Microplastic Contamination: An Emerging Concern for the Aquatic Environment

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ABSTRACT

Microplastics (MPs) are so widely dispersed and abundant throughout the globe that many scientists consider them to be important markers of the recent and current time - Plasticene. The pollution of aquatic ecosystems by plastic litter is considered a common topic of serious ecological concern. Microplastics are plastic wastes with particulates less than 5 mm in size that are absorbed by sediments, water, atmosphere, and living organisms therefore affecting environmental and human health. This review focuses on the sources, transport, fate and factors influencing the release of microplastics into aquatic ecosystems and also highlights the possible impact of these toxic micro-sized particles on aquatic lives and human health. It also discusses the available microplastic challenges, remediation and perspective for microplastic pollution management as well as green strategies for reducing microplastic contamination in water bodies. Potential ecological and health risks emanate from their ability to adsorb and transport toxic chemicals, and ease of absorption into the cells of living organisms and interfering with physiological processes. Mitigation strategies have been identified to overcome effects of the microplastics on the environment including educational campaigns aimed at improving public awareness of the plastics contamination, encouraging reuse and recycling, placing prohibitions on microplastics-free (Microbead-Free) in personal care products, putting heavy fines for plastic consumers among others. Several methods for removing microplastics, are grouped into three categories: engineered, biodegradable, and bioengineered approaches. This review promotes concise literature on microplastics and encourages further studies among researchers on this aspect of science.

INTRODUCTION

Microplastics (MPs) have emerged as a novel type of contaminants in aquatic environments, posing risks to both ecosystems and human health (Abdel-Ghani *et al.,* 2024). The presence of microplastics in aquatic environments has raised concerns about their abundance and potential hazards to aquatic organisms (Khan *et al.,* 2024). Contamination of water by microplastics is alarming due to their widespread dispersal and possible threat to underwater life (Wang *et al.,* 2020). Microplastics have been defined as debris from plastics less than 5 mm (Bilal *et al.,* 2023). The occurrence of MPs in the environments "stretches from the equator to the poles", and the problems associated with them are at the centre of scientific discussions and global concerns today (Xu *et al.,* 2020). They can persist in the environment and have been found in many aquatic ecosystems such as surface waters, beaches, oceans, and seas, as well as in aquatic organisms (Imisi *et al.,* 2023).

Microplastics enter into the water from inland sources, namely rivers, industrial and urban discharges, and runoff from residues and surrounding areas (Rahman *et al.,* 2020; Hassan *et al.,* 2024). It can also be caused by direct inputs such as aquaculture, oil and gas production, net loss in fisheries, and garbage discharged during maritime activities like tourism and salt production (Siddique *et al.,* 2023). Microplastics exert multiple stress with a variety of physico-chemical characteristics thus, understanding their impact is quite complicated (Hamza *et al.*, 2024). Smaller sizes of MPs result in their ingestion by a wide range of aquatic organisms ranging from zooplankton to fish, implying the potentials for microplastics to accumulate in the marine food web (Amrik and Khare, 2019).

The impact of microplastics on the environment and biota is not yet fully understood, but laboratory and field studies have shown that they have toxic effect on varieties of species such as fish, birds and mammals (Rochman *et al.,* 2015). Microplastics have been shown to adsorb toxic pollutants from the surrounding environment, making them even more hazardous to wildlife and human health (Wagner *et al.,* 2020). Increasing concern over the detrimental impacts of microplastics has prompted some countries, such as the UK, US and Canada to act. These campaigns have mainly focused on banning the use of microbeads from various items, for example, cosmetic and personal care products (Meng *et al.*, 2020).

Therefore, this review focused on the challenges and perspectives of microplastics contamination as emerging concern in aquatic environment. It details the sources and routes through which microplastics enter the aquatic environment. It also examines the existing information on the occurrence and the fate of microplastics in aquatic environment as well as highlights the future perspectives and challenges of combating microplastics pollution in the aquatic environment.

