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Microplastics in the ecosystems: Impacts on environmental sustainability

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ABSTRACT

The need for assured well-being and self-perpetuation entails that humans will subtly disturb their natural ecosystems to augment beneficial product yields. The use of certain agricultural inputs and containers introduces levels of environmental pollutants and contaminants pesticides, fertilizers, plant growth regulators, and recently microplastics (MPs). Microplastics pollution is a significant burden on ecosystems and has potential ecological impacts. The contamination by MPs has been observed in various environmental areas such as land, water, and air compartments are interconnected and should be studied in an integrated way. Literature on MPs research and recognition of research gaps in various environmental field issues that need to be addressed to set future research priorities. MPs may increase possible ecological risks by introducing additional micropollutants into living things. Additional impacts of MPs and organic pollutants (OPs) coexisting include increased toxicity, bioaccumulation, physical harm, altered microbial populations, and ecological disruption. The ecological harm that MPs, OPs, and heavy metals provide to biota in freshwater, marine, and terrestrial environments is being revealed by this endeavor. Additionally, the potential ecological and environmental preservation viewpoint on sustainable growth was clarified. Effective mitigation methods, an examination of ecological impacts, and a thorough understanding of contamination sources are necessary for managing MPs pollution.

1. INTRODUCTION

Microplastics (MPs) are ubiquitous tiny plastic particles (<5 mm) non-biodegradable and have a large surface area in the environment or the body of living things due to anthropogenic activities or fragmentation of plastic debris [1]. They can be classified as primary MPs and secondary MPs [2]. Primary MPs are used in targeted ways in small dimensions, such as microspheres incorporated into mutual care products, microfiber from textiles, or plastic pellets [3]. As raw materials for the plastic manufacturing industry, these particles enter the environment through various substance routes, including sewage discharge, industrial processes, or accidental spills [4]. Primary MPs are those that are made to be smaller than 5 mm and are primarily present in textiles, medications, and personal hygiene items such as body and face washes. Primary MPs can also have polyethylene (PE) particles, polypropylene (PP), and polystyrene (PS) intentionally added to cosmetics and medical products. These MPs can be used for various purposes such as peeling, use as a facial scrub, or filler, in some cases dosage, and enter the aquatic ecosystem through various sources [5].

The possible source of MPs released through the sewage system can occur when manufacturing synthetic fabrics, clothing, personal care micro beads products, and other small plastic particles wash away substances contained in household waste, enter the drain, and eventually end up in a sewage treatment plants [6]. Despite several treatment processes, MPs can still penetrate and spread. It is discharged into rivers, lakes, and seas. This is MPs in aquatic ecosystems plastic resin

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talc or pellets spillage [7]. Accidental spills can happen during shipping and handling emissions of these tiny plastic particles and the aqua bodies go with the flow and contribute to MPs pollution. Secondary MPs degradation and crushing of giant plastic articles [8]. Over time, we will generate large amounts of plastic waste, including bottles, bags, and fishing nets, shattered into small pieces, crumbling, ultraviolet (UV), and mechanical effort [9].

Significantly, it was shown that secondary MPs make up the bulk of MPs and that their prevalence in waters increases in direct proportion to the amount of plastic debris that is added, originating from various sources. This constant transition of secondary MPs occurs because of their smaller sizes; MPs have a greater likelihood of breaking down into nanoplastics, which could represent greater environmental hazards, when exposed to the environment [10] (Table 1). The separation of plastic waste is a complex process influenced by many factors. Environmental factors can have significant impacts dimensional scale of MPs and their characters [11]. Diffusion of sewage sludge is the rest of the material, the sewage treatment plant, and land [12]. Sewage sludge may contain clothing synthetic fibers, MPs from personal care products (e.g., exfoliation of microbeads or MP particles), or other small plastic debris recorded between wastewater treatment circuits. If so, sludge is spread as soil on farmland could bring MPs to the world; transportable soil flows into bodies of water through drains or leaches out [13]. These are the primary sources of MPs, emphasizing the importance of understanding the deal with different paths through which MPs find their way into the water surroundings. The trial is developed to improve wastewater treatment processes. To minimize the release of MPs from sewage and to develop strategies for adequately managing and disposing of plastic resin pellets to prevent spills [14], regulations and guidelines are being developed to address the utilization and discarding of plastic-based items that contribute to MPs contamination, such as microbeads in personal care items [15].

