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Microplastics in Ecological System: Their Prevalence, Health Effects, and Remediation

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Abstract

Water is a fundamental component of human physiological processes, playing a crucial role in functions such as nutrient assimilation and metabolic activities. Furthermore, it plays a crucial role in guaranteeing a plentiful food supply for all organisms. In addition to its duty in providing nutrition, water serves as a home for many life forms and plays a vital part in establishing a conducive living environment. However, the introduction of plastic materials has led to the occurrence of microplastics (MPs) in aquatic environments, which has become a global issue that has attracted significant interest from both the scientific community and the general public. The increasing worldwide demand for plastics can be ascribed to its multifunctionality in commercial and industrial contexts, combined with its cost-effectiveness. Members of Parliament have been identified through multiple sources, including but not limited to cosmetic products, industrial wastes, and fishing operations. The primary aim of this research is to conduct a thorough examination of the consequences resulting from the widespread presence of MPs on both terrestrial and marine ecosystems, as well as the impact on human welfare. Therefore, it is crucial to develop efficient mitigation measures in order to remove MPs from water reservoirs, protect ecological integrity, and provide a safer environment for future generations. Furthermore, this work evaluates the benefits and limitations of utilized methodologies, elucidating the inherent difficulties in MPs research that require resolution in order to achieve a thorough comprehension of these particles. International

collaboration plays a crucial role in efficiently resolving concerns related to marine pollutants, as they have the ability to disperse by wind and sea currents, leading to possible repercussions that are difficult to predict.

Keywords: Emerging pollutants; sources; fate and transport; methods used; challenges faced

1. Introduction

Plastics are widely recognized for their notable attributes such as flexibility, low weight, mechanical strength, and superior thermal and electrical insulation capabilities. These characteristics make plastics durable and well-suited for use in demanding environments (Thompson et al. 2009). The advent of synthetic plastics may be traced back to the development of Bakelite in 1907, which served as the catalyst for the establishment of the worldwide plastic manufacturing sector. Significantly, it was not until the 1950s that there was a substantial increase in global plastic output (Klöckner et al. 2021). The significant increase in popularity of this phenomenon may be primarily ascribed to its economical nature and its ability to be utilized in a diverse range of commercial and industrial contexts. During the following 65-year period, there was a significant increase in plastic production, reaching a magnitude almost 200 times more than its initial level. In 2015, the total plastic production exceeded 0.380 billion tonnes, which is roughly equivalent to 67 percent of the global population (Klöckner et al. 2021; Thompson et al. 2009). Plastics have been pervasive in several domains of civilization, serving practical purposes in transportation, electrical gadgets, apparel, and packaging materials intended for containing food, beverages, and other goods (Thompson et al. 2009). Plastics are classified into various groups based on their ingredients and fabrication materials (Klöckner et al. 2021). Table 1 presents a comprehensive analysis of several plastic kinds, encompassing their distinct characteristics and diverse range of applications. The exponential growth of plastic manufacturing, combined with the difficulties in its disposal and the impact of human actions, has resulted in a significant strain on ecosystems worldwide (Horton and Barnes 2020).

Table 1. Types of plastics with their uses and features.

Plastic Types	**Applications**	**Characteristics**	**Soften temperature (℃)**	**Average densities (g/cm^3)**	**Reference**
Polyethylene terephthalates (PET)	Clothes, food or beverage containers, soft drinks	-Robust -Transparent -Thin	80	1.40	Alabi et al. (2019); Guo et al. (2016)
High-density polyethylene (HDPE)	Agriculture tubing, pail, plastic bottles	-Heat resistant -Chemicals and water resilient -Light impermeable	75	0.95	Alabi et al. (2019); Guo et al. (2016)
Polyvinyl Chloride (PVC)	Electrical circuits, bottles, skincare containers	-Heat resistant -Durable -High toxicity	80	1.45	Alabi et al. (2019); Guo et al. (2016); Singha et al. (2016)
Polypropylene (PP)	Wrapping tape, containers, lawn	-Strong -Translucent	140	0.88	Alabi et al. (2019); Guo et al. (2016);

	appliances, snacks bags				
Polystyrene (PS)	CD boxes, plastic tableware, artificial glassware, packaging	-Alkaline resistant -Moderate tough -Brittle -Light impermeable	95	1.06	Alabi et al. (2019); Guo et al. (2016)

Plastic can be classified into four main categories: macroplastics, mesoplastics, microplastics, and nanoplastics. MPs refer to tiny particles composed primarily of synthetic polymers, which vary in size from 1 micrometre (μm) to 5 millimetres (mm) (Horton and Barnes 2020; Danopoulos et al. 2019). Although the discovery of this persistent pollution may be traced back to the early 1970s, it is only in recent times that the spatial dispersion and ecological ramifications of this phenomenon have gained attention and been subject to thorough investigation (Horton and Barnes 2020). The organisms in question exhibit a wide distribution over both terrestrial and aquatic habitats, causing significant disruption to marine ecosystems, agricultural plantations, and human populations (Horton and Barnes 2020; Danopoulos et al. 2019). The increase in ambient MP concentrations enhances the likelihood of ecosystem exposure, ingestion, and subsequent adversities among different trophic levels (Horton and Barnes 2020). As a result, these particles have emerged as plausible risks to food safety. MPs have been found to cause disturbances in biota through several processes, leading to the unsettling and disruption of ecosystems (Lim et al. 2023; Horton and Barnes 2020; Danopoulos et al. 2019). The aforementioned situation has garnered considerable scientific and public interest, prompting the need for strategies to remove MPs from water sources in order to protect human well-being. Significantly, the primary pathways via which MPs infiltrate the human body are via the ingestion of water and the eating of contaminated food, as evidenced by studies conducted by Danopoulos et al. (2019) and Hu et al. (2021). The primary aim of this research is to conduct a comprehensive investigation of the relationship between MPs and the environment. The project seeks to enhance our understanding of this relationship and develop effective strategies to mitigate the adverse impacts of MP pollution. The comprehensive summary of the yearly environmental impact caused by plastic trash from various countries is summarized in Table 2.

Table 2. Summary of countries that contribute plastic waste to the environment

Country	**Average of mismanaged plastic waste (x10^6 kg/year)**	**Average of plastic marine debris (x10^6 kg/year)**	**Reference**
China	8820	2425	Jambeck et al. (2015)
Indonesia	3220	885	Jambeck et al. (2015)
Philippines	1880	515	Jambeck et al. (2015)
Vietnam	1830	505	Jambeck et al. (2015)

Sri Lanka	1590	440	Jambeck et al. (2015)
United State	2750	75	Law et al. (2020); Jambeck et al. (2015)
Malaysia	940	255	Chen et al. (2021); Jambeck et al. (2015)
South Africa	630	215	Jambeck et al. (2015)
Brazil	280	130	Jambeck et al. (2015)

2. Type, sources and transport of MPs

In the present era, MPs have become a prominent worldwide environmental concern, arising from several origins, as illustrated in Figure 1. The following sources are further expounded upon in subsequent sections: Jaikumar et al. (2019), Boucher and Friot (2017), and Webb et al (2013). This situation has introduced additional stress on human livelihoods and presents a concrete threat to our ecology. There are two prominent classifications of microplastics, namely primary and secondary microplastics. Primary microplastics are introduced into the environment in the form of small beads, pellets, and fibers, which are widely present in cosmetics, personal care products, and industrial uses. Secondary microplastics are generated by the process of fragmentation, which occurs when larger plastic objects such as bags, bottles, and fishing nets break down into smaller particles. The process of weathering and degradation of diverse plastic items, including automobile tires and textiles, can also contribute to the generation of microplastics. The sources of MPs cover a wide range of activities that span across home, industrial, and agricultural sectors (Boucher and Friot 2017; Webb et al. 2013). Urban sewage systems are significant sources of MPs in aquatic ecosystems, as they transfer huge amounts of MPs into water bodies. Furthermore, waste treatment facilities and landfills emit MPs that have the potential to collect over time and ultimately contaminate adjacent water bodies. Industrial activities such as plastic manufacture, shipyards, and ports have a significant role in contributing to plastic pollution, mostly due to the extensive utilization of plastic items within these sectors. The transportation routes for MPs encompass several mediums, including air, water, and soil. The dispersion of MPs over long distances in the atmosphere is primarily facilitated by atmospheric movement, which is driven by wind and precipitation (Boucher and Friot 2017; Obbard 2018; Anderson et al. 2016). Once introduced into aquatic environments, MPs can be dispersed through the movement of ocean currents, tides, and river flows (Karing et al. 2023; New et al. 2023a). Moreover, the ingestion of microplastics by marine creatures can unintentionally facilitate their transportation to various regions within the ocean. Soil can also function as a pathway for MPs transportation, especially in agricultural environments, where the movement of MPs can occur through runoff and irrigation systems (Anderson et al. 2016).

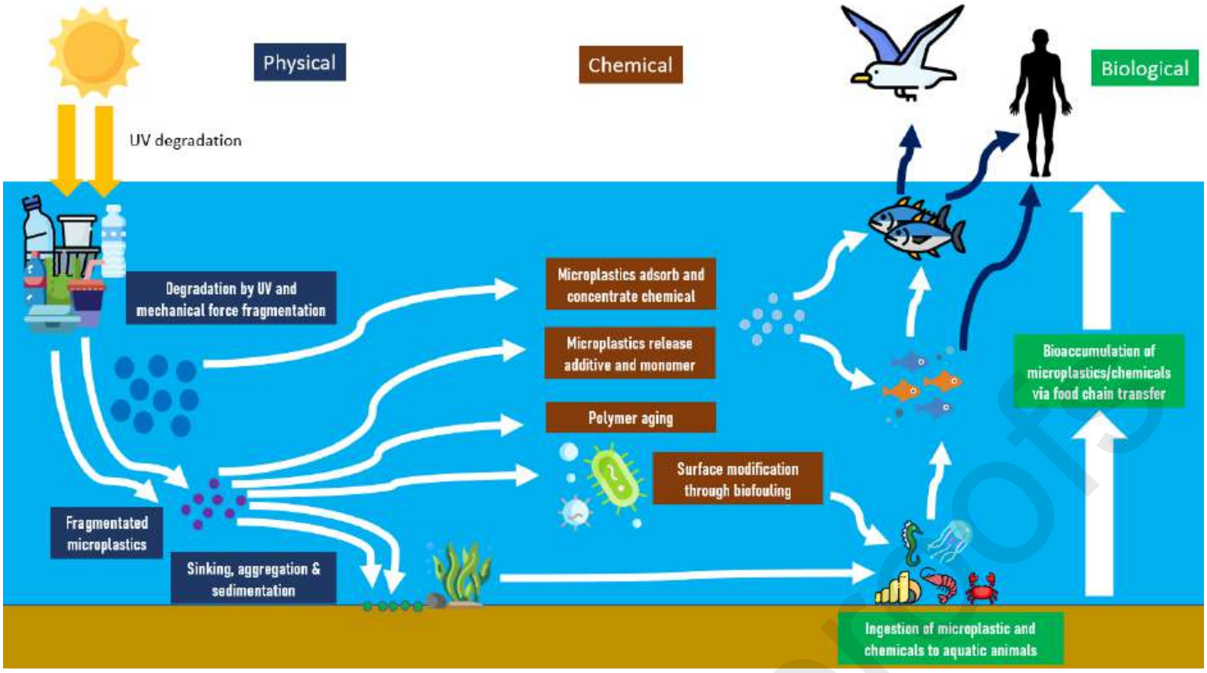

Figure 1. Sources and pathway of MPs in aquatic environment.

