegradable polymers or other material types that are biodegradable, which consider the product application. Solutions include designing alternatives to microbeads in personal care products, considering bio-based, natural and biodegradable materials in product design, optimizing textile production processes, improving the filtering of washing machines, and designing alternatives to reduce wear and tear in general. The most cost-effective prevention measures are expected to be regulatory. The restriction of microplastics in consumer products is considered the most effective way to prevent microplastic pollution in water bodies. To increase the knowledge about the release of microplastics into the environment, regulations regarding product labeling with information such as the percentage of polymers and the type of polymer are needed. Regulatory measures could combine the restriction of consumer products that, as released into the environment, are likely to result in the emission of microplastics, and the promotion of sustainable practices in all plastic manufacturing sectors. Risk assessment should be performed for any polymer type used in products, and the regulations for each product or sector should be set accordingly. Regarding textiles, there is a need to investigate the implications of policies and behavioral changes to reduce the release of microfibers into water bodies, such as garments washing at lower temperatures. The protection of the environment and human health should be regulated to mitigate the plastic emission problems with preventive action. In addition to regulatory measures, consumer awareness and behavioral changes play a vital role in addressing this pollution source. An effective way to mitigate the problem of consumer use plastics is working cooperatively with the manufacturers to influence their practices towards sustainable options. Initially, a voluntary collaborative approach with industry is effective. A number of case studies have been successful in reducing pollution linked to water bodies on the basis of an industry partnership. Successful practices were taken to address water pollution from the prevention side. Thus, they correspond entirely to the proposal because they reduce the unnecessary use of pollutants and thus work preventively against their undoubted effects. Measures taken included comprehensive regulation, influencing consumer choice, and working closely with industry towards sustainable practices. Shown evidence that the eradication of the source of pollution is by far the most effective way to mitigate it and for this it is necessary to approach the problem in full breadth, through regulation, consumer education and cooperation with industry.

4.2. Removal Technologies

The widespread presence of microplastics in water bodies endangers aquatic life and human health. As an emerging environmental challenge, numerous technologies have been tested for the efficient removal of microplastics from water bodies, including microfiltration, ultrafiltration, chemical treatment, sedimentation, and biological treatments. Micro- or ultrafiltration was found to achieve significant removal of tiny microplastics in the water phases. It was revealed that filtration performance was increased with a lower feed flow rate, and the removal efficiency decreased at higher concentrations both for flat-sheet and hollow- fiber membranes (Sharma et al., 2023). An understanding is emerging that combined treatment processes can provide exceptional efficiency in microplastic removal from water environments. Despite growing evidence to suggest the feasibility and efficiency of these technologies in eliminating microplastics from water bodies, scalability and cost-effectiveness remain important factors to be considered by policymakers and stakeholders. Current developments in removal technologies are reviewed, recent research into optimization strategies is discussed, and future R&D directions are proposed toward the advancement of scalable and efficient technologies for microplastic removal from water bodies.

Effective measures to address the global threat to water bodies posed by the accumulation of microplastics are urgently needed. It is broadly recognized that optimized policies and well-informed strategies to prevent and control pollutant sources are essential for removing microplastic pollutants from water environments. The rapid increase in research and innovation on microplastic removal technologies reflects the increasing awareness and recognition of the toxins and potential risks due to their degradation byproducts in eco-environments. Cooperation between scientific communities, policymakers, and industry is crucial to accelerating advancements in the development of efficient microplastic removal technologies. It is essential to design robust monitoring systems to inspect the removal efficiencies of these current and still-developing removal technologies. To this end, the key developments, challenges, and future directions of prevalent and emerging microplastic removal technologies are fully discussed herein.

5. Conclusion

Aquatic ecosystems provide important resources such as drinking water, food, energy, and recreational services, but are subject to numerous environmental stressors (Wagner et al., 2014). Plastic debris, and in particular microplastics less than 5 mm in size, poses an emerging concern for aquatic biodiversity and human well-being. The investigation of microplastics in freshwater ecosystems lags behind marine research, but worldwide scientific efforts are now attempting to close existing knowledge gaps, concerning primarily the presence and distribution of microplastics and associated chemicals in freshwater bodies such as lakes and rivers, the accumulation of microplastics in biota, and microplastics effects on freshwater species and ecosystems. While increasing human population growth and urbanization reduces the availability and modifies the quality of surface freshwater bodies, the demand for clean drinking water requires the utilization of treated water that is often withdrawn from rivers, lakes, and reservoirs. Microplastic pollution of this water can result in an increase of public health issues related to the ingestion of microplastics through freshwater species, the resuspension of riverbed sediments and the production of harmful algal blooms. The present scientific knowledge and management of microplastic pollution in freshwater ecosystems are critically examined to give a realistic overview of the environmental problem. Finally, general strategies are suggested to mitigate the pollution of freshwater bodies by microplastics and alleviate its harmful effects on aquatic species and biosystems. The concerted effort of the international scientific community, the private sector, local and national authorities, legislative bodies, and non-governmental organizations is necessary and abatement of plastic pollution and safeguarding of aquatic ecosystems and their services (Tursi et al., 2022).

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