By addressing these primary sources, along with other sources of MPs such as plastic waste mismanagement and fragmentation of huge plastic items, it is possible to mitigate MPs into the aquatic ecosystem and reduce their reverberation on ecosystems and human health [16]. MPs come in many shapes, including circular, fragment, and fibers. Most (except for intentionally created microspheres) are created by the disintegration of larger plastics (macroplastics). MPs break down into smaller pieces over time and eventually become nanoplastics [17]. MPs are, therefore, primarily a transitional state between macrodebris and nanomaterials. It has been estimated that the fragmentation of spherical MPs could generate over ten times more nanoparticles. Understanding MP's origin, fate, and impact requires looking at the continuum from plastic products or waste to MPs and nanoplastics [18]. Primary MPs are small pieces of intentionally manufactured plastic. They are mainly used in facial cleansers and cosmetics or air jet technology [19]. Sometimes, it has been reported to be used medically as a drug vector. MPs "scrubbers" used in exfoliating hand cleansers and facial scrubs have replaced traditionally used natural ingredients such as almond shells, oatmeal, and pumice stone. Primary MPs have also been produced for air jet technology. Made from acrylic, melamine, or polyester, MPs cleaners are sprayed from machines, engines, and boat hulls to remove rust and paint [6]. These scrubbers are often contaminated with heavy metals (HMs) such as cadmium, chromium, and lead as they are used repeatedly until they reduce size and cutting ability. Many companies are reducing microbe and production. However, bioplastic microbeads, which have a long degradation cycle similar to regular plastic, are still prevalent, and the United States is phasing out toothpaste and other washable cosmetics increase [20]. It was phased out in 2015, but since 2015, many industries have started using it instead. Use Food and Drug Administration-approved flushable metalized plastic glitter as a primary polish [16].

Secondary plastics are small pieces of plastic from large plastic wastes that end up in the ocean or on land. Over time, physical, biological, and chemical photo-degradation peaks, including photo-oxidation from exposure to sunlight, meaning that the structural integrity of plastic waste will eventually become undetectable to the naked eye [21]. This process of breaking large plastic materials into smaller pieces is called fragmentation. MPs are thought to continue to break down and shrink, but the smallest MPs found in the ocean are reportedly 1.6 μm (6.3×10^{-5} inches) in diameter. The growth of irregularly shaped MPs suggests that fragmentation is the leading cause. It has been observed that more MPs can form from biodegradable polymers than from non-biodegradable polymers in both seawater and freshwater [22]. By reviewing many literatures, there have been many studies conducted on the impact of MP in ecosystems [23]; however. there has not been enough depth examination of the source, impact on MPs in different environmental ecosystem, and their analysis method. Therefore, the present review provided board range of impact of MPs in ecosystem, factor influencing MPs toxicity, its method of analysis, national and international status and awareness of MPs pollution. By providing insights into prevention and control strategies, the study aims to contribute to the long-term ecological sustainability of natural environments.

2. MPS TOXICITY

MPs' toxicity refers to the potentially harmful effects of MPs on organisms and ecosystems when ingested or come into contact with living organisms. MPs absorb persistent organic and inorganic pollutants (such as toxic metals) in the natural environment [15]. This phenomenon has been exploited to develop passive polymer-based samplers for dissolved organic contaminants. However, the adsorption of contaminants to MPs surfaces can be affected by competing interactions with other chemicals present. The increased surface area of MPs compared to the original waste increases the potential for contaminant absorption [14]. These chemical particle distributions usually decreased in particle size, except for minor nanoplastics, where aggregation may have reduced the cumulative surface area. Although most of these studies have investigated organic pollutants (OP), they also found interactions between mercury and MPs, resulting in toxicological effects on fish [24]. There is ongoing research to understand better the toxicity of MPs and their potential influence on different creatures, including aquatic and terrestrial species.

MPs cause bodily harm to the organism and can accumulate in the whole body. Organisms can cause constipation, tissue damage, or disturbance of normal state physiological processes [25]. MPs can adsorb and accumulate toxic chemicals in the environment, accordingly measures against persistent OPs and HMs. These chemicals can leach and enter tissues through MPs if swallowed, possibly microorganisms causing toxic effects such as synthetic particles may lead to chronic inflammation and increase the risk of neoplasia [26]. MPs have been proven to have an inducing effect on immune response and inflammation creature. Inflammation can cause health problems, including tissue damage and weakened immune function [27]. MPs can be accidentally ingested by marine organisms such as confused creatures and organism's leftovers. This ingestion can cause improper diet or eating habits resulting in lower growth, lower energy imbalance, and malnutrition [27]. MPs can affect nature, reproductive success, and survival, possibly causative organism population-level impacts and changes in ecological

Table 1. Distribution characteristics of MPs in environmental ecosystems.

