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Editorial

Microplastic Pollutants in Aquatic Ecosystems: Present and Future Challenges

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Microplastics (MPs), an emerging contaminant in aquatic environments, are the cause of ecological and climatic risk and have thus become a hot topic for the global scientific community [1]. of the plastic waste that appears in natural environments [2] can be categorized into four main classes: macroplastics (MPs > 25 mm), mesoplastics (5–25 mm), microplastics (0.1–5 mm), and nanoplastics (NPs < 100 nm). Generally, plastic products generated throughout the human-dominated era are regarded as a sink in aquatic environments [3,4]. Understanding the potential sources of MPs in both freshwater and marine environments, along with their types, activities, makeup, and prevalence, poses a significant obstacle for those involved in water resource management, planning, and environmental advocacy. In developing countries (such as India, China, and other South Asian regions), millions of tons of single-use plastic materials are manufactured and disposed of annually, adjoining to the marine system through coastal regions and rivers and, thereby, affecting marine life [5,6]. It is highly likely that, due to anthropogenic disturbances and the excessive use of MP products, these artificial polymers accumulating in freshwater habitats are leading to devastating alterations in aquatic ecosystems. Research activities are predominantly concentrated on marine ecosystems, neglecting freshwater systems, especially rivers, despite an understanding that rivers and land areas are significant sources and pathways transporting microplastics into the oceans. A number of methods, tools, and techniques have been adopted to sample, isolate, characterize, quantify, and identify microplastics in water columns and benthic sediment but quantification techniques that are more accurate still need to be explored [7]. Recently, MPs have been identified in both drinking water and its sources of origin, prompting deliberation concerning the practical implications of these developments and potential risks to human health. The absence of a standardized procedure for identifying, extracting, and sampling these MPs renders the qualitative aspect of their occurrence uncertain, leaving a realm yet to be investigated by researchers working in this field.

Since the 1950s (after the pre-industrial era), owing to their multifaceted applications, the worldwide consumption of plastic products grew exponentially [8]. To be more specific, the production of plastic rapidly increased from 2 million tons (Mt) in 1950 to 367 Mt in 2020—about 0.3% less than in the year 2019 due to COVID-19 outbreaks [9]. Moreover, it is estimated that plastic production will further rise to about 600 Mt in 2025, if proactive mitigation strategies have not been implemented in advance (Figure 1A). In general, based on their origin, sources of microplastics can be categorized into two groups, these being primary (macro-to-micro plastics) and secondary MPs (Figure 1B). Notably, most terrestrial microplastics are directly discharged (without conventional treatment) into freshwater ecosystems such as rivers and lakes via urban and/or household wastewater treatment facilities or industrial effluents. Generally, lightweight or small debris is suspended on the surface of the aquatic systems, while heavy or larger debris is deposited on the benthic sediment [10,11]. Under certain circumstances, buoyant plastics present on the water's

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surface undergo influence from water currents, leading to their aggregation and the formation of localized microplastic accumulations. This occurrence heightens ecological hazards for both aquatic ecosystems and adjacent environments. Therefore, it is essential to take immediate action to regulate through the three Rs: reduce, reuse, and recycle the possible sources and sinking velocities of beach debris in benthic sediments. The adoption of a cost-effective, eco-friendly, and advanced circular flow model based on the working principle of 3Rs is much-needed for sustainable management of MP pollutants in aquatic environs (Figure 1C).