MICROPLASTICS

Microplastics (MPs) are scientifically defined as plastic fragments with sizes of less than 5 mm and are of different shapes, sizes, and polymer compositions (Smith *et al.,* 2018). According to Lambert and Wagner (2018) “microplastics” is an umbrella term that covers many particle shapes, sizes and polymer types, and as such, the physical and chemical properties of environmental microplastics will differ from the primary microbeads commonly used for ecotoxicity testing. Other authors consider particles >5 mm as macroplastics, mesoplastics from 5mm to >1 mm, microplastics from 1 mm to >0.1 µm, and nanoplastics as 0.1 µm (Lambert and Wagner 2016). They are largely classified by their morphological characteristics: size, shape and colour (FAO, 2017). Size is in particular an important factor when studying microplastics as it dictates the range of organisms it may affect.

MPs are further classified into two, which are primary and secondary MPs (Andrady, 2017). Primary microplastics are minute plastic pieces that are free and can be released directly or indirectly in the surrounding. Direct release can be through spills, sewage, domestic and industrial effluents, whereas microplastics indirect release takes place via an overspill. Primary microplastics with a diameter of less than 5 mm are intentionally manufactured by the plastics industries (Auta *et al.*, 2017). Primary microplastics are found in many cosmetics, cleaning products, artificial turf and fishing nets. The four main sources of these are, in descending order of importance, car tires, paint-based markings, plastic resins and synthetic clothing in the form of synthetic fibers (Ziani *et al.,* 2023)

Secondary MPs originate through physical, chemical, and biological processes that lead to the breakdown of plastic debris (Shim *et al.,* 2018). Secondary microplastic are derived from the breakdown of larger plastic debris through gradual fragmentation or degradation through several process such as weathering, photolysis, abrasion, mechanical, and even microbial decomposition (Vivekanand *et al.,* 2021). Figure 1 shows the sources of MPs in the aquatic environment and how it gets back to humans and wildlife.

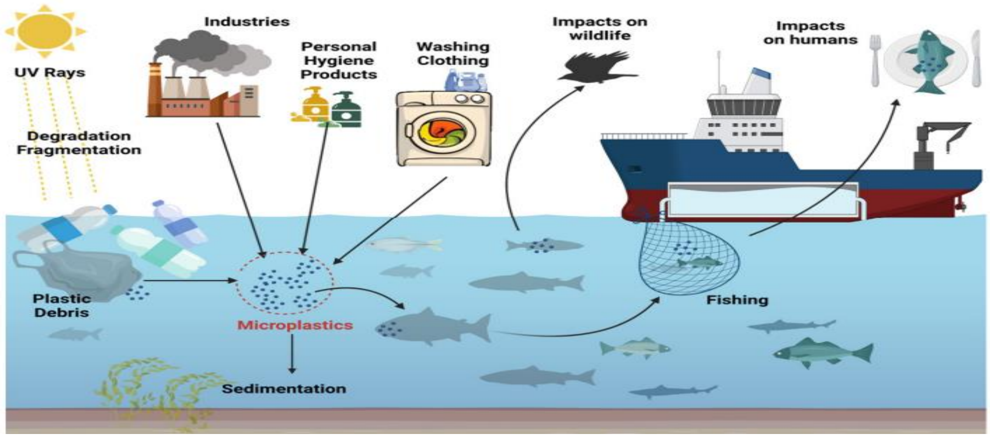

Figure 1. Microplastics in aquatic environment
Source: Ziani *et al*., (2023).

SOURCES AND FATE OF MICROPLASTICS IN AQUATIC ENVIRONMENT

The primary pathways through which microplastics enter aquatic environments include fragmentation of larger plastics, abrasion from products, runoff from urban areas, shipping and fishing activities, wastewater treatment, plant effluents and atmospheric deposition (Mao *et al.*, 2022). The route of exposure to microplastics for animals and humans is food (Wright and Kelly 2017). The diagrammatic representation of the sources, transformation and transport of microplastics is shown in Figure 1.