Location	Environment	Main MPs	Abundance	Size	Dominant shape	References
			In soil			
Spain	Farmland	PP, PVC	960 ± 420 items kg^{-1}	150–250 μm	Fragments, fibers, films	[156]
Korea	Forest, urban, and agricultural soils	PE, PP, PS, PVC	700 ± 75 items kg^{-1}	0–5,000 μm	Fragments, film, fibers, spheres	[157]
Mexico	Garden soils	PE	0.87 ± 1.9 × 103 items kg^{-1}	10–50 μm	Particles	[158]
China	Agricultural soils	PE, PP, PS	1,860 ± 1,212 items kg^{-1}	0–5,000 μm	Fragments, fibers, pellets, films, foams	[159]
Germany	Soil with compost application	PP, PET, PS, Nylon, HDPE, PVC	0–64 items kg^{-1}	65–5,000 μm	Fragments, fibers, particles	[160]
Germany	Compost	PVC, PES, PP, PE	39–102 items kg^{-1}	1,000–5,000 μm	Films, fragments, fibers	[161]
			Sediments			
Nigeria	Beaches sediments	PE, PS, PP, PA, PVC, PET	324.4 items kg^{-1}	1,000–5,000 μm	Pellets, foams, fragments, fibers	[162]
Netherlands	Marine sediments	Rubber, PP, PS,PE, EVA, PC	27–962 items kg^{-1}	100–5,000 μm	N/A	[163]
Vietnam	Peatlands	PVC, PE, PP, PVCA, EPDM, DINCH	192.3 ± 261.3 items kg^{-1}	300–5,000 μm	Fragments, films, fibers, foams	[164]
America	Tidal freshwater wetland	PE, PS	334–3,068 items kg^{-1}	<5,000 μm	Fibers	[165]
UK	Sewage sludge	PES, PVC, PE, ABS	37,700–286,500 items kg^{-1}	<500 μm	Particles and fibers	[166]
			Aquatic			
China	Freshwater	PE	1,760 ± 710–10,120 ± 4,090 items l^{-1}	<2,000 μm	Fibers	[167]
Portugal	Antua River	PE, PS, PP, PET	0.058–1.265 items l^{-1}	<5,000 μm	Fragments, fibers, films	[168]
Italy	Marine caves	PE, PVC	18–22 items l^{-1}	8–5,000 μm	Fragments, fibers	[169]
USA	Groundwater	PE	15.2 items l^{-1}	<1,500 μm	Fibers	[170]
Indonesia	Surface water	PE, nylon	5.85 ± 3.28 items l^{-1}	50–100 μm	Fibers	[171]
			Organisms			
Malaysia	*C. dorab* and *D. longimana* (fish)	PA, PET, PP, PE, PS, ABS, acrylic latex, and phenolic resins	1.89 ± 1.88–3.43 ± 1.95 items g^{-1}	63–5,000 μm	Fibers	[172]
Persian Gulf	Fish and prawn	MPs	0.16 items g^{-1} – 1.5 items g^{-1}	100–500 μm	Fibers	[173]
Korea	Large marine animals: whale (*Balaenoptera physalus*), turtles (*Caretta caretta*), dolphin (*Delphinus delphis*)	PP	3.42 ± 3.2 items g^{-1}	<200 μm	Fragments	[174]
Hong Kong	Marine mussels; *Brachidontes variabilis, Perna viridis, Xenostrobus securis*	MPs	0.2–0.7 items ind^{-1}, 2.8–14.7 items ind^{-1}, 0.6–3.1 items ind^{-1}	<5,000 μm	Fibers, fragments	[175]
Baltic Sea	Macroalgae	PE, PP, PVC, PA	376 ± 404 items kg^{-1}	500–1,000 μm	Fibers	[176]
Italy	Edible fruit and vegetables	Micro- and nano-plastics	52,050–223,000 items g^{-1}	<10 μm	N/A	[177]
Japan	Wild birds	PP, PE, EVA	13.6% (detection rate)	<100 μm	Fragments	[178]
			Air			
France	Outdoor air	PP, PE, PA, PES	0.3–1.5 items m^{-2}	<1,650 μm	Fibers	[179]
Germany	Atmospheric deposition	PE, PVA, PTFE	items m^{-2} day^{-1}	<63 μm	Fragments, fibers	[180]
Iran	Street dust	MPs	200–900 items 15 g^{-1}	<100 μm	Spherules, films	[181]
USA	Suspended particulate matter	PVC, PES, PS, PE	0.02–1.1 items m^{-3}	5–5,000 μm	Fibrous, Fragments	[182]

processes [26]. Considering different environments have different biological communities, ambient circumstances, and interactions with pollutants, different ecosystems are affected by MPs in different ways. In light of these variables, MPs behave differently in every ecosystem, having different impacts on both the environment and organisms (Fig. 1).

