



REVIEW

# Microplastics in marine and aquatic habitats: sources, impact, and sustainable remediation approaches

Hemen Sarma<sup>1</sup> · Rupshikha Patowary Hazarika<sup>2</sup> · Vivek Kumar<sup>3</sup> · Arpita Roy<sup>4</sup> · Soumya Pandit<sup>5</sup> · Ram Prasad<sup>6</sup>

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## Abstract

Plastic trash dumped into water bodies degrade over time into small fragments. These plastic fragments, which come under the category of micro-plastics (MPs), are generally 0.05–5 mm in size, and due to their small size they are frequently consumed by aquatic organisms. As a result, widespread MPs infiltration is a global concern for the aquatic environment, posing a threat to existing life forms. MPs easily bind to other toxic chemicals or metals, acting as vector for such toxic substances and introducing them into life forms. Polyethylene, polypropylene, polystyrene, and other polymers are emerging pollutants that are detrimental to all types of organisms. The main route for MPs into the aquatic ecosystems is through the flushing of urban wastewater. The current paper investigates the origin, environmental fate, and toxicity of MPs, shedding light on their sustainable remediation.

**Keywords** Microplastics · Pollutants · Aquatic environment · Urban wastewater · Sustainable remediation

## Introduction

Plastic is a material that is commonly used in everyday life for multiple purposes and in multiple forms equipment, packaging material. Although invented for convenience, plastic has become a curse to life forms due to its persistent nature. Smaller plastics (0.05–5 mm) or "microplastics" (MPs) are of particular interest to researchers because they can harm living organisms (Ma et al. 2020; Rezania et al. 2018). MPs are a global concern because of ubiquitous presence, thus affecting aquatic (freshwater and marine),

terrestrial, and remote arctic ecosystems, thereby impacting various lifeforms (Woodall et al. 2014; Nizzetto et al. 2016). MPs are widely used for a variety of purposes due to their low-cost and attractive properties such as high durability (Zhang et al. 2020).

According to recent statistical analysis, global plastic waste generation will triple between 2015 and 2060 (Lebreton and Andrady 2019). Bayer Plastics (Germany) and General Electric (USA) began producing bisphenol A (BPA)-based plastics for industrial applications in 1955 (Sarma and Lee 2018). Nowadays diverse types of day-to-day materials like cosmetics, skincare, cleaning fluids, soaps, shampoos, face or body washing, facial goods, skin cleaner, epoxy,

Hemen Sarma and Rupshikha Patowary Hazarika: first authorship is shared among those who contributed to the manuscript.

✉ Soumya Pandit  
sounip@gmail.com

✉ Ram Prasad  
rpjnu2001@gmail.com

Hemen Sarma  
hemen@buniv.edu.in

<sup>1</sup> Bioremediation Technology Research Group, Department of Botany, Bodoland University, Rangalikhata, Deborgaon, Kokrajhar (BTR), Assam 783370, India

<sup>2</sup> Environmental Chemistry Laboratory, Life Sciences Division, Institute of Advanced Study in Science and Technology (IASST), Guwahati, Assam 781035, India

<sup>3</sup> Himalayan School of Biosciences, Swami Rama Himalayan University, Dehradun, Uttarakhand, India

<sup>4</sup> Department of Biotechnology, School of Engineering and Technology, Sharda University, Greater Noida 201306, India

<sup>5</sup> Department of Life Sciences, School of Basic Sciences and Research, Sharda University, Greater Noida 201306, India

<sup>6</sup> Department of Botany, Mahatma Gandhi Central University, Motihari, Bihar 845401, India