2.1. Type of MPs

The classification of MPs into primary and secondary groups is contingent upon their deliberate production as particles with micron-scale dimensions or their formation as a result of the breakdown of bigger polymer materials (New et al. 2023b; Jaikumar et al. 2019; Anderson et al. 2016). The aforementioned distinction carries great importance as it facilitates the identification of relevant factors and approaches to mitigate their ecological consequences. Primary MPs refer to particles that have a diameter of less than 5 mm. These particles are intentionally added to various commercial products such as cosmetics and textile fibers (Jaikumar et al. 2019). On the other hand, secondary MPs are derived from larger plastic objects that experience disintegration or weathering as a result of several environmental factors, including wave action, temperature changes, UV radiation, alkalinity, polymer composition, and aging (Jaikumar et al. 2019). The degradation of plastics occurs as a consequence of exposure to UV or solar radiation, leading to various detrimental effects such as diminished tensile strength, discoloration, the formation of surface cracks, and ultimately, increased brittleness and fragility. The plastic materials in question exhibit reduced strength and are susceptible to fragmentation when subjected to external forces such as waves, wind, or human activities, resulting in the formation of smaller fragments (Webb et al. 2013). Another category of microplastics (MP) includes microfibers, which are tiny fibers that are released from textiles during washing, drying, and everyday use. The presence of microfibers is particularly prevalent in synthetic textiles composed of materials such as polyester, nylon, and acrylic. The diminutive dimensions of these organisms facilitate their passage through wastewater treatment systems, ultimately leading to their presence in aquatic environments. Nurdles, commonly known as "mermaid tears," represent a distinct subset of MPs that are regularly observed in various environmental settings. The aforementioned minuscule plastic pellets serve as primary inputs in the manufacturing process of plastic commodities. Nurdles are susceptible to spilling during the process of transportation and handling, frequently resulting in their presence in waterways. This presence poses a significant risk to marine creatures. Finally, fragments originating from bigger plastic trash, such as fishing gear, ropes, and other equipment, possess the capability to undergo degradation into smaller particles, thus transforming into MPs. The shards can be transported by ocean currents to remote regions of the ocean, posing a threat to marine life and ecosystems (Ding et al. 2021; Anderson et al. 2016).

2.2. Sources of MPs

According to Anderson et al (2016), the personal care and cosmetic sectors are significant sources of MPs that are released into the environment. Many exfoliants and cleansers in the market include MPs as substitutes for conventional ingredients including almonds, oats, and corn. Surprisingly, a single application of an exfoliant has been found to release as many as 94,000 MPs (Ding et al. 2021; Anderson et al. 2016). Previous research indicates that around 4,000 tonnes of MPs are employed in cosmetics across the European Union, Norway, and Switzerland. Consequently, these particles frequently find their way into home wastewater systems. Due to their small size, MPs have an increased likelihood of evading conventional wastewater treatment methods and entering aquatic habitats, so compromising the quality of freshwater and posing a threat to the surrounding creatures. In actuality, wastewater treatment plants have the capacity to capture solely 95% of MPs, resulting in the discharge of the remaining percentage. It is worth noting that the sewage sludge, which contains MPs and is utilized as compost following the treatment of wastewater, is typically not considered within this particular framework. In recent years, there has been a growing body of information that has drawn attention to the ecological hazards associated with MPs. The inclusion of MPs in commercial merchandise has garnered significant interest from both scientists and the general public. As a result, several countries, including Canada, New Zealand, Ireland, and Sweden, have implemented regulations prohibiting the use of MPs in cosmetic products. Some manufacturers have already begun to phase out the utilization of MPs in response to these regulations. The primary objective of any regulation of this kind should be to minimize or eliminate the discharge of superfluous plastic particles into the environment, as stated by Anderson et al. (2016).

In addition, it is worth noting that various activities such as fishing, farming, and aquaculture possess the capacity to introduce MPs into aquatic environments. It is worth mentioning that in 2011, agricultural operations in China utilized a significant amount of plastic materials, in total more than 1.20 million tons. Similarly, in European and American farming, sewage sludge containing around 250,000 and 170,000 tons of MPs was employed as fertilizer, as reported by Ding et al. (2021). The utilization of plastic mulching is a commonly employed method in residential agriculture to effectively maintain heat and moisture levels, promote the interaction of fertilizers, and improve the overall quality of soil. Nevertheless, this particular approach results in a notable buildup of plastic inside farmed soils, subsequently facilitating its transfer into freshwater habitats through the mechanisms of water and wind (Ding et al. 2021; Meng et al. 2020). The migration and dispersion of MPs are influenced by various factors, including density, structure, and volume (Ding et al. 2021). Furthermore, the presence of MPs in aquatic habitats can be attributed to the complex nature of aquaculture activities. Plastics are commonly employed in various fishing apparatus, including nets, breeding and farming equipment, and containers, hence constituting a significant proportion of MPs found in aquaculture habitats (Ding et al. 2021; Zhou et al. 2021). In the specific domain of Norwegian fishing, the quantity of abandoned fishing gear has experienced a significant increase of 3,500 tonnes over a relatively short span of nine years. As a result, fish-based goods frequently exhibit substantial levels of MPs, as evidenced by the identification of over 300 distinct MPs in samples obtained from different Malaysian brands. Furthermore, it should be noted that fish medication and animal supplements might serve as significant sources of MPs, as there is a clear association between MPs and antimicrobial drugs. The possible negative consequences of aquaculture on marine ecosystems and, by extension, human well-being is emphasized by the implications of these factors on aquaculture habitats (Ding et al. 2021).

Fibrous materials, whether derived from natural or synthetic sources, are a prominent type of microplastics commonly detected in environmental samples. These microplastics mostly originate from textile sources. Polyester, a cost-effective and readily produced alternative to cotton, has become the predominant synthetic fibre responsible for the presence of microplastics in terrestrial, aerial, and aquatic environments (Almroth et al. 2018). The primary source of microfiber release stems from synthetic clothes, as a result of the mechanical and chemical forces exerted during the washing procedure, causing them to separate from the fabric fibers (De Falco et al. 2019). According to a study conducted by Almroth et al. (2018), recent research findings suggest that the quantity of fibers released during the process of washing could potentially surpass 110,000 fibers per kilogram of laundry. In the last twenty years, there has been a significant increase of 80 percent in global average fibre consumption. This surge in consumption is particularly notable in the usage of synthetic fibers, which has tripled during this period. Consequently, there has been a substantial increase in the overall presence of fibers in wastewater treatment plants (WWTPs). The aforementioned statement underscores the need of technological progress in wastewater treatment systems as a means to mitigate the environmental consequences associated with microplastics (De Falco et al. 2019; Boucher and Friot 2017). Researchers are currently investigating advanced manufacturing techniques and vacuum procedures at production facilities, as well as the incorporation of additional filters in home laundry settings, as strategies to reduce the occurrence of microplastics in the environment (Almroth et al. 2018).

2.3. Fate and distribution of MPs

In order to have a comprehensive understanding of the ecological implications of MPs, it is crucial to acknowledge their mobility and deposition patterns. The transportation of MPs through several means of conveyance amplifies their influence on populations and ecosystems beyond their initial introduction, resulting in consequences that surpass initial expectations. The interaction between MPs and species, encompassing their ingestion and subsequent incorporation into the food chain, is subject to the influence of transport dynamics, including the movement of MPs, the duration of their presence, and their deposition. In addition, the transportation dynamics play a significant role in determining the density of MPs contamination and its subsequent impact on organisms (Petersen and Hubbart 2020). Therefore, it is imperative to evaluate the fate of MPs in freshwater ecosystems and their ultimate transport in order to appreciate their implications and possible influence (Ding et al. 2021; Petersen and Hubbart 2020). Table 3 and Figure 2 illustrate the mean concentration of MPs in different geographical areas, considering their mobility and ultimate destiny. There are two main classifications of MP distribution that have been identified: vertical (VD) and horizontal (HD). These classifications are significantly influenced by various parameters including MP dimensions, structure, density, hydrogeology, and the presence of organisms (Ding et al. 2021).

Table 3. The average concentration of MP discovered in different regions as a result of their movement.