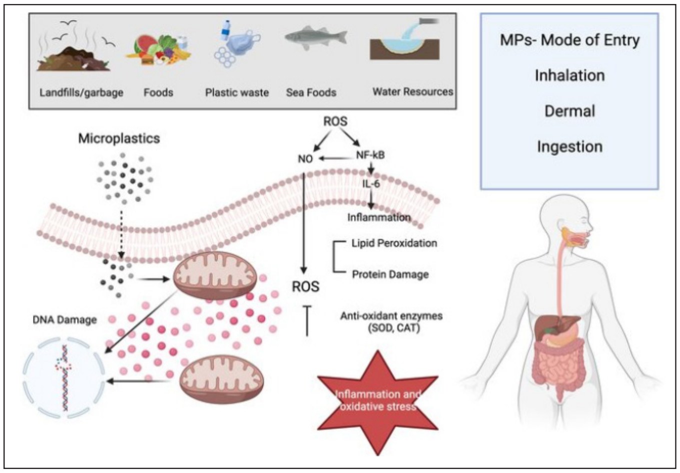


Figure 1. Schematic illustration showing the different sources of MPs and their possible mechanism of action involved in human toxicity. Adopted from Thapliyal *et al.* [155].

3. FACTORS INFLUENCING MPS TOXICITY

The most significant sign of the possible impact of MPs on various species, bioavailability, is dependent on the characteristics of the pollutant as well as the organisms preferred means of feeding [28]. In contrast to the majority of selective forgers, species that display generalist feeding preferences and employ restricted criteria to distinguish food from other substances, such as predators, are more likely to consume MPs that bear similarities to their natural prey [29]. Physical characteristics influence the shape and movement of MPs in the aquatic environment, which modifies their distribution and impacts bioavailability by resembling natural materials and inflicting varying degrees of physical harm on the organism. The size, color, density, and form of MPs are the most researched physical characteristics, and each attribute contributes differently to the adverse impacts (Table 2).

3.1 Size

A variety of organisms, particularly the nonselective foragers, have access to MPs since they are in the same size range as sand grains, microalgae, and plankton [30]. *Daphnia magnas* rate of MPs uptake has been found to be exponentially correlated with size; as average particle size increases, fewer *Daphnia* are found to have MPs in their guts. The majority of MPs that *Daphnia* consumed had a size below 100 µm, which is in line with their predilection for smaller food pieces [31]. Due to smaller food feeding preferences (<50 µm), *Artemia franciscana* swallowed fewer MPs particles under the same MPs exposure circumstances as *Daphnia* [32]. Particle size also plays a critical role in determining how well MPs can relocate throughout an organism's body after ingestion. Within *Mytilus edulis*, the smaller MPs (about 3.0 µm) translocate more easily and readily than the bigger particles (approximately 9.6 µm) [33]. Particle size also plays a critical role in determining how well MPs can relocate throughout an organism's body after ingestion. Within *Mytilus edulis*, the smaller MPs (about 3.0 µm) translocate more easily and readily than the bigger particles (approximately 9.6 µm) [34]. Therefore, because of the increased rates of ingestion and translocation inside the organism, the smaller MPs for this particular species demonstrated higher bioavailability. Conversely, for many species, the body size of the creatures and their variable preferences for meal sizes also affected the biological reactions.

3.2 Color

Another feature of MPs that interferes with visual predators ability to forage is color, which might lead to different ingestion biases. About 80% of the amber stripe scads (*Decapterus muroadsi*) consumed mostly blue plastic fragments, which exhibited a comparable morphology in size and color to their blue copepod food [35]. The flathead grey mullet's digestive tracts contained MPs that were primarily dark in color, particularly green MPs fibers that resembled sea plankton *Mugil cranialus* [36]. The most prevalent colors of MPs consumed by planktivorous fish in the North Pacific central gyre were white, clear, and blue, which are comparable in color to the local plankton. This is because the MPs resembled the fishes food supply [37]. Thus, color has a major effect on visual predators' susceptibility to consume MPs. Apart from its influence on the preferences of consumption, the color was also examined as a natural signal of the possible toxicity of MPs. While the darkening of the color was accompanied by an expected increase in polycyclic aromatic hydrocarbon (PAH) content, there was no difference in the enrichment of PAH in MPs made of PE and PP. Additionally, darker MPs contain higher weight PAH, while lighter-colored MPs tend to have lower molecular weight PAH [38].

Additionally, this color-dependent variation in adsorption capacity showed that the black MPs tended to absorb more compounds than the white ones, including polychlorinated biphenyls (PCBs) and PAHs [39]. Consequently, consumption of the enhanced pollutants, combined with MPs, will cause additional stress to the organisms throughout the circulatory system, tissues, and organs. One explanation might be that differing colored pigments help MPs' ability to bind to surfaces [40]. Furthermore, the color may indicate the MP's relative age and level of weathering. A low degree of adsorption arises from the loss of pollutants on the surface of the MPs during weathering, which alters the affinity between the MPs surfaces and contaminants. Color and pollutant enrichment are directly correlated, which is a novel discovery in toxicological research. More research should be done on the underlying mechanisms pertaining to the chemical composition and the behavior of the varied colored MPs in the aquatic environment.