The fate, amount, and transportation OF MPs depend on factors such as market demand, uses, and post-use management (Imsi *et al*., 2023). Despite several studies on microplastics, their fate in the environment is poorly understood. Numerous studies have shown that microplastics are prone to degradation and are easily dispersed in the indoor and outdoor environment (Waller *et al.*, 2017). The position of microplastics in aquatic systems is influenced by various dynamics including fouling and their density determines their impacts on marine organisms. After fragmentation, lower density microplastics float on the water surface, while higher density ones sink to accumulate in the sediment (Wright *et al.*, 2013). Thereafter, there is an interchanging of the microplastics between biota, water, and sediment through bioturbation, ingestion, and excretion. In fact, the freshwater input with the accompanying turbulence can result in the mixing or disturbance of microplastics in the sea or ocean, causing a redistribution of the microplastics. A recent modelling study on the transportation of microplastics confirmed that river hydrodynamics greatly influence microplastics distribution in rivers and their introduction into marine systems (Besseling *et al.*, 2017).

IMPACTS OF MICROPLASTICS IN AQUATIC SYSTEM

Table 1 summarizes some of the reported effects of MPs on organisms and ecosystems.

Table 1. Some known effects of microplastics on organisms and the environment

Category	Hazard	Effect
Physical harm	Ingestion	Marine organisms can ingest MPs, leading to blockages in their digestive system, physical damage to their internal organs, and a reduced ability to absorb nutrients.
	Entanglement	Marine animals can become entangled in MPs, restricting their movement, and causing physical injury, suffocation, and even death.
	Laceration	The sharp edges of MPs can shred the tissues of organisms, causing physical harm and increasing the risk of infection
	Impaired growth	The ingestion of MPs by marine life can have long-term effects on their growth and reproduction.

	Altered behaviour	MPs can alter the behaviour of marine animals, such as affecting their feeding and migration patterns.
Chemical toxicity	Leaching of additives	Chemical additives in plastics, such as plasticizers and flame retardants, can be released into the environment when MPs break down, potentially harming the health of marine organisms.
	Chemical transfer	MPs can absorb and transfer harmful chemicals and pollutants from the environment to organisms, resulting in toxicity. Many chemical interactions, as well as physisorption, have been reported elsewhere.
	Oxidative stress	The ingestion of MPs can cause oxidative stress in marine organisms, resulting in cellular and tissue damage.
	Endocrine disruption	Some studies suggest that MPs may disrupt the endocrine systems of marine organisms, affecting their growth, development, and reproductive health.
	Carbon cycle disruption	The accumulation of MPs in the environment can impact the ability of ecosystems to sequester and store carbon, potentially accelerating global warming and climate change
Biological effects	Direct impacts	MPs can physically harm organisms such as fish, birds, and marine mammals, leading to entanglement, ingestion, and internal damage. These effects can cause death or impair the organism's ability to survive and reproduce.
	Indirect impacts	The indirect impacts of MPs are far-reaching and occur throughout the food chain.
	Bioaccumulation	MPs can accumulate persistent chemicals from the surrounding environment and transfer them up the food chain, posing a risk to organisms at higher trophic levels, including humans.
	Reduced fertility	Exposure to MPs can damage the reproductive system of organisms, reducing their fertility.
	Spread of diseases	MPs can host pathogenic bacteria and viruses, potentially spreading diseases
Potential risks to humans and organisms	Detected in tissues and organs	MPs have been detected in n various tissues and organs of both humans and other organisms, including the gastrointestinal tract, liver, lungs, kidneys, blood, placenta, brain, and breast milk.
	Health risks	MPs have been associated with a range of health issues, including respiratory problems, allergies, developmental and reproductive problems, hormone function interference, inflammation, oxidative stress, and DNA damage. Ingestion of MPs has been shown to cause cellular and molecular damage, which may increase the risks of chronic diseases, such as cancer, asthma, and chronic obstructive pulmonary disease (COPD).