Location	Region	Average MP concentration	References
Sediments	**Asia**		
	Gulf of Thailand	150.4 ± 86.2 particles/kg	Wang et al. (2020)
	Santubong (Kuching, Malaysia)	0.223 g	Noik and Tuah 2015
	Trombol (Kuching, Malaysia)	1.635 g	Noik and Tuah 2015
	Karnataka, India	664 particles/kg	Noik and Tuah (2015)
	Kish Island, Iran	580.00 particles/kg	Yaranal et al. (2021)
	Dongshan Bay, China	971 particles/kg	Pan et al. (2023)
	Jagir Estuary, Indonesia	253 particles/kg	Firdaus et al. (2020)
	Wonorejo coast, Indonesia	537 particles/kg	Firdaus et al. (2020)
	America		
	Tampa Bay, Florida	280 (± 290) particles/kg	McEachern et al. (2019)
	Galapagos Island, Ecuador	74.6 particles/kg	Jones et al. (2021)
	Amazon River, Brazil	417 to 8178 particles/kg	Gerolin et al. (2020)
	Tampico, Gulf of Mexico	13.392 particles/kg	Flores-Ocampo and Amstrong-Altrin (2023)
	Camburi and Curva da Jurema, Brazil	1488 particles/kg	da Costa et al. (2023)

Location	Region	Average MP concentration	References
	Paranaguá Estuarine,Brazil	398 particles/kg	Mengatto and Nagai (2022)
	Australia		
	Adelaide, South Australia	0.5 – 2.2 ± 0 – 1.2 items/kg	Hayes et al. (2021)
	Eden, Eastern Coast Australia	350 particles/kg	Jahan et al. (2019)
	Great Australian Bight	13100 particles/kg	Barret et al. (2020)
	Africa		
	Western Cape, South Africa	185.07 ± 15.25 SE particles/kg	Julius et al. (2023)
	Algeria	182.66 ± 27.32 to 649.33 ± 184.02 kg/particles	Tata et al. (2020)
	Ghana	144 ± 61 items/kg	Nuamah et al. (2023)
	Dar es Salaam and Zanzibar (Tanzania)	864.15 ± 275.10 particles/kg	Nchimbi et al. (2022)
	Taghazout Bay (Morrocco)	1448 particles/kg	Ben-Haddad et al. (2022)
	Rimel Beach, Bizerta lagoon and Ichkeul lake (Tunisia)	130.55 ± 65.61 items/kg	Jaouani et al. (2022)
	Europe		
	Kaliningrad, Russia	1.3–36.2 particles/kg	Esiukova (2017)

Location	Region	Average MP concentration	References
	Brest Bay, France	0.97± 2.08 particles/ kg	Frere et al. (2017)
	Pacheia Ammos, Yunani	149 ± 148 MP particles/kg	Piperagkas and papargeoiou (2021)
	Cartagena (Spain)	30.01 particles/kg	Bayo et al. 2022
	Cala Cortina, Spain	30.01 ± 7.26 items/kg	Bayo et al. (2022)
	Black sea, Turkey	64 particles/kg	Terzi et al. (2022
	Tromsø, Norway	72 ± 24 particles/kg	Lots et al. (2017)
Seawaters	**Asia**		
	Xincun Bay, China	60.9 ± 21.5 particles /L	Wei et al. (2022)
	Can Gio Beach, Vietnam	6.44 ± 2.98 particles /L	Khuyen et al. (2021)
	Singapore Strait	106000 to 238000 particles /L	Curren and Leong (2023)
	Jakarta Bay, Indonesia	55.8 to 86.6 particles /L	Takarina et al. 2022
	Java Island (Indonesia)	405 particles/L	Cordova et al. (2019)
	Tambak Lorok (Indonesia)	6000 particles/L	Cordova et al. (2019)
	Kenjeraan Beach (Indonesia)	0.505 particles /L	Cordova et al. (2019)
	Jagir estuary (Indonesia)	253 particles/kg	Firdaus et al. (2020)
	Wonorejo coast (Indonesia)	537 particles/kg	Firdaus et al. (2020)
	Tanjung Benoa, Bali, Indonesia	0.00061 particles /L	Suteja et al. (2021)
	Off Nagasaki, Japan	0.00049 particles/L	Kobayashi et al. (2021)

Location	Region	Average MP concentration	References
	America		
	Tampa Bay, Florida	0.94 ± 0.52 particles/L	McEachern et al. (2019)
	Galapagos Island, Ecuador	0.00016 ± 0.00003 particles/L	Jones et al. (2021)
	Patagonia, Argentina	10.5 particles /L	Rios et al. 2020
	Rio de Plata, Uruguay	0.024 particles/L	Pazos et al. (2021)
	Guanabara Bay,Brazil	0.0048 particles/L	Figueiredo and Vianna (2018)
	Santa Cruz, California	0.0321 particles/ L	Kashiwabara et al. (2021)
	Australia		
	Adelaide, South Australia	0.0000430 ± 0.0000169 particles /L	Hayes et al. (2021)
	Africa		
	Kenya	0.11 particles/L	Kosore et al. (2018)
	Bay of Biscay, South Africa	0.00115 ± 0.00145 particles/L	Kanhai et al. (2018)
	South-eastern coastline of South Africa	0.2579–1.215 particles/L	Nel and Froneman (2015)
	Durban, South Africa	0.00703 ± 0.01193 particles /L	Naido and Glassom (2019)

Location	Region	Average MP concentration	References
	Western Cape, South Africa	1.33 ± 0.15 SE particles/L	Julius et al. (2023)
	Europe		
	Weser North Sea, German	5.4 particles/L	Roscher et al. (2021)
	Brest Bay, France	0.24 ± 0.35 particles/L	Frere et al. (2017)
	Gulf of Trieste	0.00629 ± 0.00268 particles/L	Gajšt et al. 2016
	Black Sea	0.01868 ± 0.0301 particles/L	Terzi et al. (2022)
	Kattegart, Denmark	0.103 ± 0.086 particles/L	Liu et al. (2023)
	North West Portuguise (recreational marina)	4.028 ± 1.878 particles/L	Rodrigues et al. (2020)

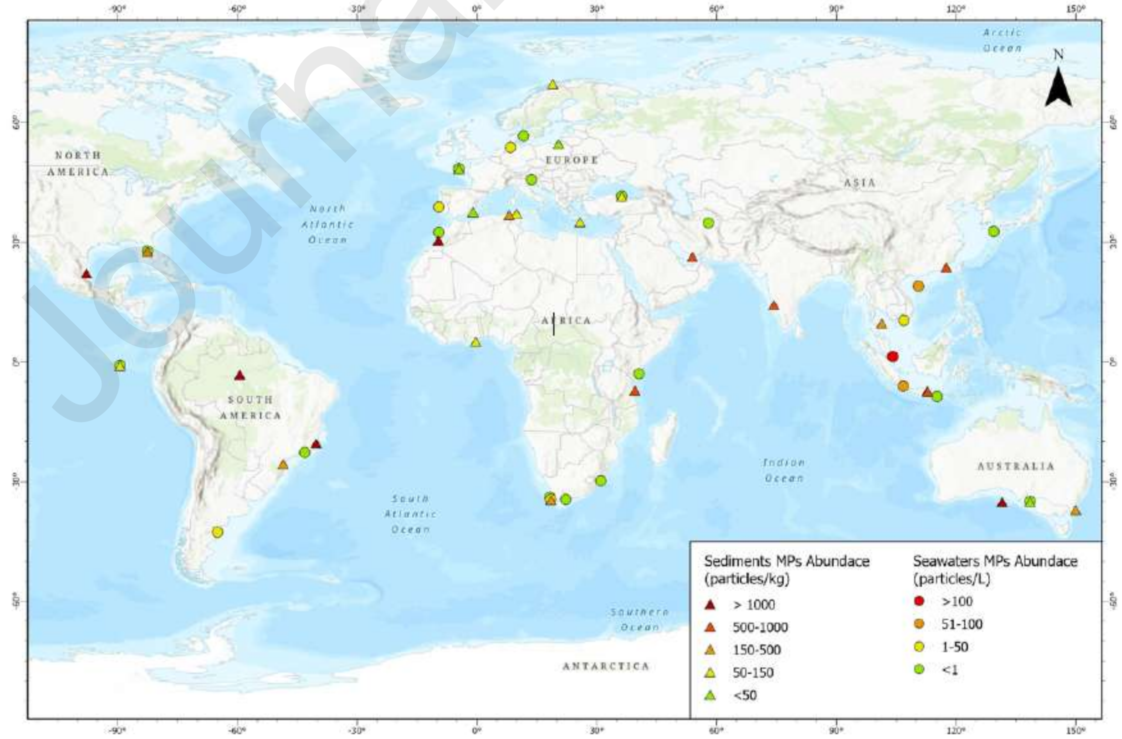

Figure 2. Sediments and seawaters MPs abundance various regions of the world.

The flow of MPs into water bodies is influenced by key processes such as aggregation, homo-aggregation, and hetero-aggregation, which are crucial for understanding the vertical distribution (VD) of MPs. The term "aggregation" pertains to the occurrence in which MPs, or microplastics, engage in interactions and merge together within the water column prior to their eventual deposition into sediment. The impact of MP volume on homo-aggregation is substantial; nevertheless, the current body of research on this topic is restricted. This limitation arises from the difficulties associated with producing homo-aggregations in aquatic systems using the Derjaguin−Landau−Verwey−Overbeek (DLVO) hypothesis, as noted by Ding et al. (2021). It is worth mentioning that MPs characterized by densities above 0.001 mg/m^3, such as polyvinyl chloride (PVC) and polyethylene terephthalate (PET), exhibit a tendency to rapidly settle, frequently observed in freshwater sediments (Ding et al. 2021; Carr et al. 2016). According to Song et al. (2018), PE and PP are commonly observed in the upper water layers of Korean coastal regions, in contrast to PVC and PET. This distribution pattern can be attributed to the lower densities of PE and PP, which enable them to migrate more easily in aquatic settings influenced by circulation patterns. The hetero-aggregation of MPs in aquatic environments is influenced by various factors, including the characteristics of algae species, chemical content, and geometric properties. The process of biofilm development and particle adhesion plays a significant role in the hetero-aggregation of MPs, which is regulated by several parameters such as temperature, nutrition availability, and the presence of colloidal matter. Hetero-aggregation has the potential to induce modifications in the structural attributes of MPs, thereby influencing their fate and distribution patterns (Ding et al. 2021).

The horizontal distribution (HD) of MPs was influenced by the surrounding environmental conditions and the distribution of biotic factors, which are mainly affected by variations in hydraulic states. Within local freshwater ecosystems, MPs can travel horizontally from streams to lakes, as well as from rivers to the ocean and even to the Arctic regions (Ding et al. 2021; Song et al. 2018). In terms of biotic dispersal, MPs can be ingested or adhere to the exterior of organisms and may subsequently detach during biotic movements. Notably, factors that affect this type of distribution include aquatic species and the size, geometry, and appearance of MPs. Different aquatic species possess varying capabilities to transport MPs, and filter-feeding fish have a greater potential to translocate MPs among aquatic organisms. The volume and shape of MPs significantly influence their ingestion possibilities, as round-shaped MPs are more easily mistaken as food by marine creatures (Ding et al. 2021).