3.3 Density

Density impacts the trajectory, sinking velocity, and spatial distribution of MPs, which further affects the distribution of MPs in the various biota and habitats. These factors together determine the distribution and destination of MPs. For instance, the accumulation of low-density plastics in surface water hinders zooplankton respiration and algal photosynthesis [41], high-density MPs have been consistently detected in the digestive tracts of the benthic invertebrates [42], and the MPs that sink to the sediments on the seafloor endanger the deep ocean biota [43]. The copepod-egged fecal pellets, which are crucial food sources for fish, polychaetes, crustaceans, and copepods, have a different sinking velocity depending on the density variation. In addition, pollutants such PAHs MPs toxicity are directly impacted by the tendency of fries [44], PCB [45], and phenanthrene [46] to have higher diffusion coefficients in low-density MPs than in high-density MPs.

3.4 Shape

One important morphological characteristic of MPs is their shape, which can be classified as regular or irregular depending on the initial shape, aging, and weathering conditions. To be more precise, MPs can also be categorized as pellets, films, flakes, spheres, fibers, and pieces [47]. By altering the distribution and bioavailability, the shape of MPs affects their hydrodynamic properties, which in turn affects a range

Table 2. Abundance of MPs and its properties.

Location	Sample	Abundance	Size	Shape	Color	Polymer type	Ref
Chong Ming island, China	Surface water	0–259 items/m^3	<1 mm	Fragment (9.2%)	White	PE (37.3%)	[183]
	Sediments	10–60 items /kg	<1 mm	Fiber (66.7%)	Transparent	PP (28.6%)	
Southern Mariana Trench	Bottom water	2.06–13.51 items/l	1–3 mm	Fiber	Blue, red, green, white, purple	PET (19%), PA (14%), PVC (13%), PUR (12%), PS (11%)	[111]
Spanish Mediterranean continental shelf	Sediments	113.2 ± 88.9 items/kg d.w	0.5–1 mm (35%) 1–2 mm (34%) 2–5 mm (31%)	Fiber (82.9%)	Transparent	-	[184]
Taihu Lake, China	Surface water	3.4–25.8 items/l	100–333 µm	Fiber (48%–81%)	Transparent (29%)	PET	[172]
	Sediments	11.0–234.6 items/ kg d.w			White (44%)		
Tibet Plateau, China	Sediments	563 items/m^2	1–5 mm	Sheet, line, fragment, and foam	-	PE, PP, PET, PVC and PS	[109]
Tehran metropolis, Iran	Air	2.93–20.17 items/g	250–500 µm (33.7%)	Granule (65.9%)	Black (29.9%) Yellow (26.4%)	-	[113]
YanTai city, China	Air	30–624 items/m^2/day	<0.5 mm	Fiber (95%)	-	Polyester (40%), PVC (10%)	[185]
Asaluyeh County, Iran	Street dust	200–900 particles/15 g	<100 µm (75%)	Spherule (74%), film (14%)	White and Transparent (66%)	-	[186]
Paris city, France	Indoor air	1–60 items/m^2	<3,250 µm	Fiber	-	PP, PE, PA	[182]
	Outdoor air	0.3–1.5 items/m^2	<1,650 µm			PES	
Hamburg, Germany	Atmospheric deposition	275 particles/m^2/day	<63 µm	Fragment (95%)	-	PE, PVA, PTFE	[180]
French Pyrenees	Atmospheric deposition	365 particles/m^2/day	50–2,600 µm	Fragment, film, fiber	-	PS, PP, PE, PET	[181]
Nordic Seas	Surface water	EGC: 1.19 ± 0.28 items/l	0.1–2 mm (63.9%)	Fiber (87.16%)	Transparent (87.6%), blue (6.6%)	Polyester (35%), cellulose (9%), PE (9%), PP (8%), PS (2%), PVC (6%), PA (5%)	[187]
		GSG: 2.43 ± 0.84 items/l	0.5–5 mm (41.9%)	Fiber (76.13%), Line (8.39%), film (2.44%), Fragment (11.21%)	Transparent (76.2%), blue (16.17%)		
Wuhan city, China	Agricultural soils	320–12,560 items/kg d.w	<0.2 mm (70%)	Granule, fiber, fragment and foam	-	PA (32.5%), PP (28.8%). PS (16.9%), PE (4.2%), PVC (1.9%)	[188]

of biological and toxicological impacts. The dynamics of MPs are indirectly influenced by shape as opposed to density [48]. Even though the debris has the same mass and volume, plastic fibers and thin films exhibit stronger buoyancy and lower settling velocity than spherical plastic particles [49]. The form of the MPs has an impact on the body's ejection and residence period after intake. Both regularly shaped and irregularly shaped PE MP particles are rapidly ingested by *D. magna*; however, the irregularly shaped MP particles' gut clearance and apparent gut residence times were longer than those of the regularly shaped MP particles, and they even showed more pronounced acute inhibitory effects [50]. Higher toxicities were discovered for the MP fibers, which were linked to longer residence times because of their structure. The amphipod *Hyalella azteca* consumed more MP fibers than spheres, requiring longer clearance times than the spheres [51].