Adapted from Arowojolu et al., 2023

CONTROL OF MICROPLASTICS IN AQUATIC ECOSYSTEM

Microplastic problems associated with the environment can be solved by focusing on controlling MPs sources attained by law regulation and eradicating MPs particles present in water (Picó *et al*., 2019). Remediation technology is divided into various sub-tools that are discussed below. These technologies involved wastewater and drinking water treatment and various bacterial applications to biodegrade the plastics already in the aquatic environment (Anuj *et al.*, 2023).

Biodegradable or Biobased Polymers Method

It has been observed that several biodegradable bioplastics are compostable in nature and can be degraded by a microorganism into nutrient-rich biomass within three months and no toxins or residue remain after degradation (Picó and Barcelo, 2019). The use of biodegradable material is another best way to reduce the presence of plastics in natural habitats. Biodegradable material is made up of renewable starting materials such as cellulose, starch, bioethanol, and lignin. About 0.5% of 335 million tonnes of plastics are currently contributed by bioplastics, which is expected to escalate in the future (Picó and Barcelo, 2019).

Bioengineering-Based Solutions

Another method used for solving MP's problems associated with the environment is the bioengineering-based solution—different types of bacteria, fungi, or isolated enzymes are used for the biodegradation of plastic by the enzymatic hydrolysis method. Extracellular carboxylesterases can be used for hydrolyzing biodegradable polyesters (Zumstein *et al.*, 2017). Specialized bacteria can degrade different types of plastics. Polyethylene terephthalate can be degraded by *Ideonella sakaiensis*, and polyethylene can be broken down by the marine fungus *Zalerion maritimum* (Picó and Barcelo, 2019).

Engineering Tools

The MPs present in the influents (90–98%) are eliminated by conventional Waste Water Treatment Plant (WWTP) (Lares *et al.*, 2018). Electrodeposition, coagulation, and membrane are the most frequent and advanced wastewater technologies. The most promising method is membrane bioreactors (MBR). Implementing novel technologies in water plants is the best way to manage MP pollution (Picó and Barcelo, 2019).

CHALLENGES AND PERSPECTIVE FOR MICROPLASTIC POLLUTION MANAGEMENT

Strategies have been proposed to overcome effects of the microplastics on the environment including educational campaigns aimed at improving awareness of the plastics contamination, encouraging reuse and recycling, placing prohibitions on microplastics -free (Microbead - Free) in personal care products, putting heavy fines for plastic consumers (Dolatabadi and Ahmadzadeh, 2020). To date, numerous solutions are proposed to treat microplastic from the environment which can be categorized into containment, mitigation, and remediation.

Containment Approach

The containment approach mainly focuses on recycling and proper landfill management (He *et al.*, 2019). Chen *et al.* (2021) have proposed a model for plastic waste management in Malaysia using a concept combining a circular economy introduced by Kirchherr *et al.* (2018) and an integrated solid waste management hierarchy. Figure 2 shows few treatment methods being practiced for plastic waste management in Malaysia. As observed in Figure 6, there was no waste incineration practiced until 2006. According to Fazeli *et al.*, (2016) the earlier usage of unsanitary landfills might effectively reduce incineration and concurrently generate energy comparable to the sum of fossil fuels. On the other hand, recycling, composting, incineration, inert landfill, and sanitary landfill were targeted with high percentages in 2020, which are 22, 8, 16.8, 9.1 and 44.1%, respectively. As shown in Figure 3, the total recycling rate in Malaysia kept increasing annually and reached above the target of 30.67% in 2020.