3. Potential effects of the presence of plastics

Plastics are widely recognized for their inherent ability to withstand degradation, resulting in their prolonged presence in the environment. Consequently, they provide substantial risks to both ecosystems and human welfare. One of the most concerning ramifications of plastics is their adverse effect on aquatic organisms. Plastic waste has the potential to entangle and suffocate marine organisms, as well as being consumed by them. The act of consuming plastics can lead to physical injury, inadequate nourishment, and mortality, in addition to the transmission of hazardous compounds from the plastic materials into the organism's bodily structures. A diverse range of marine species, encompassing fish, avian species, turtles, and marine mammals, have been extensively reported as being affected by the ingestion of plastic materials. The fragmentation of plastics into microplastic particles has the potential to infiltrate the food chain, hence posing a potential risk to human health (Shen et al. 2020; Rillig et al. 2019). The increasing presence of plastics in freshwater environments has emerged as a significant concern. Plastic garbage has the potential to disturb the natural flow of water, hinder the functioning of aquatic habitats, and pose a threat to aquatic organisms by entangling and suffocating them. The ingestion of plastics by freshwater species can lead to similar health effects as those reported in marine species. This has the potential to affect human health if contaminated freshwater fish are consumed (Kumar et al. 2020; Rillig et al. 2019). Nevertheless, the consequences of plastics go beyond the obvious physical damage inflicted on animals. The presence of plastics in the environment has the potential to disrupt ecosystem dynamics, including nutrient cycle and species interactions, which may have implications for the overall functionality of ecosystems. In addition, the production of plastic requires significant amounts of energy and resources, leading to the exacerbation of climate change and the depletion of natural resources (Rillig et al. 2019). There are ongoing endeavors aimed at mitigating the detrimental impacts of plastics on the environment. A number of nations have implemented prohibitions or imposed charges on plastic bags, while a multitude of corporations are actively endeavoring to diminish the utilization of plastic in their merchandise and packaging. However, it is crucial to emphasize the need for a more thorough and coordinated approach in order to effectively tackle this issue (Rillig and Lehmann 2020; Rillig et al. 2019).

3.1. Terrestrial plantations

MPs are widely acknowledged as a tangible form of pollution in soil, and recent research indicates that they have a diverse range of effects. Microfibers, which are a type of MPs, have been found to have both beneficial and detrimental effects on soil dynamics, as demonstrated by Rillig et al. (2019). One perspective is that they have been linked to a drop-in soil bulk density, resulting in a reduction in resistance to root penetration and an improvement in soil aeration. This, in turn, promotes the growth of roots (Rillig et al. 2019). Nevertheless, the inclusion of MPs may present certain difficulties as they might establish pathways for water circulation, hence potentially resulting in heightened water evaporation and soil desiccation. Consequently, this can impede plant productivity (Rillig and Lehmann 2020; Rillig et al. 2019). The modifications in soil composition might result in a range of unforeseen outcomes, and accurately forecasting the whole ramifications on soil functionality poses a significant challenge. As exemplified by this field experiment, it has been determined that microfibers can exert a detrimental impact on soil aggregation, a crucial component of soil architecture that significantly determines the ecological niche of soil microorganisms (Rillig and Lehmann 2020). If microfibers possess the ability to bind soil particles and promote the development of soil aggregates, there may be possible advantages for soil aeration and root growth, as previously indicated by Rillig and Lehmann (2020) and Rillig et al. (2019). However, it is imperative to recognize the potential negative impacts that plastic additives can exert on the growth of plants (Rillig and Lehmann 2020). Hence, it is imperative for future research endeavors to further investigate and comprehend the precise categories of MPs, such as microfibers, that have the potential to either promote or hinder the process of plant biomass synthesis. This will contribute to a more comprehensive knowledge of the complex dynamics involved in this phenomenon (Rillig and Lehmann 2020).

3.2. Aquatic species

Marine organisms encounter many pathways by which they may come into contact with MPs, such as feeding, inhaling at the air-water interface, consuming prey contaminated with MPs, and direct ingestion. Among the several paths examined, it is evident that direct consumption emerges as the predominant route for marine organisms. Regrettably, the use of MPs has resulted in more than 690 recorded instances of marine organisms ingesting these particles across different geographical regions. This phenomenon has given rise to substantial worldwide concerns, including adverse effects on species and disruptions in population dynamics. Fish encounter challenges when it comes to differentiating between food and MPs due to the minute dimensions, buoyancy, and visual characteristics of these particles. After ingestion, MPs present in fish undergo a journey through the gastrointestinal tract and gills, eventually entering the circulatory system. This process allows for the possible dissemination of MPs to various organs and tissues within the fish. The consumption of MPs has been found to have detrimental effects on the health of fish. These effects include impaired nutrient absorption in the intestines, lower stomach capacity, internal bleeding, increased appetite, and elevated mortality rates (Kumar et al. 2020). Furthermore, a significant proportion of MPs comprises neurotoxic compounds such as dyes, plasticizers, and disinfectants. These substances have the potential to cause more severe complications in fish, including behavioral abnormalities, gastrointestinal disturbances, metabolic disorders, and genetic anomalies (Kumar et al. 2020; Clark et al. 2016). The findings of a case study done in the Skudai River, Malaysia, indicate that almost 40% of the fish studied had consumed MPs, highlighting the notable occurrence of interactions between MPs and fish species in the region. It is worth noting that a significant number of the fish species seen in this study exhibited herbivorous feeding behavior. This observation implies that MPs could potentially have a resemblance to aquatic plant species, rendering them more susceptible to ingestion by these herbivorous fish. Fibers were identified as the predominant constituents of MPs present in the gastrointestinal tracts of fish. This can be attributed to their comparatively lower density and their capacity to remain buoyant in the aquatic milieu for prolonged durations (Sarijan et al. 2019).

3.3. Climate change

The extensive presence of plastics in the Earth's oceans has resulted in a distressing aftermath, exerting a substantial influence on the carbon cycle. Plastics have emerged as a significant constituent within this cycle, exerting enduring and detrimental impacts on marine organisms and their associated ecosystems, exhibiting persistence over extended periods ranging from decades to even centuries (Tang 2023a; Kumar et al. 2020). Plastics are a type of artificial polymers predominantly consisting of carbon-based chemical linkages. These polymers are commonly manufactured from fossil fuels or natural gas sources, both of which have been linked to the release of greenhouse gases (Shen et al. 2020; Kumar et al. 2020). The intrinsic association with fossil fuels amplifies the environmental ramifications of plastics. The presence of plastic contamination in aquatic habitats has significant implications for the carbon cycle. The marine flora and fauna have a significant impact on the sequestration of atmospheric carbon and its subsequent transportation to the ocean floor, resulting in its effective removal from the atmosphere. Nevertheless, the existence of plastics hinders this crucial process. The presence of plastic contamination has been observed to hinder the photosynthetic capacity of phytoplankton, hence impeding their ability to effectively sequester carbon dioxide and contribute to atmospheric carbon restoration. Furthermore, it exerts a detrimental influence on the survival and reproductive capacities of zooplankton, hence diminishing the pace at which carbon is transmitted to the marine ecosystem. Consequently, this phenomenon has significant implications for the Earth's climate on a global scale (Shen et al. 2020). In addition, the exposure of plastics to sunlight and UV radiation has the potential to generate potent greenhouse gases such as methane and ethylene, so expediting the process of climate change. The aforementioned occurrence engenders a perilous cycle of cause and effect, as evidenced by a scholarly investigation conducted by Kumar et al. (2020) and Royer et al. (2018). Plastic pollution not only presents direct risks to marine organisms but also amplifies the overarching issue of climate change, emphasizing the pressing necessity for efficient mitigation and conservation endeavors.

4. Human health effects

The World Health Organization (WHO) has performed an extensive study that has provided valuable insights into the widespread occurrence of MPs in the environment. This study has brought attention to the significant issues surrounding the introduction of MPs into human systems and the potential health consequences associated with them. The several routes through which MPs can enter the human body include the ingestion of food and water that has been contaminated, inhalation, or direct dermal contact (Campanale et al. 2020; Rahman et al. 2020). Significantly, MPs have the ability to go via the gastrointestinal tract of humans and afterwards enter the systemic circulation, so enabling them to reach various regions within the body. According to Campanale et al. (2020), it is widely considered that the toxicity associated with this phenomenon is persistent and varies depending on the dosage, with certain qualifiers. The effects of MPs on human health can be categorized into chemical and physical impacts, which are further influenced by the route of exposure and potential therapeutic outcomes (Blackburn and Gree 2021; Smith et al. 2018).

4.1. Effects of chemicals

Numerous studies have provided persuasive evidence indicating that MPs possess the ability to serve as carriers for detrimental substances, such as persistent organic pollutants (POPs) and endocrine-disrupting chemicals (EDCs), hence enabling their transportation to diverse anatomical regions, including the brain (Table 4). The presence of these substances might lead to genetic mutations, developmental defects, and hormonal imbalances, hence exhibiting hazardous properties. Furthermore, MPs have the capacity to act as absorbers of toxic heavy metals such as lead and mercury, resulting in their gradual accumulation within the human body and subsequent manifestation of chronic health complications (Campanale et al. 2020; Hadibarata et al. 2020; Kristanti et al. 2018; Kristanti et al. 2016). The discharge of these harmful compounds from MPs might also lead to inflammation, oxidative stress, and several detrimental health consequences (Rahman et al. 2020). The key factors responsible for the adverse effects on human health are the additives employed in plastics to improve their aesthetic appeal and functional properties, including but not limited to waterproofing, tensile strength, non-degradability, and electrical resistance (Campanale et al. 2020). According to Alabi et al. (2019), a number of these chemicals possess carcinogenic properties and can interfere with hormonal balance. Furthermore, different additives exhibit unique effects and are employed in diverse categories of plastics.

Table 4. Plastic additives with their corresponding health impacts and applications.