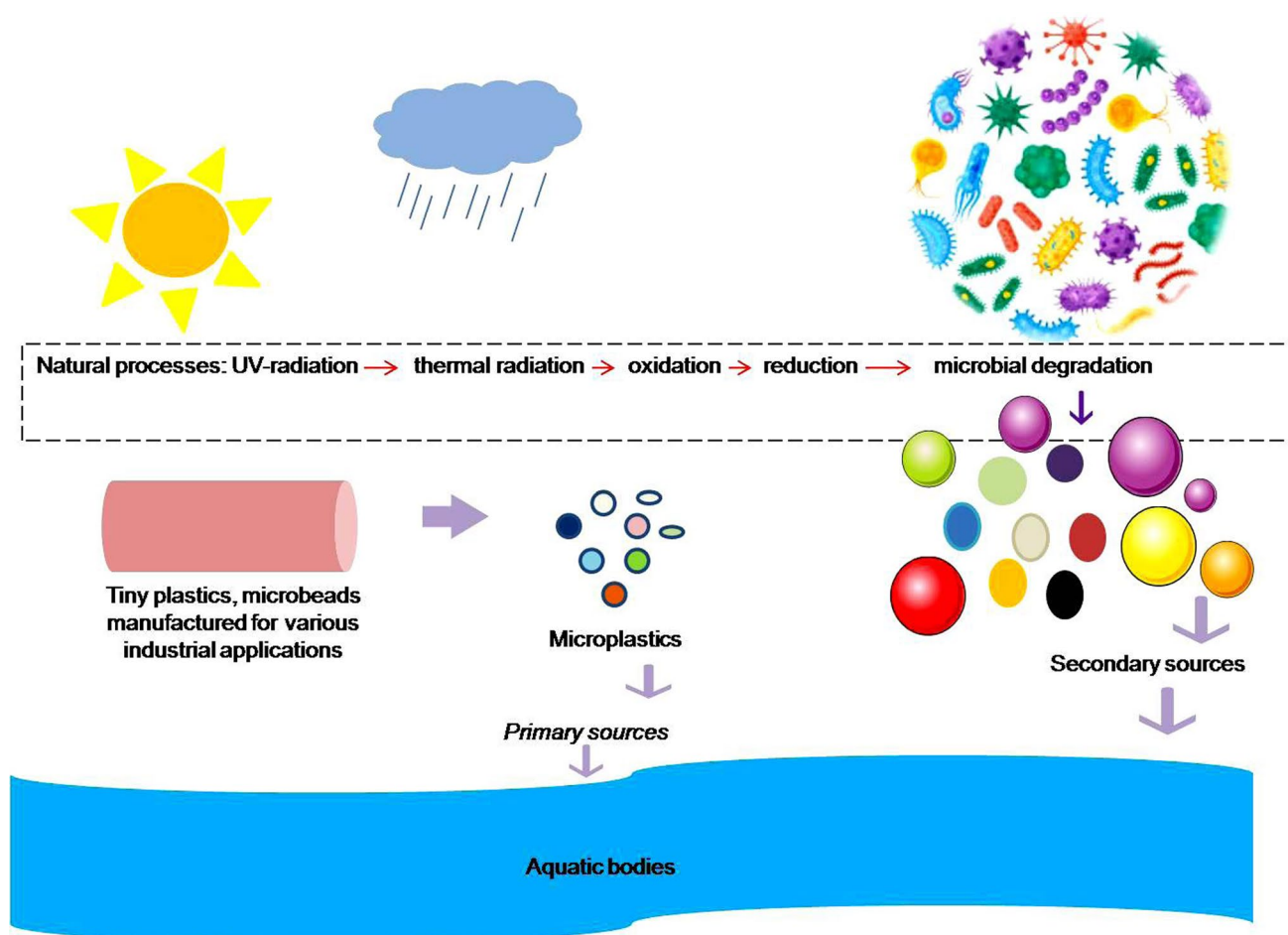
vehicles, glass construction, sports protective equipment, medical laboratories and equipment, chairs, and reusable bottles contain plastics.

Plastic has recently been identified as a pollutant in the context of the international economic and environmental crisis, owing to its ability to last for several decades (Worm et al. 2017). According to research, the aquatic environment in several regions has been polluted by plastic debris (Barletta et al. 2019; Wagner et al. 2014). Large plastic particles have long been known to interact with a variety of aquatic species via processes such as entanglement and ingestion (Duncan et al. 2017). Multiple genera, ranging from invertebrates to vertebrates, are affected by marine MPs pollution (Deudero and Alomar 2015).

Plastics can easily enter water bodies along with wastewater (Wu et al. 2020). These plastics can persist in the water bodies or break down into smaller parts as a result of physical stress, ultraviolet radiation, temperature changes, wave impacts, and also biological processes (Wu et al.

2019). Figure 1 shows the mechanism of the production of MPs. These MPs can make up more than 95% of marine litter that accumulate and spread over marine environment matrixes, water surfaces and water columns, marine sediments, coastlines, sea floors, and even inj marine species, and show major spatial and temporal variations (Barboza and Gimenez 2015; Bergmann et al. 2015). MPs have been globally distributed throughout the marine ecosystem due to hydrodynamic processes and diffusion mechanisms (Kukulka et al. 2012). MPs enter marine environments via sewer, wind, and tidal processes (Zalaszewicz et al. 2016), putting organisms at risk due to their consumption (Guo et al. 2020; Wang et al. 2016).