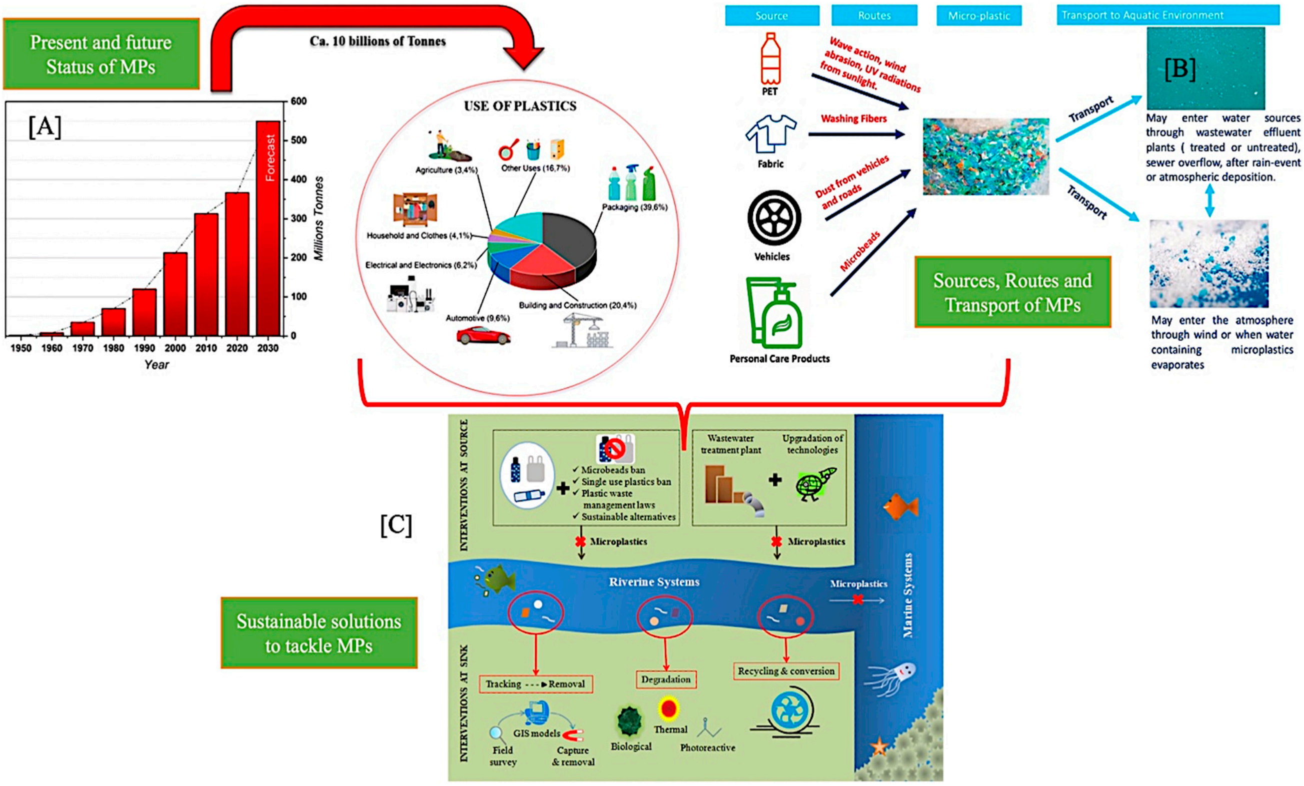

Figure 1. Microplastics in the aquatic environment: (**A**) present and future status [8] (**B**) sources, routes and transport of MPs [12], and (**C**) sustainable solution to tackle MPs [13].

In the era of rapid urbanization, industrialization, and the ongoing population explosion, demands on freshwater are increasing at a tremendous pace. As mentioned in the UN's sustainable development goals (SDGs) of 2030, sustainable cities and communities, clean water and sanitation, good health and well-being, and responsible consumption and production are the important aims of global scientists that need to be kept in mind as plastic production and its circulation continue to progress. Recently, the prevalence of MP pollution in river systems has garnered increasing attention worldwide but there is little scientific literature on this subject [1]. Rivers are active transporters of microplastic debris to marine environments; however, due to inadequate datasets (mostly concerning polluted rivers) and lack of appropriate methodologies for precise sampling and estimation, which require a great deal of attention, the complete picture of the effects of riverine MPs on ecological and river biodiversity are still under debate [13,14]. The current approaches to assessing MP pollution in the aquatic environment are interdisciplinary, comprising principles from the fields of hydrology, limnology, toxicology, environmental modeling, monitoring, and chemistry [6]. Therefore, multidisciplinary approaches must be encouraged to improve MP removal techniques, which will further help to achieve the targets of the SDGs. Moreover, a balance of societal, engineering, epidemiological, biological, and socio-technological approaches can bridge the knowledge gap to help researchers understand the key environmental factors and anthropogenic activities involved in increasing the volume of plastics making their way to aquatic environments.