3.5 Plastic Polymer Type

The fate of a polymer is determined by its intrinsic structural characteristics, such as its acid–base character, molecular chain arrangement, and surface charge and area. These characteristics affect the sorption processes and the kinds of organic contaminants that are deposited on the plastic particle's surface [52]. Regarding sorption processes, one of the most significant plastic characteristics is the degree of polymer crystallinity, which is correlated with the molecular chain arrangement. Both crystalline and amorphous regions make up polymers. The crystalline zone is made up of segments of molecules with a regular structure, while the amorphous region is made up of regions where chains are randomly packed. Chemical absorption requires a significant amount of energy in the structured domain. On the other hand, due to the space between polymeric chains, random regions have a greater degree of free volume, making it easier for chemicals to permeate into the polymer. Polymers can only be semi-crystalline, combining crystalline and amorphous regions, or entirely amorphous due to the size and intricacy of these chains [53]. PE, PP, PE terephthalate (PET), and polytetrafluoroethylene (PTFE) are a few instances of semi-crystalline polymers. Polymer crystallinity is influenced by a number of variables, such as polymer complexity, chain configuration, isomerism, and solidification cooling rate.

According to earlier research, PE is the polymer that, when compared to PP and polyvinyl chloride (PVC), sorbs and concentrates the greatest amount of organic contaminants [54,55]. Because PVC and PS are glassy polymers, the sorbate has low diffusivity and poor mobility. However, the crystallinity effect can be overcome by other polymer properties; thus, its impact is minimal. According to Rochman *et al.* [56], PS, a glassy polymer, has comparable sorption capabilities for several PAHs compared to low-density PE (LDPE) and high-density PE (HDPE), rubbery polymers. In this instance, the authors contended that the longer distance between polymeric chains in PS made up for the increased segmental mobility of PE. A similar finding has been concluded by Seidensticker *et al.* [57], a larger porous size of PS compared to PE enables a major sorption capacity of PS with respect to PE. Hence, these observations imply that the structural characteristics of each polymer have a profound influence on the sorption capacities of organic chemicals by plastics.

3.6 Age and Degree of Weathering of Plastic

Virgin or pristine plastics are those that have just been produced and have not been harmed by the environment. On the other hand, plastics that have aged or weathered have been subjected to various degradation processes, such as oxidative breakdown, hydrolysis, mechanical, biological, thermal, or radiation [58]. Plastic waste can break down into tiny pieces due to its susceptibility to certain environmental factors. It is also crucial to remember that aged pellets could experience chemical alterations. For instance, weathering has the potential to improve the crystallinity of polymers. According to the study, aged MPs were better than pure pellets at adsorbing HMs. The scientists provided an explanation for this observation by examining the relationship between the enhanced surface area and the appearance of oxygen-containing functional groups on the surface of aged MPs following UV treatment [59]. Accordingly, it appears that MPs' functional groups and polarities play a major role in the build-up of many environmental contaminants. The polarity of plastic pellet surfaces and their particular surface–volume ratio can be modified by biological events, such as the formation of biofilms on the pellet surface [60]. Richard *et al.* [61] reported that biofilms promoted the accumulation of different metals (such as gallium, manganese, lead, copper, cobalt, iron, nickel, and aluminum) in plastic waste. Furthermore, a report indicated that the increased surface area made feasible by the biofilms' action enabled the higher cesium sorption and sorption of strontium onto PE and PP MPs [62].

3.7 Chemical Properties of Pollutants

Organic pollution's chemical qualities are just as important in deciding how quickly they absorb into plastics as polymer properties are. The best characteristics that describe an organic chemicals ability to absorb are its molecular weight and hydrophobicity [63]. The pKa is another chemical characteristic that might have a big influence on the MPs sorption rates. The way that MPs-pollutant interactions are modulated is significantly impacted by pH. Because of this, pKa may be used to assess whether substances taken by MPs are more likely to be released when the pH of the surrounding environment changes noticeably. Thus, pKa may provide an explanation for which environmental contaminants might be more likely to desorbs in a physiological setting [64]. The sorption rate of the molecule may also be influenced by its three-dimensional geometry. Because planar molecules exhibit stronger surface adsorption than non-planar molecules with identical hydrophobicity, planar molecules generally have higher sorption coefficients [65]. PCBs and PAHs are two instances of planar organic molecules. Because of their strong affinity for the cellular protein known as the aryl hydrocarbon receptor, these chemicals have well-established toxicological consequences, including endocrine disruption, hepatotoxicity, immunotoxicity, congenital defects, and activation of several enzymes [66]. These possible dangers emphasize how crucial it is to accurately assess the toxicological effects of plastic debris' capacity to produce the "Trojan horse" effect, particularly for MPs and NPs.