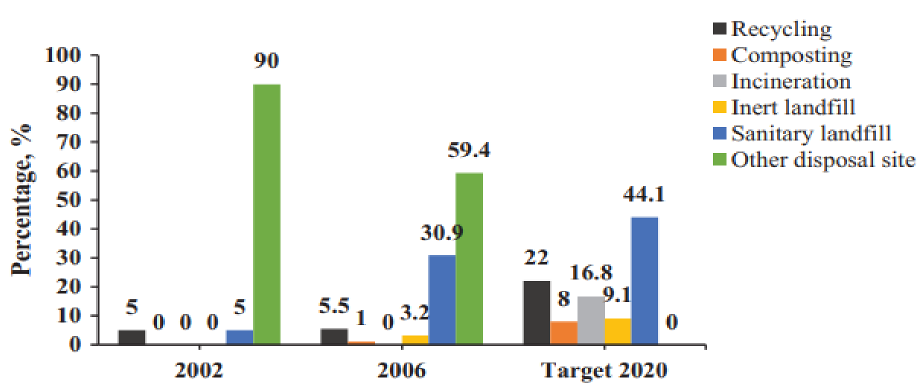

Figure 2. Treatment methods practiced for waste management in Malaysia.

Source: Sulaiman et al., 2023

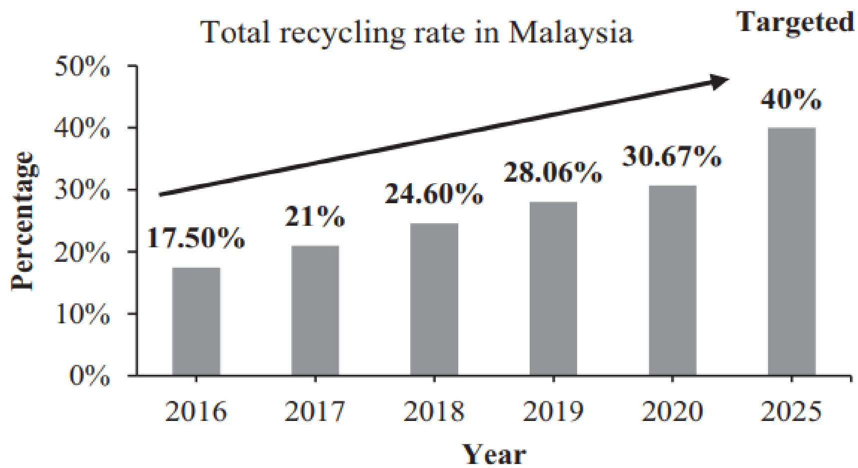

Figure 3. Total recycling rate of waste in Malaysia. ***Source: (Sulaiman et al., 2023).***

Mitigation Strategy

Mitigation strategy focuses on the practice of regulations and legislative measures. The mitigation's goal is to enhance people's awareness of the harmful threat of microplastic. Some countries have banned plastic bags, such as New Zealand (since 2019), Thailand (since 2020) and India (next 2022) (Ministry of Education, Malaysia's roadmap towards zero, 2018). For sustainable development, the Malaysian government has introduced a plan on "Malaysia's Roadmap to Zero Single-Use Plastics" starting from 2018 to 2030 (Fauziah *et al.,* 2021).

Use of biodegradable plastic materials as far as possible in place of synthetic plastic is another major option to minimize the plastic menace. Considering ubiquitous presence of MPs and its rising level in the environment, the role of policy makers to regulate the MP pollution from industries and other prominent sources is highly advisable. Furthermore, public awareness with respect to MPs pollution and its detrimental effects on environment is also one of the prominent ways to curb menace of MPs pollution (Amrik and Khare, 2019).

Remediation Strategy

In terms of remediation, microplastics are currently not included in the treatment scope of sewage treatment plants, and research into the treatment efficiency of microplastics is still in its early stages. Although microplastics can be removed in a sewage treatment plant using existing treatment methods, some microplastics can still bypass the treatment plant and reach the aquatic environment.