Plastic Additives	**Applications**	**Health effects**	**Plastic categories**	**References**
Bisphenol A	Packaging materials, aluminium cans, bottles	Coronary illness, reproductive abnormalities, breast cancer, hormonal disorders	PC, PVC	Campanale et al. (2020); Alabi et al. (2019); Meeker et al. (2009)
Phthalates	Rubber, paints, inks, synthetic perfumes, toys	Genetic mutation, allergic, psoriasis, reproductive disorders	PS, PVC	Campanale et al. (2020); Alabi et al. (2019)
Polychlorinated biphenyls	Electrical appliances, varnishes, lubricants, coatings	Reproductive disorders, high disease progression, hormonal issues	PVC, PC, PS, PE, PP, PTFE, PA	Alabi et al. (2019); Erickson and Kaley (2011)
Flame retardants	Textiles, electronic devices, housewares	Infertility, developmental consequences, thyroid hormone levels imbalance, prostate cancer	Polyurethane foam, PVC	Meeker et al. (2009)
Persistent organic pollutants	Insecticides	Growth retardation, chronic diseases, endocrine dysfunction	PVC, PC, PS, PE, PP, PTFE, PA	Campanale et al. (2020); Rahman et al. (2020)

4.1.1. The compound known as Bisphenol A (BPA)

Bisphenol A (BPA), an artificial carbon-based compound possessing a subtle phenolic aroma, is frequently employed in the manufacturing of plastics and for the purpose of packaging food items. Its exceptional ability to withstand elevated temperatures and pressures renders it very suitable for the fabrication of safety mechanisms and food products that are subjected to thermal treatment in the context of home appliance utilization. Bisphenol A (BPA) is additionally found in resins employed for the purpose of protective coatings, which encompasses the internal lining of beverage cans. In spite of its inherent resilience, bisphenol A (BPA) has the potential to migrate from plastic goods, resulting in elevated levels of pollution in aquatic environments and heightened human contact (Campanale et al 2020; Hadibarata et al. 2020). Bisphenol A (BPA) is a chemical that exhibits estrogenic properties and has been associated with adverse health effects such as congenital malformations, endometriosis, and impaired fertility. The disruption of thyroid gland gene transcription can have an impact on metabolic rates and growth. The existing body of research has firmly established a discernible correlation between levels of urine bisphenol A (BPA) and the functioning of the liver, the occurrence of heart disease, and the development of diabetes (Blackburn and Green 2021). According to Campanale et al. (2020), there was a notable association between the presence of BPA contamination in food and a significant increase in the prevalence of childhood obesity, with over 10,000 reported cases in 2008. Additionally, it was found that there was a subsequent rise of 30,000 new instances of cardiovascular disease during the same period.

4.1.2. Phthalates

Phthalates are a class of artificial chemicals that are widely employed in a range of consumer goods, such as plastics, personal care products, and medical equipment, in order to improve their flexibility, durability, and ability to retain aroma. Remarkably, the annual production of the aforementioned entity has constantly maintained a level of roughly 6 million tonnes over the course of the previous two decades, as documented by Campanale et al. (2020). Nevertheless, the presence of phthalates has been linked to adverse health consequences in human beings. Phthalates have been identified as endocrine disruptors with the ability to imitate or hinder the functioning of the body's hormonal systems. The association between exposure to phthalates and a range of negative health outcomes has been shown, including reproductive and developmental problems, as well as illnesses such as asthma, allergies, and some types of cancer. Furthermore, these chemical substances have the potential to hinder the optimal operation of essential bodily organs, including the liver, kidneys, and lungs. Phthalates are frequently detected in a diverse range of commodities, encompassing raincoats, medications, cosmetic products, and toys (Alabi et al. 2019). The compounds in question have been acknowledged for their ability to alter the endocrine system, potentially impacting human reproductive functions. Additionally, they have been classified as carcinogenic by Campanale et al. (2020) and Alabi et al. (2019). The problem is compounded by the presence of phthalates in diverse forms, each having distinct consequences for human health. Consequently, it is imperative to examine the potential interactions of these phthalates with other additives (Campanale et al. 2020). Certain populations who are more susceptible to the adverse health effects linked to phthalates include pregnant women and children. There exists a correlation between prenatal exposure and atypical fetal development, encompassing phenomena such as reduced birth weight and anomalous genitalia. In the context of children, the exposure to phthalates has been linked to behavioral problems, attention deficit hyperactivity disorder (ADHD), and reduced intelligence quotient (IQ) scores. Within the European Union, there exists a stringent prohibition on the utilization of toys and baby care goods that include phthalates at concentrations beyond 0.1%. Children are especially vulnerable to phthalate exposure because of their inclination to often engage in oral activities, such as placing objects in their mouths, including hands that have come into touch with plastic toys or baby bottles (Campanale et al. 2020; Alabi et al. 2019).

4.2. Physical effects

The global occurrence of airborne MPs has exhibited an upward trend, primarily attributed to synthetic fabrics and dust as the predominant origins of these atmospheric MPs. The presence of minuscule plastic particles, specifically fibers, can be attributed to routine clothing usage and laundering practices, whereby a solitary garment can release as many as 2000 fibers subsequent to undergoing a washing cycle. Research has revealed the presence of MPs in the dust particles found in metropolitan regions such as Tehran, Iran. The concentrations of MPs in these areas were measured to be 11.55 and 60 particles per gram of dust, respectively. While a significant proportion of these fibers can be expelled from the respiratory system, the residual particles possess the capacity to induce inflammatory reactions and lung infections, especially in persons with compromised mechanisms for removing them. Significantly, a study revealed the presence of plastic fibers in the lung tissues of more than 85% of persons who had undergone surgical removal of lung tumors. This finding indicates that these minuscule fibers exhibited resistance to expulsion during breath and instead accumulated within the lung tissue. According to Blackburn and Green (2021), additional pollutants linked to MPs exhibit characteristics of reactive oxygen species and are regularly inhaled by individuals. This inhalation results in oxidative stress, tissue harm, and the potential for tumor formation. Consequently, even individuals exposed to minimal amounts of plastic fibers face an increased susceptibility to respiratory ailments and lung cancer.

Moreover, as a result of the extensive global consumption of seafood, it has become unavoidable for humans to be exposed to MPs (Blackburn and Green 2021; Smith et al. 2018). According to Blackburn and Green (2021), an evaluation of the quantity of microplastic particles (MPs) consumed by the typical daily dietary intake indicated a yearly consumption rate of 45,500 particles per year. It is noteworthy that the human body has the ability to eliminate over 90% of ingested MPs by fecal excretion. However, a portion of these MPs remains within the body due to their bigger size, form, and composition. The presence of accumulated MPs in the human body has several physical implications, including increased vulnerability to infectious agents, absorption of hazardous substances, and disturbances to the composition of the intestinal microbiota. Microparticles (MPs) has the ability to penetrate cellular membranes and collect throughout different physiological tissues, hence intensifying damage to the immune system. Furthermore, it has been observed that these microorganisms have the ability to penetrate the blood-brain barrier, thereby infiltrating the digestive and respiratory systems. This capability, along with their small size and significant specific surface area, might result in considerable detrimental effects (Smith et al. 2018).

5. Remediation technologies for MP removal

The escalating occurrence of MPs in global water resources has become a substantial apprehension for both human well-being and the natural surroundings (Table 5). As stated before, MPs refer to minuscule entities that vary in dimensions from a few micrometres to several millimetres, predominantly consisting of artificial polymers. The aforementioned contaminants are derived from a wide range of sources, encompassing industrial effluent, home sewage, agricultural runoff, and the decomposition of plastic garbage. The presence of MPs in water resources poses a range of possible health hazards that are complex and varied.

Table 5. Summary of MP incidence in various regions of the world

Region	Range of MPs abundance (particles/m^3)	Structure	References
Asia			
Nakdong River Estuary, Korea	210.00 – 5560.00	PE, PP	Shahul et al. (2018)
Oujiang Estuary, China	395.40 – 964.60	PP, PE, PTFE, PVC	Shahul et al. (2018); Zhao et al. 2015)
Jiaojiang Estuary, China	106.90 – 1804.30	PP, PE, PTFE, PVC	Shahul et al. 2018; Zhao et al. 2015
MinJiang Estuary, China	714.30 – 1777.30	PP, PE, PTFE, PVC	Shahul et al. 2018); Zhao et al. (2015)
Yangtze Estuary, China	1675.80 – 6598.80	-	Zhao et al. (2014)
Kuala Nerus, Malaysia	130.00 – 690.00	PA, PP	Khalik et al. (2018)
Kuantan Port, Malaysia	140.00 – 150.00	PS, PA, PVC, PE	Khalik et al. (2018)
Lamong Bay, Indonesia	380.00 - 610.00	PS, PE, PP, PET	Curren et al. (2021)
Wonorejo Beach, Indonesia	440.00 – 530.00	PS, PE, PP, PET	Curren et al. (2021)
Can Gio Beach, Vietnam	6440 ± 2980	PET, PVC, PP, PS, PA, PMMA,	Khuyen et al. (2021)
Jakarta Bay, Indonesia	55800 to 86600	PP, PS, PE	Takarina et al. (2022)
Singapore Strait	106000000 to 238000000	PP, TPC, PE	Curren and Leong (2023)

Region	Range of MPs abundance (particles/m^3)	Structure	References
Tanjung Benoa, Bali, Indonesia	0.61	PP, PE, PS, Nylon	Suteja et al. (2021)
Europe			
Black Sea, Turkey	18.68 – 64.06	PET, PE, PP, styrene acrylonitrile copolymer (SAC)	Terzi et al. (2022)
Brest Bay, France	240 ± 350	PE, PP, PS	Frere et al. (2017)
Gulf of Trieste	6.29 ± 2.68	PP, PE, PO, PS, PVC	Gajšt et al. (2016)
Weser North Sea, German	5400	PE, PP, PS, PC, PA, PVC, CMC, PEST, PSU, PEEK, PLA, PCL, EVA	Roscher et al. (2021)
America			
Galapagos Island, Ecuador	0.16 ± 0.03	HDPE, PE, PP, PS, PA, PES, PVC	Jones et al. (2021)
Patagonia, Argentina	10500	PE, PET, PVC, Polyester	Rios et al. (2020)
Rio de Plata, Uruguay	24	PE, PP, PS, PA	Pazos et al. (2021)
Guanabara Bay, Brazil	4.8	PE	Figueiredo and Vianna (2018)
Australia			
Adelaide, South Australia	43 ± 16.9	PP, PPCO, HDP, PS	Hayes et al. (2021)