3.8 Environmental Factors

The pollutant–plastic interaction is also modulated by the surrounding environmental circumstances. The unique chemical–plastic interaction resulting from chemical speciation determines how pH affects sorption rates. In this regard, a study found that while perfluorooctanesulfonamide (PFOSA) adsorption was unaffected by pH change, perfluorooctanesulfonate (PFOS) sorption by PS and PE would be greatly affected by a drop in pH. This fact demonstrated the electrostatic interactions that PFOS-plastic sorption systems go through [67]. Similarly, a study found that tetrabromobisphenol A sorption capacity on MPs beads was significantly influenced by pH. In this instance, a drop in pH caused this flame-retardant compound's sorption rate to increase [68]. In accordance with these findings, Guo *et al.* [69] revealed that the sorption pattern of nonsteroidal anti-inflammatory medicines on MP particles (MPs) showed a strong pH dependency because of the impact of pH on the compounds' speciation and the particle's surface charge. On the other hand, as the pH of the solution rose, more sorption was seen for cationic species that produce metals, such as Pb^{2+}, Cd^{2+}, Ni^{2+}, and Co^{2}+. The authors proposed that this experimental discovery could be explained by a decrease in the relative quantity of free ions [70]. Moreover, the sorption and desorption of chemicals from plastics on environments may also be influenced by other environmental parameters including salinity, ionic strength, or the presence of dissolved organic matter (DOM). The relevance of the ionic strength depends on the extent of the electrostatic interactions involved in the sorption/desorption mechanisms. The study performed by Wang *et al.* [67] revealed that the sorption of PFOS was the only one impacted by an increase in ionic strength, whereas the adsorption of PFOSA remained independent. This discrepancy suggested that electrostatic interactions are the method by which PFOS sorbs to plastic.

4. IMPACT OF MPS

4.1 Soil Ecosystems

The adequate management of plastic materials has led to the relative abundance of MPs in the terrestrial system, thus affecting the microbes, plants, and other organisms directly or indirectly dependent on them (Fig. 2). MPs are a potent risk to the soil microbiome as these microbial bodies being sensitive try to adapt the changes in soil properties and substrate leading to disordered functions [71]. Minute plastics have the tenacity to be an obstacle in the interaction between soil-plant and soil-microbe, along with having a negative impact on the abiotic characteristics of the soil. The size of MPs similar to the native soil particles brought about substantially little difference with respect to

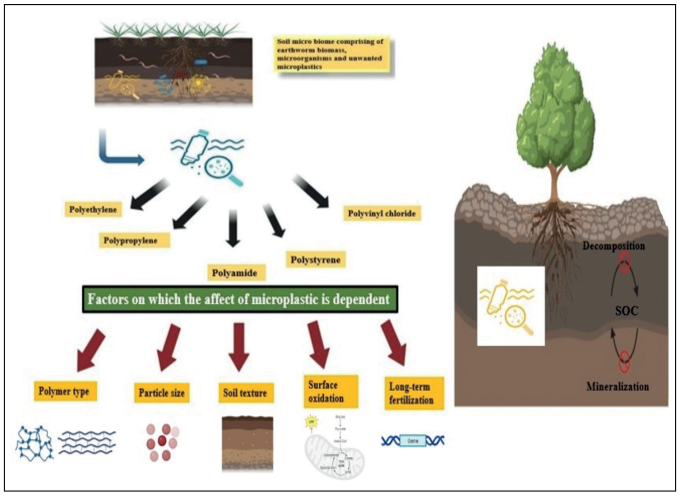


Figure 2. Soil ecosystem comprises earthworm biome, microorganisms, and unwanted MPs.

control compared to other varied-sized particles [72]. The biophysical environment of the soil, namely, water-holding capacity, the functional relationship between water-soluble aggregates-microbial activity, and bulk density, is altered due to the addition of MPs into the land, ultimately leading to a disturbed terrestrial ecosystem. Along with this, specific idiosyncratic effects such as polymer type, particle structure, and status of surface oxidation can have varying effects on the biota of soil [73]. A novel study on the history of long-term fertilization and its relation with MPs-based soil alteration showed a genotypic view of the interaction between MPs and soil microbiome. Different fertilization histories can change the impact of MPs exposure on the structure, function, and composition of the microorganism residing within the soil [74].