MPs infiltration on algae has been reported (Besseling et al. 2014), which not only harms the algae but may also pose a risk to humans, as some seaweeds are popular in many countries. This could be an example of MPs entering the food chain and eventually reaching higher trophic levels, including humans (Reisser et al. 2014; Van Cauwenberghe



**Fig. 1** Mechanism of production of MPs. Tiny plastics are manufactured for various industrial applications e.g., cosmetic production, medicine formulations, etc. (primary sources of MPs). Larger-sized

plastics are degraded into smaller fragments by natural processes and MPs are produced (secondary source of MPs)

et al. 2015). Much attention to MPs is given because of their detection in human-related foods such as honey, beer, milk, table salts, etc. (Zhang et al. 2020). MPs pollution has significant adverse consequences upon public health and global economy.

MPs can lead to serious health hazards and can inflict toxic effects on individuals through oral or dermal infusion, and inhalation. MPs have also been reported to be inhaled along with air (Vethaak and Legler 2021). Strict regulatory guidelines and strategies are warranted to minimize MPs penetration into the aquatic as well as the marine ecosystems. Even though many countries have adopted different strategies for this purpose, most countries are unable to effectively regulate plastics penetration into the environment (Reisser et al. 2014; Guo et al. 2020; Wang et al. 2016).

Keeping in mind the detrimental effects of plastics and MPs, the present review focuses on the primary sources of MPs, its hazardous effects, and possible measures to mitigate the pollution sustainably. It also discusses the future prospects of research in the concerned area, so that in-depth knowledge on MPs is obtained which will eventually help in arousing awareness among the masses.

## Plastics and microplastics

Plastic accounts for approximately 85% of marine litter. Plastics and microplastics are persistent pollutants that are increasingly found in the littering of every environmental niche on a global scale (Barletta et al. 2019; Jambeck et al. 2015). Plastic waste is becoming a major concern due to its persistent nature and impact on aquatic organisms as well as humans (Thompson et al. 2009). The pores in MPs can absorb various chemicals from their surroundings and can transport toxic components to living organisms (Yuan et al. 2020; Wu et al. 2019). MPs have been shown in studies to inhibit growth, reduce immune function, and cause oxidative stress in marine organisms (Avio et al. 2015). Plastic particle aggregation in the ecosystem has toxic effects on biodiversity (Dawson et al. 2018; Gall and Thompson, 2015; Lu et al. 2016). As a result, immediate management strategies are required to reduce or eliminate potential threats to organism life (Barletta et al. 2019; Bour et al. 2018; Daiwile et al. 2015).

## Origin and sources of MPs

According to the United States Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), plastic is now a significant type of aquatic junk particle (Westphalen and Abdelrasoul 2017). MPs are difficult to be traced back to their origins due to their fragmented existence and

small size. Understanding the origins of both plastic materials and MPs will aid in the development of effective methods for reducing their entry into marine environments. MPs are commonly introduced into the environment via (1) wastewater treatment plants (Murphy et al. 2016), (2) drainage systems (Wagner et al. 2018), (3) litter from ships and recreational events, (4) dissolution from agricultural polyethylene foils, (5) washing and cleaning of cloths (Mintenig et al. 2017), (6) car tire abrasions, (7) fertilizer runoff (Dubai and Liebezeit 2013). The origin of the sources, the size of the particles, and the transfer of MPs through ocean waves and currents—all these factors affect variation in an aquatic ecosystem (Kukulka et al. 2012). MPs are derived from two sources: primary and secondary (Fig. 2).