Region	Range of MPs abundance (particles/m^3)	Structure	References
Africa			
Kenya	110	PP, LDPE	Kosore et al. (2018)
Morocco	6– 65	PE, PA	Kanhai et al. (2017)
Bay of Biscay, South Africa	1.15 ± 1.45	PE, PA	Kanhai et al. (2018)
south-eastern coastline of South Africa	257.9–1215 particles/L	PE, PC	Nel and Froneman (2015)
Durban, South Africa	7.03 ± 11.93 particles /L	PE, PS	Naido and Glassom (2019)
Western Cape, South Africa	1330 ± 150 SE particles/L	PET, PE, PS, PAA, SSR	Julius et al. (2023)

Numerous studies have provided evidence indicating that Members of Parliament can effectively enhance the bioaccumulation of deleterious chemicals and heavy metals within the physiological systems of aquatic creatures. This phenomenon has been observed to result in diminished reproductive efficacy, behavioral modifications, and heightened susceptibility to various diseases. In addition, individuals who ingest water or food items that have been polluted with MPs derived from aquatic species may face exposure to these harmful compounds, leading to potential long-term health consequences including cancer, reproductive and developmental disorders, and neurological impacts. Therefore, it is crucial to prioritize the development of efficient and reliable methods for the extraction of MPs from water sources. There exist various remediation procedures that can be employed to effectively eradicate MPs from water sources. Physical approaches include several techniques such as electrocoagulation, magnetic extraction, and filtration, which are employed to achieve the physical separation of MPs from water. Nevertheless, the exclusive reliance on physical procedures may not yield complete efficacy in the removal of MPs owing to their diminutive dimensions and vast surface area. Hence, various chemical methodologies, including adsorption, oxidation, photocatalysis, and coagulation, can be utilized to augment the efficacy of microplastic removal. A wide range of remediation procedures, encompassing physical, chemical, and biological methods, can be employed to effectively remove MPs from water resources, as seen in Table 6.

Table 6. Remediation methods with their pros and cons.

Methods	**Roles**	**Advantages**	**Disadvantages**	**References**
Electrocoagulation	Coagulants are formed utilising metal electrodes and an electrical source	• High efficiency • Low operating costs • Automated systems • Able to remove tiny particles	• High chemicals consumption • High consumption of electrodes replacement • Electricity reliant	Padervan et al. (2020); Dey et al. (2021)
Magnetic extraction	MPs are separated by using magnetic particles, acid, and magnetism	• Low operation cost • Able to remove tiny-sized MP	• Secondary MP generated that cause pollution	Dey et al. (2021)
Membrane filtration	MPs are trapped by allowing the contaminated water to pass through the film	• Simple operation • Low operating cost • No chemical is required	• Membrane clogging • Regular maintenance needed	Padervan et al. (2020); Dey et al. (2021)
Photocatalytic degradation	Decompose MPs into water and carbon dioxide	• No chemicals are needed • Ecologically sustainable • Less energy required	• Low removal efficiency • Secondary MP generated that cause contamination	Kaewkam et al. (2022); Ouyang et al. (2021); Tofa et al. (2019); Han et al. (2017)
Adsorption	Adsorption occurs due to the Van der Waals forces between the adsorption material and the microplastics. These forces are weak and are affected by the size, shape, and polarity of the microplastics. The microplastics come in contact with the adsorption material and	Effective removal Cost-effective does not require the use of chemicals	Limited capacity Secondary pollution Not a complete solution	Yu et al. (2016); Rani et al. (2019); Shang et al. (2019); Wang et al. (2021)

Methods	Roles	Advantages	Disadvantages	References
	are attracted to its surface through these forces			
Bacterial degradation	Break down plastics through enzymatic activities	• Low operating cost • Environmental-friendly • Complete degradation • Potential for upcycling	• Long period of time needed • Low efficiency • Environmental conditions are unpredictable • Risk of contamination	Roohi et al. (2017)
Fungal degradation	lipases, proteases, and cellulases can break down various types of plastics)	• Low operating cost • Environmental-friendly • Low energy required	• Limited effectiveness • Slow process	Lacerda et al. (2020); Tournier et al. (2020); Devi et al. (2015)
Algae degradation	MPs are degraded into other chemical compounds (CH_4, H_2S, CO_2, H_2O)	• High efficiency • Natural process • CO_2 sequestration	• Nutrient requirements • Difficulty on implementation on a large scale • Breakdown products	Kim et al. (2020); Moog et al. (2019)

5.1. Electrocoagulation (EC)

Electrocoagulation (EC) is an electrochemical process utilized for the purpose of eliminating water pollutants by means of applying an electrical current. During this procedure, water that contains impurities is exposed to metal electrodes, and an electric current is applied to them. During the EC process, coagulants are produced through the interaction of metallic ions, namely ferrous (Fe^{2+}) and aluminum (Al^{3+}) ions, which are released from the anode and cathode via electrolysis. Simultaneously, hydroxyl (OH-) ions present in the solution are also participating in this chemical reaction. The primary function of these coagulants is to counterbalance the charges that exist on the surfaces of suspended MPs, so facilitating their contact through attractive forces. Concurrently, the formation of a slurry layer occurs, which effectively captures the microplastic particles (MPs) that are present within the contaminated water. For more comprehensive details, please refer to the works of Padervand et al. (2020) and Perren et al. (2018). Perren et al. (2018) observed that during the EC process, the liberation of hydrogen gas causes the resulting slurry to ascend towards the surface of the solution. According to the research conducted by Padervand et al. (2020), it has been seen that the technique of EC has significant efficacy in the removal of MPs. The study reveals that this effectiveness is particularly evident when the process is carried out under mildly alkaline circumstances, characterized by a pH of roughly 7.5. Furthermore, the research findings suggest that the sodium chloride (NaCl) solution concentration, ranging from 0 to 2000 mg/L, also plays a crucial role in achieving high removal rates, with up to 99% of MPs being effectively eliminated. This method is recognized for its notable attributes of simplicity and cost-effectiveness, principally employing metal electrodes in the treatment procedure. However, it is crucial to consider certain operational factors. Regular maintenance or replacement of electrodes is necessary in electrocoagulation (EC) due to the increased pressures they are subjected to during the coagulation process. These electrodes play a crucial role in transmitting electricity into the fluid, which leads to mechanical degradation over time. Moreover, it is important to acknowledge that this procedure is dependent on a consistent supply of electrical energy, requiring direct current (DC) power for its functionality, as emphasized by Perren et al. (2018).

5.2. Magnetic extraction (ME)

Magnetic extraction, sometimes referred to as magnetic separation, is a method utilized to separate magnetic substances from non-magnetic substances through the application of magnetic fields. The procedure involves the utilization of a magnetic field on a combination consisting of materials that exhibit both magnetic and non-magnetic properties. Consequently, magnetic particles are attracted to the magnet as a consequence of their inherent magnetic properties, whilst non-magnetic particles remain unaffected and are subsequently segregated from the magnetic particles. The utilization of magnetic extraction is widely observed in various industries such as mining, food processing, and wastewater treatment. The major objective of this process is to segregate and retrieve magnetic materials, specifically iron and steel, from substances that lack magnetic properties. The approach described in Shen et al. (2020) has notable characteristics of simplicity and versatility, rendering it well-suited for the elimination of magnetic pollutants from various mediums, including liquids, gases, and solids. Iron-based nanoparticles are widely recognized as a preferred option within the field of magnetic extraction (ME). The utilization of these nanoparticles is favored because of their cost-effectiveness, substantial surface area-to-volume ratio, and elevated magnetic susceptibility. In addition, the use of water-insoluble materials as a coating renders them hydrophobic, facilitating the magnetic retrieval of MPs from aqueous environments. Significantly, magnetic extraction (ME) exhibits remarkable effectiveness in the elimination of small MPs with dimensions below 0.02 mm, with recovery rates surpassing 90% in marine environments. Nevertheless, when considering freshwater bodies and riverbeds, the recuperation rates for medium-sized microplastics (range from 0.2 mm to 1 mm) are relatively diminished, with percentages of 84% and 78% respectively, as reported by Dey et al. (2021) and Shen et al. (2020). The decrease in recuperation rates observed in medium-sized MPs can be ascribed to various causes, including their comparatively reduced specific surface area, which hinders their contact with nanoparticles. Moreover, the presence of soil particles can impede the movement of nanoparticles, so restricting their ability to interact with plastics and bioactive compounds present in riverbeds, leading to reduced rates of recovery (as outlined in the study conducted by Grbic et al. 2019). The utilization of magnetic extraction has been proposed as a feasible approach for the purification of drinking water, principally attributed to its enhanced rates of recovery. Nevertheless, it is imperative to consider that the nanoparticles utilized in magnetic hyperthermia (ME) lack reusability and convenient disposal, hence presenting possible concerns regarding secondary contamination, as highlighted in the studies conducted by Shen et al. (2020) and Grbic et al. (2019).

5.3. Membrane filtration

Membrane filtration is a physical separation method that utilizes semi-permeable membranes to remove particles and contaminants from a fluid by selectively allowing certain molecules to pass through the membrane. Within the realm of microplastic removal, this particular approach has demonstrated considerable efficacy, particularly by employing ultrafiltration and nanofiltration membranes. Ultrafiltration membranes have a range of pore diameters spanning from approximately 0.001 to 0.1 µm. The range of pore sizes enables effective removal of microplastics ranging from 0.02 to 100 µm. In contrast, nanofiltration membranes possess reduced pore sizes, typically around 0.001 µm, which endows them with the capability to eliminate finer microplastics, dissolved organic molecules, and diverse pollutants (as evidenced by Shen et al. 2020). However, membrane fouling is a prevalent issue encountered in membrane filtration, which results in a reduction in permeability and flow velocity. Therefore, it is imperative to implement regular cleaning or pre-treatment measures in order to effectively address fouling concerns, as elucidated by Dey et al. (2021). The utilization of coagulation has become a prominent pre-treatment approach in order to enhance the process of microplastic flocculation. Microplastics exhibit a propensity for aggregation due to their intrinsic properties. Nevertheless, this conglomeration is intrinsically unstable and susceptible to disintegration. Consequently, it is crucial to provide coagulants in order to establish a stronger structure, which in turn facilitates a more streamlined extraction process (as emphasized by Shen et al. 2020). Multiple research investigations have consistently emphasized the effectiveness of membrane filtering in the removal of microplastics from various water sources. An example of this may be seen in the study conducted by Wang et al. (2018), where they demonstrated the efficacy of a polyvinylidene fluoride (PVDF) ultrafiltration membrane in removing a significant proportion, up to 99%, of microplastics from the effluent of a wastewater treatment facility.