Estahbanati (2016) reported that the combination of both separation and degradation processes are amongst the promising approaches to treat microplastic in waste water treatment plants (WWTPs) for the secondary and tertiary stages of treatment. The main challenge for microplastic pollution is improving tertiary wastewater treatment, particularly the filtering process. Ozone, quicksand filtration, reverse osmosis, dissolved air flotation, and membrane bioreactors are some of the wastewater treatment solutions available. (Sol *et al.,* 2021, Zhang *et al.,* 2020).

The most widely practiced approach in managing plastics is recycling. Global recycling rates have gradually risen to account for 24% of non-fiber plastic waste produced in 2014. In that year, the most recycling was in Europe (30%) and China (25%), while in the United States it was 9%, a value comparable to the rest of the world (Geyer *et al.,* 2016). To date, textiles are not commonly recycled but are incinerated or co-disposed with other solid waste. Around 53% of the plastic waste is used for energy and 46% for recycling, and about 1% ends up on dumpsites (Venghaus and Barjenbruch, 2017). Overall, while recycling can prolong the life of plastics before they are finally disposed of into the environment, the handling that is associated with recycling processes can potentially generate microplastics. One of the major drawbacks of plastic is their poor biodegradability.

Bioremediation appears to be an attractive strategy for mitigating the spread and effects of microplastics and this has been demonstrated by a pilot-scale Anaerobic Membrane Bioreactor (AnMBR), showing that it is possible to release only small anthropogenic litter (SAL) per liter, with a removal rate of 99.1%, by combining tertiary treatment (membrane filtration) and the AnMBR (Michielssen *et al.,* 2016)

GREEN STRATEGIES ON MICROPLASTIC REDUCTION

Several strategies can be conducted to achieve a green environment with lower amount of microplastics waste. Initially, measures focusing on the reduction of plastic waste at the industrial level are necessary. For instance, eco-designing schemes can be applied to change the existing methods. Plastics are being manufactured with the aim of reduction or prevention and reuse that involves a delicate mix of rules and incentives. Other alternatives are the development of plastics that are devoid of harmful compounds, use of alternative materials, or the expansion of longlasting plastics (Calero *et al.*, 2021).

Meanwhile, prohibiting the use of certain single-use plastics such as bags, food packaging, bottles, and containers that are only used once before being discarded can be applied by several governments around the world to reduce the plastic pollution in the ocean (Deng *et al.,* 2020). Also, recycled plastic market need to be supported with several initiatives such as imposing taxes on the usage of single plastics, create awareness regarding the environmental benefits of recycled plastics as well as incentivizing the manufacture of recycled plastics (Gu *et al.,* 2020)

CONCLUSION

Microplastic contamination has been a complex environmental challenge across the globe with significant implications for both ecological and human health. Global plastic production has led to the contamination of the environment (especially the water environments, contributing to excess water pollution), increasing a threat to society. Microplastics (MPs) have been found in rivers, oceans and terrestrial ecosystems. Wind can transport MPs over long distances, and settle on remote areas such as snow and ice caps or mountain peaks. Aquatic organisms suffer immensely from microplastics pollution with manifestations of damaging gills, skin, gastrointestinal tract, organs, and mostly, even minute particles reach the brain after crossing the blood-brain barrier. The transfer of microplastics through fish to humans is one of the major challenges for food safety.

Solutions to microplastic contamination include using eco-friendly alternatives, such as natural fiber clothing and biodegradable packaging, implementing strict regulations on plastic production and waste management, and educating the public on the harmful effects of microplastics. Use of biodegradable plastic materials as far as possible in place of synthetic plastic is another major option to minimize the plastic menace.

Overall, it can be concluded that microplastic contamination has reached alarming situation. Its toxicity and other environmental implications now are easily visualized. Before the situation further deteriorates there is an urgent need to control the spread of MPs in the environment.

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