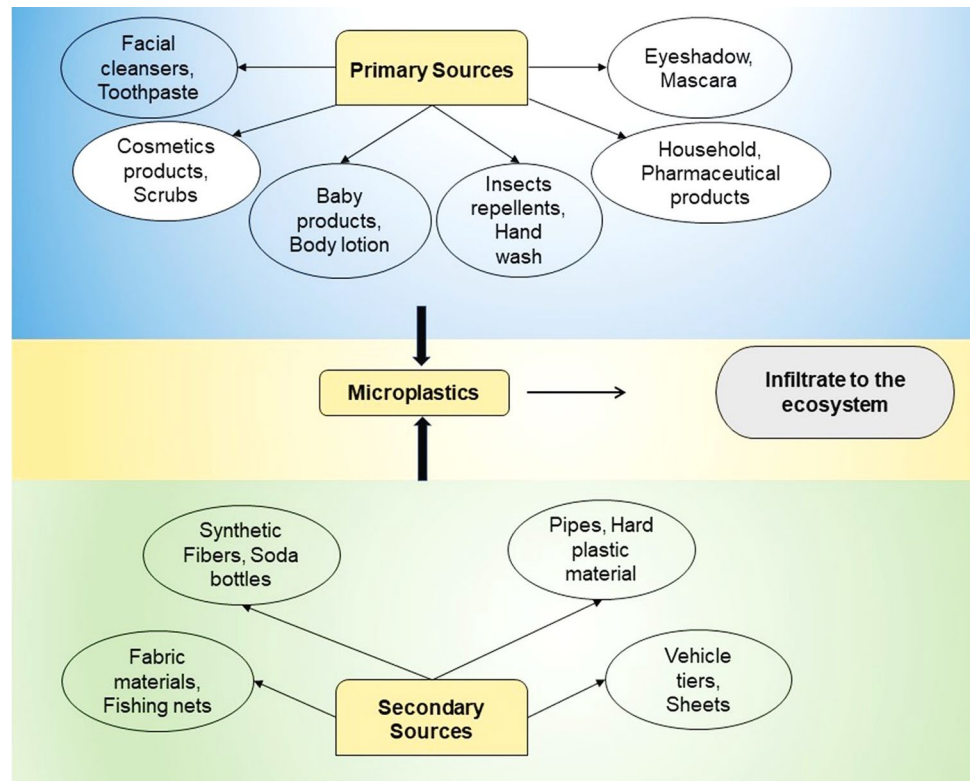
### Primary MPs

Primary MPs are those that are designed for specific industrial applications and can be as small as nanoscale. Furthermore, these small particles are used in the manufacturing of consumer goods as resin pellets or catalysts (Duis and Coors 2016). Mechanical exfoliants include: microfiber clothing, adhesive scrub sheets, and wide range of cosmetic products such as handwash, facewash, eyeliner, scents, beauty talc, hair care products, nail polish, sunscreen, insecticides, and toothpaste' in which primary MPs have been widely used (Auta et al. 2017). These products are freely used and discarded (Castaneda et al. 2014). These MPs are also widely used in wind turbines. Again, MPs are involved in clinical applications, such as serving as carriers in medicines and producing products used by dental surgeons to clean teeth (Lassen et al. 2015; Auta et al. 2017).

### Secondary MPs

Secondary MPs are formed in marine environments as a result of the fragmentation of larger plastic products into fine particulate matter. Secondary MPs are released into the water from hard plastic, synthetic fibers, clothing, pipes, plastic sheets, bottles, and nets, to name a few. MP fiber has been found in aquatic ecosystems as a result of secondary MPs production processes such as oxidation, photothermal degradation, and mechanical abrasion (Wagner et al. 2014). Plastics have been reduced in size in coastal areas due to excessive ultraviolet light, physiological tide erosion, and the availability of oxygen (Shim and Thomposon 2015).

**Fig. 2** Sources of MPs that infiltrate the marine environment



## Factors influencing MPs bioavailability

### Size

MPs are bioavailable due to their small size. Because of their small size, MPs can be mistaken by natural predators during regular feeding activities and consumed passively. Certain zooplankton species consume MPs ranging in size from 0.5 to 816  $\mu\text{m}$  (Cole and Galloway 2015; Desforges et al. 2015).

### Density

The bioavailability of plastic debris in the water column would be assessed by its density. Filter feeders, even suspension eaters are likely to experience sustainable, lower-density plastics on their ocean face in planktivores' surface waters, such as polyethylene (PE). For example, PE 20  $\times$  28 cm long food bags showed a well-developed biofilm within one week, and due to the neutral elasticity, these PE bags started to drain after third week under the ocean's surface (Lobelle and Cunliffe 2011).

### Affluence (abundance)

MPs are typically more prevalent in marine environments. Certain types of MPs are more abundant in certain regions, whereas other types of MPs may be abundant in other areas. According to one study, expanded polystyrene was more

abundant in Eastern and South-Eastern Asia, whereas polyethylene and polypropylene were found elsewhere (Shahul Hamid et al. 2018). Furthermore, seasonal variation was discovered to influence MP abundance (Kang et al. 2015). The greater the abundance of MPs in a given environment, the greater the chance of their consumption by organisms.

### Colour

The colour of the MPs can significantly influence their consumption by aquatic organisms. The bioavailability of MPs may be enhanced by microplastic colours, and the similarity of MPs to prey particles may increase the likelihood of consumption (Wright et al. 2013). Only a few studies have looked at the effect of MP colour on zooplankton. Euphausiids and copepods are important MP grazers in the North-Eastern Pacific coastal waters, where they are mostly black, red, and blue in colour (Desforges et al. 2015).