5.4. Photocatalysis

Photocatalysis emerges as a prospective alternative for the elimination of microplastics, presenting a range of benefits such as notable efficacy, economic viability, and ecological compatibility. The aforementioned procedure utilizes light energy to initiate the activation of a photocatalyst, subsequently resulting in the production of reactive oxygen species (ROS) that possess the ability to degrade organic molecules, such as microplastics. Titanium dioxide (TiO_2) is well recognized as a frequently employed photocatalyst for the purpose of microplastic elimination. This is attributed to its notable catalytic efficacy, minimal toxicity, easy accessibility, and cost-efficiency, as acknowledged in the works of Carpenter (2011). Zinc oxide is a widely employed photocatalyst due to its exceptional optical properties, ionic conductivity, and chemical stability. Moreover, it can be readily produced and molded into diverse configurations by uncomplicated chemical water bath methodologies, as emphasized in the study conducted by Tofa et al. (2019). The remediation strategy described in this study is cost-effective due to its lack of reliance on chemicals or electricity, and its ability to avoid the release of harmful substances into the environment, as outlined in the works of Dey et al. (2021) and Ouyang et al. (2021). Nevertheless, it is crucial to acknowledge that photocatalysis might exhibit a comparatively lower efficacy in terms of contaminant removal when compared to some alternative remediation technologies. Additionally, it may necessitate extended retention durations, as highlighted by Dey et al. (2021). A plethora of studies have provided empirical evidence supporting the efficacy of photocatalysis in the mitigation of microplastic contamination in aquatic environments. An investigation conducted by Maulana and Ibadurrohman (2021), examined the application of TiO_2 photocatalysis for the purpose of removing polyethylene microplastic. The study revealed that this method demonstrated a very effective degradation of polyethylene microplastic, resulting in a completed removal within a two-hour period of irradiation (Maulana and Ibadurrohman 2021). In a separate investigation conducted by Kaewkam et al (2022)., an examination was conducted on the application of graphene oxide/TiO2 composite photocatalysts for the purpose of microplastic elimination. The findings of this study indicated that these composite photocatalysts demonstrated enhanced photocatalytic efficacy in comparison to pure TiO_2, leading to a heightened rate of microplastic degradation (Kaewkam et al 2020). Photocatalysis presents a multitude of advantages in comparison to conventional techniques employed for the removal of microplastics. First and foremost, it exhibits a notable level of efficiency, demonstrating the capacity to attain a substantial rate of microplastic removal within a little duration. Additionally, this method is characterized by its environmental friendliness, as it does not generate any detrimental chemicals or by-products throughout its execution. Finally, it is economically advantageous, especially when utilizing easily accessible and inexpensive resources such as titanium dioxide (TiO_2).

5.5. Adsorption

Adsorption is a phenomenon characterized by the attraction and binding of a substance, termed the adsorbate, to the surface of another substance, known as the adsorbent material (Kristanti et al. 2016). Within the realm of MPs, the process of adsorption entails the utilization of adsorbent substances such as activated carbon, silica, and clay to effectively collect and retain MPs on their respective surfaces. The adsorbent materials exhibit a significant surface area, rendering them proficient in the attraction and entrapment of MPs. The effectiveness of the adsorption process is influenced by multiple aspects, such as the surface area of the adsorbent, the concentration of MPs, and the time of interaction between the adsorbent and MPs (as outlined in the study conducted by Rani et al. 2019). Numerous researches have investigated the effectiveness of adsorption as a remediation technique for MPs. An investigation conducted by Yu et al. (2018) examined the adsorption of MPs using activated carbon. The study revealed that activated carbon shown a notable capability for adsorbing polystyrene microspheres, which are frequently employed as surrogates for MPs. In a study conducted by Wang et al (2021), the adsorption of MPs onto silica-based materials was investigated, revealing the efficacy of these materials in the removal of MPs from water. The findings of this study indicate that silica-based materials exhibit a greater adsorption capacity compared to activated carbon, enabling the removal of more than 90% of MPs from water. Furthermore, the adsorption of MPs can be augmented through surface modification of the adsorbent material. An investigation carried out by Shang et al (2019) explored the process of adsorption of MPs using a clay material that has been changed through treatment with a cationic surfactant. The findings of this study demonstrate that the clay material, after undergoing modification, displayed a significantly enhanced adsorption capacity compared to the unmodified clay. As a result, it effectively eliminated more than 95% of microplastic particles from water. The application of a cationic surfactant to the surface of the clay resulted in an augmentation of the clay particles' surface charge, hence enhancing their affinity towards the negatively charged microparticles.

5.6. Bacterial degradation

The process of bacterial degradation of MPs entails the utilization of microorganisms that possess the ability to decompose plastics via enzymatic mechanisms (Hadibarata et al. 2023). Roohi et al. (2017) have explored the identification of several bacterial strains, such as Pseudomonas, Bacillus, Rhodococcus, and Alcanivorax, that have the capability to digest MPs in diverse aquatic settings. The initial stage of bacterial breakdown involves the adherence of bacteria to the surface of the MPs. Upon attachment, the bacteria in question secrete extracellular enzymes, including lipases, esterases, and proteases, which are crucial in the process of degrading the plastic polymer chains into smaller molecular components. Subsequently, the degraded compounds are conveyed into the bacterial cells to undergo subsequent catabolism and mineralization processes, finally leading to the generation of non-hazardous end products such as carbon dioxide and water. Multiple studies have demonstrated the efficacy of bacterial degradation in the removal of MPs from water. Yoshida et al. (2016) documented the discovery and isolation of *Ideonella sakaiensis*, a bacterial strain that exhibits the ability to degrade polyethylene terephthalate (PET), a widely utilized plastic material commonly seen in water bottles. The bacteria exhibit best functionality at a temperature of 30°C and is capable of synthesizing two enzymes, namely PETase and MHETase. These enzymes facilitate the hydrolysis of polyethylene terephthalate (PET) into mono(2-hydroxyethyl) terephthalic acid (MHET) and ethylene glycol. The aforementioned degradation by-products function as carbon and energy substrates for the bacterial organisms (Yoshida et al. 2016). Danso et al. (2018) additionally discovered a bacterial strain, specifically *Rhodococcus ruber* strain C208, which exhibits the capability to breakdown low-density polyethylene (LDPE), a prevalent plastic material frequently employed in packaging applications. Danso et al. (2018) reported that this particular strain exhibits the capability to synthesize enzymes such as esterase, lipase, and protease, which facilitate the degradation of polymeric polymer chains into molecules that are devoid of toxicity. Although the decomposition of microplastics (MP) by bacteria shows potential for their removal, there are still various obstacles that need to be addressed. The degradation rate of bacteria can be regulated by multiple factors, such as the specific plastic material, bacterial strain, temperature, and availability of nutrients. Moreover, the use of bacterial degradation as a means to eliminate MPs from vast water bodies such as oceans and rivers presents significant challenges attributed to the complexities associated with introducing and sustaining bacterial populations inside these ecosystems.

5.7. Fungal degradation

The utilization of fungal processes for the breakdown of microplastics has emerged as a possible avenue for resolving challenges related to plastic waste. Fungi are recognized for their ability to synthesize a diverse array of extracellular enzymes, such as lipases, proteases, and cellulases, which have the capability to degrade a wide range of polymeric materials. Fungi belonging to the phyla Ascomycota and Basidiomycota have demonstrated the capacity to degrade widely encountered plastics such as polyethylene (PE), polyurethane (PU), polystyrene (PS), and polyethylene terephthalate (PET), which are often present in the environment (Lacerda et al. 202). According to a recent study conducted by Devi et al. (2015), it was observed that *Aspergillus tubingensis*, a type of fungus, exhibited the potential to destroy HDPE in a relatively short period of time. The fungus in question is capable of producing an enzyme known as laccases and peroxidases, which serves to aid the degradation of HDPE into smaller molecular units that can be effectively utilized by the fungus as a source of carbon. Previous research has brought attention to the capacity of certain fungi, such as *Rhodotorula mucilaginosa* and Aspergillus fumigatus, to effectively degrade polystyrene (PS) and polyurethane (PU), respectively (Tournier et al. 2020). Although still in its nascent research phase, the process of fungal breakdown of microplastics offers numerous notable benefits. Fungi exhibit a notable ease of cultivation, hence facilitating the generation of enzymes in significant quantities. In addition, it should be noted that the process of fungal breakdown of microplastics does not produce any detrimental by-products, thus rendering it a viable and ecologically sound alternative to approaches such as incineration (Lacerda et al. 2020). Moreover, several enzymes have demonstrated efficacy in the degradation of plastics, particularly microplastics. An investigation conducted by Devi et al. (2015) examined the process of decomposition of polystyrene microplastics by *Aspergillus tubingensis*. The fungus released an enzyme known as endo-1,4-beta-glucanase, which facilitated the degradation of polystyrene microplastics into smaller fragments. The enzyme demonstrated stability across a broad spectrum of pH and temperature conditions, suggesting its potential suitability for utilization in diverse environmental contexts. In a study conducted by Gutierrez et al. (2018), the researchers investigated the process of PET microplastic degradation using the fungus *Pestalotiopsis* sp. The fungus was shown to secrete an enzyme known as cutinase, which exhibited efficient degradation of PET microplastics, resulting in the formation of smaller fragments. The stability of this enzyme was observed across various environmental conditions, and it exhibited the capacity to breakdown PET microplastics in both aerobic and anaerobic settings. The results of this study indicate that fungal enzymes, such as cutinase, have the potential to be employed in the bioremediation of PET microplastics in various environmental settings. The application of fungal enzymes in the breakdown of microplastics presents numerous benefits in comparison to conventional approaches. To begin with, it is noteworthy that fungal enzymes exhibit a remarkable degree of specificity, enabling them to selectively target specific categories of plastics. This characteristic proves to be advantageous as it contributes to the mitigation of detrimental by-products that may arise during the process of plastic degradation. Additionally, it is worth noting that fungal enzymes have the advantageous characteristic of being biodegradable, hence avoiding the accumulation of harmful residues in the surrounding environment. This attribute significantly contributes to the mitigation of negative environmental consequences. In conclusion, the utilization of fungal enzymes is a viable solution for microplastic breakdown due to their renewable nature and capacity for large-scale production, hence enhancing the sustainability of this technique.