Based on the preceding discourse, a concise overview of the technological and economic viability, forthcoming hurdles, and constraints associated with each of these remedies is provided. These factors bear significant importance in tackling the management of microplastic pollution. The authors assert that plastic waste management in the future depends on community involvement and initiatives, the effectiveness of local, regional and national governments, and recycling schemes. What is more, the healthy participation of the stakeholders such as customs agencies, industry insiders, regulators, non-governmental organizations (NGOs), intergovernmental organizations, and civil society needs to be achieved [4]. Hence, currently, MP pollution poses a set of diverse challenges, necessitating prompt strategic interventions for their mitigation. To surmount these challenges, various recommendations to global scientific communities are delineated below. These suggestions aim to assist environmentalists, policymakers, and interested scientists in addressing this emerging issue and progressing toward viable engineering solutions. Methods for the characterization, sampling, and sorting of MPs should be standardized to foster precise estimations and reproducible results.

- An in-depth (surface to bottom) assessment of MP distribution in the water column and benthic sediment is required for a better understanding of how MPs interact with the system they inhabit;
- Intensification of source apportionment studies to better investigate the diffuse point sources necessitates the establishment of monitoring stations at hotspot locations;
- Discharge standards of MP pollutants should be uniform to minimize uncontrolled discharges;
- More R&D is needed to evaluate the behavioral alterations that MPs experience over the course of their lifetime;
- Research on the medium- to long-term effects of the trophic transmission of MPs in various food chains should be given top priority;
- For deeper insights into the variety of MP sources and/or sinks, advanced technologies and methodologies should be employed in conjunction with remote sensing (RS) and geographic information systems (GIS);
- Sustainable and cost-effective technologies should be explored for integration in current WWTPs to achieve a high rate of microplastic removal efficiencies;
- Revalidation of the circular flow model should be undertaken based on the working principle of the three Rs for sustainable management and mitigation of MP pollutants in the aquatic environment.

However, there are still fundamental gaps in the knowledge and many questions remain unanswered. In summary, the key questions still outstanding are:

- How much MPs pollution is there currently in freshwater habitats, and how does it compare to the known levels of contamination in marine environments? Which polymers are the most prevalent and hazardous, and do these differ amongst aquatic environments, regions, and habitats?
- How much do the characteristics of various plastic materials and the environment impact the behavior and bioavailability of microplastics in freshwater and marine environments?
- Do negative consequences stem mainly from the particle's physical impact, chemical toxicity, or combined effects, and how do they differ between species and polymers? Are there any similarities to what is understood about the mechanisms of action of some MPs?
- Under realistic exposure conditions (i.e., microplastics of the sort and amounts likely to be encountered by organisms), what are the potential ecological impacts of plastics?

The objective of this Special Issue is to encourage forthcoming investigations concerning MP contamination of aquatic ecosystems. We also endeavors to present existing insights and potential climatic threats that might impact the availability of water resources and their demand in the future if preemptive strategic interventions are not implemented appropriately. Additionally, the ultimate aim is to underscore the significant environmental issues, hurdles, and areas lacking comprehensive research with which we will surely be confronted in the forthcoming decades. There is an imperative necessity to formulate robust strategies and policy frameworks to reverse the prevailing circumstances and enhance the efficacy of removal methodologies in order to mitigate the environmental ramifications associated with microplastics.

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