### Shape

MPs can be introduced into the environment directly as cylindrical beads used in the treatment of sewage in treatment plants, in clothes-washed fibers and cosmetic products (Napper and Thompson 2016; Thompson 2015). MPs in the form of shaped components can be found improperly due to the weathering and deterioration of large plastic materials. A recent study has discovered that zooplankton *Calanus*

*finmarchicus* easily consume microbeads, including microplastic fragments of size less than 30  $\mu\text{m}$  (Vroom et al. 2017).

## MPs' impacts on the marine environment

In many cases, aquatic organisms mistake MPs as food, while other species may intentionally use them as food (Lönnstedt and Eklöv 2016). Chemical and physical paralysis occurs if MPs are consumed by aquatic species. The binding of plastic with the cell surfaces can block flexibility as well as create blockages in the digestive system; additionally, it can also lead to hepatic stresses and reduced growth (Setala et al. 2016).

The MPs might carry organic compounds, such as diethylhexylphtalate (DEHP), which are harmful to aquatic organisms (Bakir et al. 2014). Table 1 shows a few MPs that have been reported to be consumed by aquatic organisms. Furthermore, different chemicals and metals can remain associated with MPs that can have additional negative impacts on aquatic organisms (Mammo et al. 2020). The neurotoxic effect of MPs has also been reported in previous studies, where acetylcholinesterase activity was measured under laboratory setup (Oliveira et al. 2013; Barboza et al. 2018). MPs can also lead to oxidative stress that causes lipid peroxidation of cellular membranes (Alomar et al. 2017). The detection of MPs in several commercially important edible fishes poses the threat of its transfer to higher organisms including human beings (Fossi et al. 2018). Campanale et al. (2020), discussed the effect of

MPs in humans that include respiratory troubles, accumulation in the gastrointestinal tract and the circulatory system (Campanale et al. 2020). Figure 3 depicts the hierarchical distribution of MPs across the organism system. Several studies on the effect of MPs exposure among various test organisms such as crustaceans, molluscs, fish, etc., interpret the induction of physical and chemical toxicity, genotoxicity, oxidative stress, behavioural changes, high transgenerational effects on the populations (Avio et al. 2015; Fonte et al. 2016; Barboza et al. 2018; Zhu et al. 2019). Another study (Sussarellu et al. 2016) found the detrimental effect of polystyrene MPs in reproduction and feeding of oysters affecting egg count and sperm count. Penguins were also reported to be affected by the consumption of MPs along with water (Bessa et al. 2019). The zooplankton community is also severely affected by MPs. Two economically valuable zooplanktons, Euphasia Pacific (Euphausiid) and Neocalanus cristatus (calanoid copepod), have been examined for MPs detection in the North Atlantic using the acid digestion method (Desforges et al. 2015).

## Methods of identification of MPs

MPs can be identified using both physical and analytical/instrument-based methods. Instrument-based methods are more accurate and reliable. Table 2 depicts the methods of identification as well as their characteristics and disadvantages.

**Table 1** Aquatic organisms consume MPs and the resultant effects

Type of plastic	Organism	Mechanism	Effect	References
Polyethylene	<i>Mytilus edulis</i> (Bivalves)	Ingestion	Aggregation in soft tissues	Van Cauwenberghe and Janssen (2014)
Polyethylene or polystyrene beads	<i>Artemia nauplii</i> (Brine shrimp)	Ingestion	Swelling of liver and aggregation in liver	Batel et al. (2016)
Polyethylene, polypropylene	<i>Balaenoptera Physalus</i> (Whale)	Ingestion	Toxicity symptoms increases	Fossi et al. (2016)
Polyethylene, polystyrene	<i>Mytilus edulis</i> (Blue mussel), <i>Allorchestes compressa</i> (Amphipods)	Ingestion	Granulocytoma formulation, destabilization/vector for aggregation of POPs	Avio et al. (2015), Chua et al. (2014) and von Moos et al. (2012)
Polylactic acid, Polyethylene	<i>Ostrea edulis</i> (European flat oysters), <i>Arenicola marina</i> (Lugworm)	Ingestion	Respiratory rate exaltation, metabolic rate increases	Besseling et al. (2013) and Green (2016)
Polystyrene	<i>Calanus helgolandicus</i> , <i>Centricus cristatus</i> , <i>Euphasia pacifica</i> (Copepod)	Ingestion	Feeding decreases, reproduction decreases	Cole et al. (2016) and Desforges et al. (2015)
Polystyrene microbeads	<i>Paramecium</i> sp. strain RB1 and <i>Tetrahymena</i> sp. strain RB2	Ingestion	Can aid in the transmission and bioaccumulation of MPs in freshwater food webs	Bulannga and Schmidt (2022)