5.8. Algae degradation

Algae, being photosynthetic organisms, exhibit the astonishing capacity to assimilate and exploit resources from their immediate surroundings. Moreover, these organisms possess the ability to generate a wide range of enzymes that exhibit the capability to degrade intricate organic compounds, such as plastics (Tang 2023b). Numerous researches have provided evidence supporting the efficacy of some species of algae in the degradation of microplastics. An example of relevant research in the field is the study conducted by Su et al. (2021), which focused on investigating the degradation process of polystyrene microplastics by the green alga *Ulva compressa*. The findings of the study indicate that the alga possesses the ability to degrade polystyrene microplastics by the secretion of enzymes, resulting in the fragmentation of the plastic particles into smaller fragments. Moreover, the alga exhibited the capacity to employ these deteriorated plastic particles as a carbon source to support its growth. In a similar vein, the breakdown of polyethylene microplastics by the microalga *Chlamydomonas reinhardtii* was examined by Kim et al. (2020). The research conducted by the authors revealed that the alga under investigation possesses the capability to degrade polyethylene microplastics through the secretion of enzymes that effectively assist the fragmentation of the plastic particles into smaller constituents. The alga demonstrated the ability to exploit the decomposed plastic particles as a carbon source for its own growth. The employment of algae for the breakdown of microplastics presents numerous benefits in comparison to conventional approaches. To begin with, it should be noted that algae have a significant presence in aquatic ecosystems and possess the capacity for extensive cultivation, hence offering a viable means to enhance the sustainability of microplastic breakdown. Additionally, it should be noted that algae possess the advantageous qualities of being both renewable and biodegradable, thereby effectively mitigating the total environmental consequences associated with the deterioration process. In addition, it should be noted that algae possess the ability to synthesize a diverse array of enzymes, which exhibit significant efficacy in the degradation of different forms of plastics. Consequently, algae have emerged as a very promising and adaptable resource in the ongoing endeavors to address the issue of microplastic pollution (Su et al. 2021; Kim et al. 2020).

6. Challenges faced on studies

The issue of obtaining potable water has gained significant urgency as a result of the presence of MPs in water sources. These MPs can originate from a range of different sources, such as wastewater treatment plants (WWTPs), industrial activities, and the breakdown of plastic trash (Aljaradin 2020). Despite the extensive body of research conducted on the occurrence of MPs, our comprehension of these particles remains constrained (Yu et al. 2018). Hence, it is imperative for researchers to expand the geographical range of their inquiries, incorporating both terrestrial and aquatic ecosystems (Meng et al. 2020). There is a need for the improvement of scientific methodology, as the lack of standardized techniques for ecological samples poses a significant challenge in the proper identification of MPs. The processes of collecting, extracting, and analyzing scientific data samples are laborious and time-intensive, posing a substantial challenge to conducting evaluations on a wide scale. The efficacy of MP detection is governed by a multitude of variables. The identification of basic polymers is typically complicated by the presence of plastic additives, which necessitates the use of spectrum subtraction or database analysis for correct recognition. The quantification of MPs contamination is a complex task due to the extensive presence of MPs in many ecosystems, which makes it difficult to measure without producing any influence. The implementation of practical classification methodologies in the study of aquatic environments will yield a more accurate representation of the prevalence of MPs. Additionally, it will improve the capacity to compare research findings across different studies. Hence, the utilization of suitable detection methodologies is of paramount importance (Meng et al. 2020).

Although there are several remediation technologies available for the removal of MPs from water resources, their efficacy is frequently inadequate in totally eradicating MPs in water treatment facilities. Despite the extensive body of research dedicated to verifying the existence of MPs in wastewater, our comprehension of the mechanisms involved in the removal of MPs at various stages of treatment facilities remains inadequate (Westphalen and Abdelrasoul 2018). The analysis of wastewater is of utmost importance due to its significant role as the main contributor to MPs pollution in accessible water sources, hence posing a threat to the long-term viability of these resources for human use (Aljaradin 2020). Despite the considerable reduction in microplastic particles (MPs) as evidenced in earlier studies, residual by-products may still be released into aquatic environments, exacerbating the degradation of the ecosystem (Westphalen and Abdelrasoul 2018). The integration of effective technologies into existing treatment plants can often be accompanied by high costs and complexity, leading to their utilization primarily in situations where they are deemed necessary (Aljaradin 2020).

Notwithstanding apprehensions regarding the possible biotoxicity of MPs, it is imperative to recognize that our comprehension of their adverse impacts on biodiversity, food safety, and security remains constrained (Yu et al. 2018). Hence, it is imperative to implement proactive strategies in order to effectively address the worldwide dissemination of MP contamination. It is of utmost importance that nations come together and engage in cooperation to tackle this matter, given that the majority of countries have not yet developed a comprehensive structure to address the main factors contributing to the accumulation of microplastics in water bodies or to properly handle associated elements (Westphalen and Abdelrasoul 2018). Although numerous governments have implemented measures aimed at reducing and promoting recycling of plastics in order to enhance public consciousness, there is a substantial need for further advancements in this area. The transient nature of public attention often requires continuous endeavors to sustain awareness. It is crucial to achieve a harmonious equilibrium between selecting the optimal decision and opting for the most straightforward or economically viable alternative (Horton and Barnes 2020). Communities are widely recognized as significant partners in the mitigation of MP pollution, and their collaboration with authorities is greatly esteemed in the efforts to solve this issue (Aljaradin 2020).

7. Conclusions

Plastics have undeniably yielded various benefits to humanity; nonetheless, they have also transformed into a substantial environmental concern, particularly with regard to MPs. The provision of clean and readily available water is of paramount importance for the maintenance of public health, serving as a vital resource for both potable consumption and agricultural utilization. Nevertheless, Members of Parliament (MPs) possess the ability to go significant distances from their original location via wind or water, so magnifying their environmental consequences beyond initial projections. Environmental Members of Parliament (MPs) have been found to have adverse impacts on terrestrial species, leading to the extinction of specific organisms and impeding plant growth. Additionally, these MPs are implicated in the complex phenomenon of climate change. The primary route of human exposure to MPs is through ingestion and drinking, resulting in the buildup of these particles within their bodies and potentially endangering their health. The identification of the precise origins of MPs is a challenging task due to their fragmented form, extremely small size, and wide range of potential sources. As a result, the implementation of monitoring processes is of utmost importance in the mitigation and management of MPs pollution, as it enables a more comprehensive comprehension of the destiny of MPs. In order to uphold the integrity of natural ecosystems and adhere to water quality standards for domestic use, it is imperative to employ efficacious tactics and treatments aimed at mitigating the release of MPs. One potential option is the implementation of comprehensive legislation aimed at regulating the consumption of plastic and the release MPs as a component of a worldwide approach, even in the absence of long-term assessment findings. The use of a proactive approach is crucial in mitigating the utilization and dissemination of MPs, so ensuring the protection of the environment and public health.

CRediT authorship contribution statement

Aris Ismanto: Investigation, Data curation, Writing – original draft, Supervision, Funding acquisition. **Tony Hadibarata**: Supervision, Methodology, Writing – original draft, Resources. **Risky Ayu Kristanti**: Data curation, Writing – original draft, Writing – review & editing, Correspondence. **Muhammad Zainuri**: Writing – Review & Editing. Denny Nugroho Sugianto: Writing – Review & Editing. **Wulan Kusumastuti:** Methodology and Resources. **Malya Asoka Anindita**: Methodology and Visualization.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on reasonable request.

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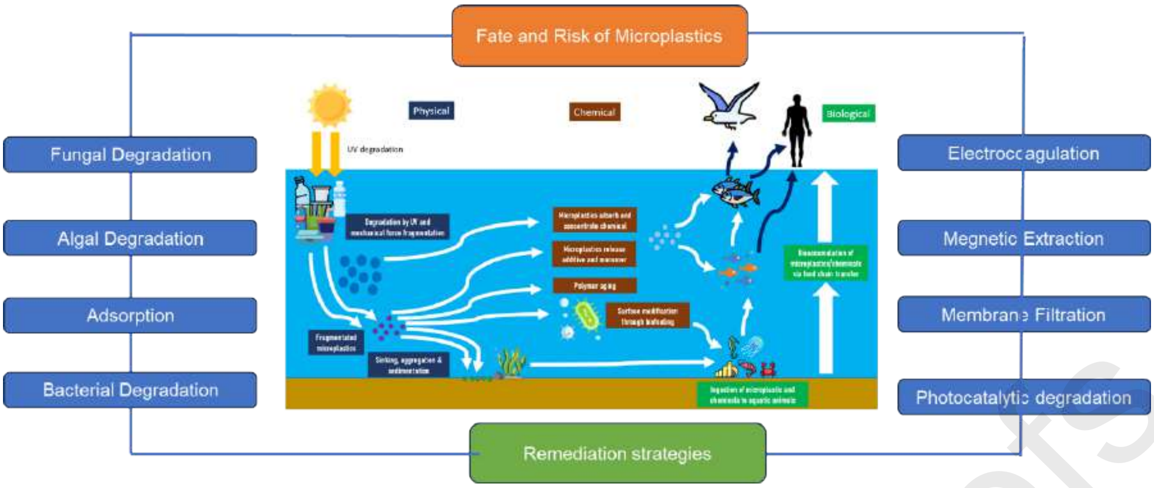
Graphical Abstract


Fate and Risk of Microplastics
Physical
Chemical
Biological
UV degradation
Degradation by UV and mechanical force fragmentation
Fragmentated microplastics
Sinking, aggregation & sedimentation
Microplastics adsorb and concentrate chemical
Microplastics release additive and monomer
Polymer aging
Surface modification through biofouling
Bioaccumulation of microplastics/chemicals via food chain transfer
Ingestion of microplastic and chemicals to aquatic animals
Fungal Degradation
Algal Degradation
Adsorption
Bacterial Degradation
Electrocoagulation
Megnetic Extraction
Membrane Filtration
Photocatalytic degradation
Remediation strategies