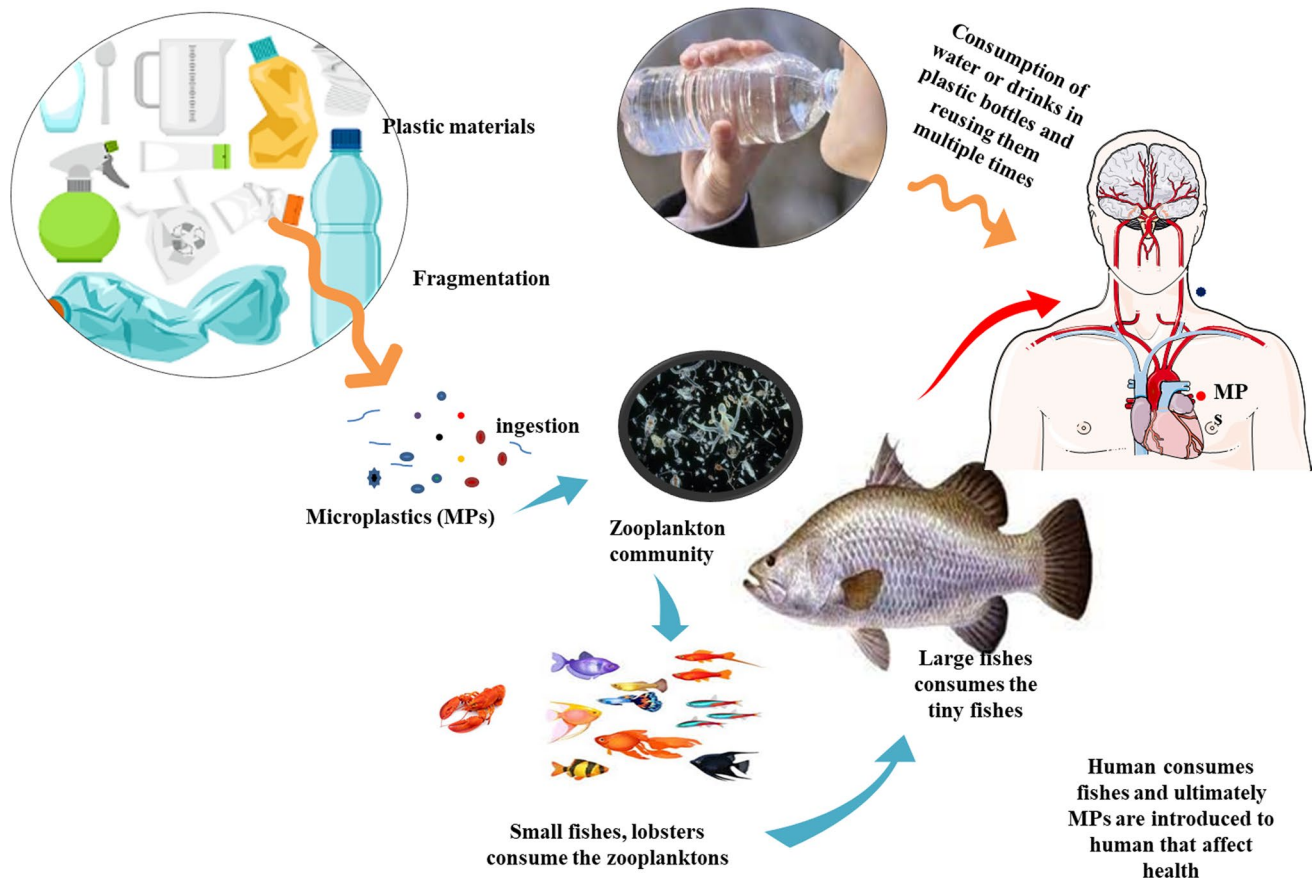


Fig. 3 Transfer of MPs to organisms across the food chain

## Measures to control pollution caused by MPs

The prevalence of MPs in our everyday life has resulted in their release into aquatic bodies. Because of the growing demand for plastic components, production is increasing at an exponential rate (Plastics Europe 2019). Plastics account for approximately 80% of marine litter, and they keep on piling in the environment, affecting living organisms (Ryan et al. 2009). As a result, it is extremely important to control the release of plastics into the environment.

### Strict regulations and Initiatives

The United Nations Convention on the Law of the Sea (UNCLOS) was proposed in 1982 to regulate all aspects of the sea's resources (United Nations 1982). It focused on a variety of issues including navigation rights, economic jurisdiction, territorial sea limits, the legal status of resources on sea-beds, and measures for marine environmental protection, including the protection of marine living organisms. Article 210 of the UNCLOS states that nations must develop frameworks to control marine pollution caused by waste dumping. Following the UNCLOS, several other programmes

and frameworks, such as the United Nations Environment Program (UNEP) and the Marine Debris Program (MDP), were designed to reduce marine pollution (da Costa et al. 2020). In 2017, the UNEP met in Kenya and adopted a draft resolution on marine litter and MPs (UNEP 2017). The draft primarily addresses the use of unnecessary plastics and promotes the use of eco-friendly alternatives. In addition, United Nations (UN) has declared the period 2021–2030 as the "Decade of Ecosystem Restoration" (United Nations 2020). The UN has set 17 sustainable development goals (SDGs); SDG14 focuses on underwater life conservation and sustainable ocean and sea resource utilisation.

To better implement the goals, the theme 'our ocean, our future, call for action' was introduced in 2017. The UN countries have made efforts to reduce plastic pollution in the ocean by minimising the use of plastics; a focus on reducing single-use plastics and single-use plastic packaging is also encouraged. The initiative's goal is to focus on long-term pollution management as well as plastic litter control. The European Union implemented a variety of waste management strategies to reduce marine litter from both the sea and the land (European Parliament 2019). Plastic restrictions in marketplaces, thereby encouraging the use of sustainable

**Table 2** Methods of identification of MPs

Method	Identification basis	Feature	Drawback
Visual identification	Characterizes the morphological and physical appearance of MPs	Usually carried to examine the big size range of MPs	It is a time-consuming technique as well as not accurate as compared to alternative approaches
Microscopy	Provides the data regarding surface quality, structural information, etc	Used for the identification method of MPs of the size ranges from 100 microns	Drawback of the microscopy includes poor separation of the light sediment particles in sediment sample
C:H:N ratio analysis	Based on the density and C:H:N ratio analysis, nature of the MPs can be detected	Recognize the type or origin of the plastic material	Takes more time for analysis, cannot analyse more samples, not applicable for the identification of the smaller particles
Thermal analysis	Based on the thermal stability of the material	Measurement of changes in the physical and chemical properties of the material in the thermal environment	The analysis of the certain minimum size of the particles, this results in the lower size limit of particles
Raman spectroscopy	Help in the analysis of microscopic plastic pieces by focusing a laser beam on a small spot to obtain Raman spectra.	Identifies plastic as well as provides a chemical composition of the polymer provides a contact-less analysis of the sample	Sensitive to additive and pigment chemicals that interfere with MPs, which interfere with the identification of polymer types
Fourier-transform infrared spectroscopy (FTIR)	FTIR, in combination with the MP hunter software, proved to be a quick and accurate method of automatically identifying microplastics.	Provides information about the polymer	Time-consuming technique for the identification of the large samples

alternatives, are among the measures being considered. Various regulatory frameworks such as the Marine Strategy Framework Directive (MSFD) (European Parliament 2008), which focuses on marine economic and social activities, have been designed to protect the marine environment and control the dumping of plastic litter (Gago et al. 2016).

Several companies and organisations are taking steps to adopt environment-friendly practises such as prohibiting single-use plastics and excluding plastics from a variety of goods (Eschener 2019). Ban on use of plastic bags has been implemented in several counties, with the goal of eradicating disposable plastic goods (Vesilevskaia 2018). However, due to the the scarcity of other cost-effective alternatives, such bans have become quite unrealistic in practise and not implemented properly. Many countries have imposed mandatory plastic bag surcharges in market areas in order to promote the use of biodegradable bags and reduce the usage of plastics. But so far these measures have not proven to be very effective.

**Modern engineering tools for contamination prevention and clean-up of MPs**

The recent developments of engineering technology provide us with opportunities to remove MPs from the environment. Waste water treatment plants (WWTPs) have been used for the elimination of plastic particles from waste waters. The efficiency of such plants have been evaluated (Talvitie et al. 2017b; Lares et al. 2018). In order to eliminate high-grade MPs, the traditional WWTPs could not be a good option and the MPs removal range is below average. Membrane agglomeration-coagulation and electrodeposition are generally used for advanced WWTPs. Membrane bioreactor (MBR) is one of the most effective processes in which membrane formulations such as ultrafiltration or microfiltration are used to clean wastewater. The conventional activated sludge-based process showed 98.3% removal of MPs, but the MBR technique showed a 99.4% increase in MPs separation performance, which is greater than the conventional activated sludge-based process (Talvitie et al. 2017a). MBRs have also been constructed with other revolutionary tertiary treatments, such as rapid gravity filtration and dissolved air flotation, which can lead to more than 95% separation of MPs from primary and secondary pollutants. The gravity filtration process, as well as dissolved air flotation, is used for revolutionary tertiary MBR treatments that can separate MPs at a level of up to 95% from primary and secondary effluents. High performance for the removal of MPs is also demonstrated by biological active filter, i.e., BAF (Talvitie et al. 2017a). BAF has been developed for advanced wastewater treatment plants with approximately 99% of the total retention capacity for MPs.

Another well-known method for the extraction of MPs from wastewater streams is electrocoagulation (EC). The EC technology is an efficient way for reducing wastewater MPs by achieving maximum separation efficiency of 99.24% at 7.5 pH (Perren et al. 2018). Harmful effects of pollutants could be treated by using Electro-oxidation (EO) in an electrochemical flow reactor using Ti/Pt or Boron Doped Diamond, i.e., BDD anodes and cathodes prior to discharge of effluents into the marine environment (Durán et al. 2018). In the discharge of MPs, the power density used for analysis with Ti/Pt, the BDD anode shows a distinct pattern and improved productivity. EO can become an economically efficient and effective therapeutic strategy for the remediation of MPs and other contaminants, particularly with the BDD anode.

### Increased recycle, recovery and reuse rate of plastic materials

Currently the emphasis is on the three R hierarchies of an integrated waste management system, namely reduction, reuse, and recycling. The use of plastic material can be reduced by prohibiting the use of certain types of plastic like that for single use. Higher recycling rates can help significantly reduce plastics in the marine environment. Plastic recycling is a complicated process that includes the following steps: (1) consumer waste management, (2) recyclable separation and pollutant removal, (3) polymer and colour grounding and differentiation, (4) polymer and colour sample distillation, and (5) recycle products to manufacturing (Bing et al. 2014; Walker, 2018). Diverse wastes should be properly treated in recycling units, and direct dumping should be avoided at all costs. A large number of plastics can be found in a large load of waste from medical units. In the current situation of the Covid-19 pandemic, the use of personal protective equipment (PPE), masks, and covers that are typically one-time use have increased exponentially. Such wastes should be properly treated, or else it can lead to severe environmental pollution in the future, affecting the ecosystem (Issac et al. 2021). The pandemic situation should not be used as an excuse for ignoring the treatment of such wastes. In fact such medical plastic wastes should be treated even more seriously.

### Utilization of biodegradable or biological based polymer materials

To solve the problem, use of a variety of recyclable products such as biodegradable plastics and nano-plastics (Paco et al. 2019) could be an alternative option. Biodegradable alternatives such as paper, jute, cotton, wool, or other fabrics can be used to make carry bags (Iheukwumere et al. 2020). Several

plant and bacterial material are also being explored for utilisation as bioplastics.

### Sustainable bioengineering solutions

Conventional BPA-based plastics can be degraded by various types of bacteria, fungi via enzymatic action (Sarma et al. 2019). Some plastics may degrade, such as polyethylene terephthalate (PET) is reported to be degraded by *Ideonella sakaiensis* (Yoshida et al. 2016) and polyethylene (PE) by the aquatic fungus *Zalerion maritimum* (Paco et al. 2017). Developing on-site biodegradation strategies for MPs with the addition of microbes or increasing natural attenuation with the use of native microflora is critical. Since environmental and physical conditions have a large impact on bioremediation, simulating such factors will make it easier and more convenient to accelerate the microbial degradation process (Tiwari et al. 2020). Yuan et al. (2020) summarised the various bacterial and fungal populations that can utilize MPs and help in their removal from the environment.

### Conclusion

MPs have become one of the most common marine litter wastes. Almost all life forms are affected by the toxic effects of MPs in the marine environment. MPs pollution can be reduced by implementing proper regulatory framework and cutting-edge biotechnology. Even though the government and policymakers have enacted numerous laws and regulations, it is the responsibility of individuals and organisations to ensure that regulations are enforced to protect ecosystems from the negative effects of plastic litter. Since there have only been a few studies on the health effects of MPs, future research in this area is important and necessary. Furthermore, using microbes to efficiently remove plastic litter from the environment can provide green solution for reducing MPs pollution and impact on ecosystems.

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**Ethical approval (include appropriate approvals or waivers)** Not applicable.

**Consent to participate (include appropriate statements)** The voluntarily agree to participate in this research study.

**Consent for publication (include appropriate statements)** I hereby transfer, assign, or otherwise convey all copyright ownership, including any and all rights incidental thereto, exclusively to the journal, in the event that such work is published by the journal.

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