Considering the soil texture MPs could also majorly affect the hydraulic characteristics of the soil. Integrating MPs into different kinds of soils decreased the saturated hydraulic properties by 69.79%, 95.79%, and 77.11% for loam, sand, and clay, respectively. Minute plastics can decrease the availability of pores by changing the distribution of soil pore size [75]. Many soil processes are particularly susceptible to changes in soil structure, which can have further effects on soil characteristics, microbial activity, greenhouse gas (GHG) emissions, and nutrient cycling. MPs have been found to affect the DOM, bulk density, water-holding capacity, and the functional connection between microbial activity and water-stabilizing aggregates in the soil in earlier studies [76]. Nevertheless, not much work has been done to describe how MPs affect soil microbes, which are the main agents in biogeochemical cycling. The three most significant GHGs that affect climate are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and one of the main sources and sinks of GHGs is farming [77,78].

Similarly, Zhang *et al.* (2022) concluded that adding about 0.01% and 0.1% MPs in the soil did not alter the respiration of soil microbes; however, a concentration of 1.0% MPs increased CO_2 emission in the soil. Also, the expression of the functional genes of the microbes degrading organic carbon declined under MPs stress [79]. To study the impact of MPs in the rhizospheric soil, Dong *et al.* (2021) experimented and concluded that MPs, along with arsenic inhibited the activity of acid phosphatase, dehydrogenase, peroxidase, protease, and soil urease by affecting the tertiary structure of enzyme along with the reduction of available phosphorus and nitrogen concentrations in the soil [80]. The diversity and richness of microbes on the surface of MPs were considerably less than those near "rhizosphere-like" soil. Moreover, the humus horizon had relatively lower microbial diversity and richness than the eluvial level. Microbes such as Chloreflexi, Mortierellomycota, and Acidobacteria were abundantly present around "rhizosphere-like" soil, while microbes such as Basidiomycota and Cyanobacteria were abundantly present on MPs surfaces. Furthermore, the negative impact of MPs above and below the soil ecosystem involves the germination of few seeds, reduced shoot height, and decreased biomass at the surface level. While at the ground level, the pH of the soil is decreased, along with the reduction of root and earthworm biomass [81]. Therefore, MPs undoubtedly harm the soil ecosystem, affecting the directly connected organisms and the indirectly attached organisms related via the food chain.

The prominently found MPs in the soil are PE, PP, polyamide, PS, and polyvinyl chloride. The factors such as polymer type, the particle size of soil and polymer, soil, texture, state of surface oxidation state, and long-term fertilization genotypic traits. MPs affect the decomposition and mineralization of the soil's organic carbon and plant growth and cause negative impact on the biophysical and chemical state of the soil. MPs alter the soil–water cycle, nutrient availability, worsen the scarcity of soil water, and have an impact on the movement of pollutants into deep soil through cracking. Because MPs enhance water-holding capacity and water-stability aggregates and nutrient availability associated with the humus content, they may lead to an increase in fulvic and humic acids (Tables 3 and 4).

4.2 Marine Ecosystem

Over the past years, marine ecosystems have seen an increase in the accumulation of MPs in various water bodies, including, coastal areas, rivers, seas, oceans, and polar regions [82]. Several land and marine activities are responsible for causing this high rise in the concentration of MPs. Domestic and industrial applications lead to the primary source of MPs. In contrast, the conversion of vast chunks of plastic into smaller fragments of plastics leads to a secondary source of the same (Fig. 3) [83]. When the MPs reach in water surface, they perform three different steps. The first step is called the physical step which involved sedimentation, accumulation (spatial and temporal), and migration of MPs. In the second step called the chemical step involving adsorption and degradation of MPs in water. In the final step, they performed biodegradation, translocation, and ingestion in water. This defined behavior of MPs holds the ability to alter the dynamics of the water system [84]. The aqueous body's distribution mechanism, exchange, and uptake of the MPs mainly depend on the particle density. The polymer density is a critical determinant that specifies the vertical distribution of these tiny plastics within the water column, and their interactions with aqueous species define the availability of buoyant MPs at greater depths [85]. The benthic region experiences the highest concentration of the polymers leading to the availability of more proportions of MPs in the body of benthic invertebrates. For instance, the species *Sabella spallanzanii* had about 42% of polymer, and *Hermodice carunculata* had about 93% of polymer content in their bodies with polymer concentrations depending on the feeding strategies of individual species [86]. Not only on benthic organisms but also on coral reefs, these MPs have quite adverse effects. When exposed to MPs, coral reefs can cause various biological effects, from mucus production to feeding impairment and changed gene expression, even though reefs can ingest polymers such as PP [87].

The other species that are prominently found in the aquatic system are microzooplankton. Likewise, MPs have a detrimental impact on these bodies as with the increase in the concentration of MPs, the

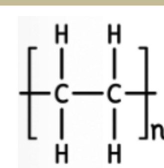
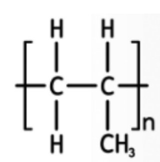
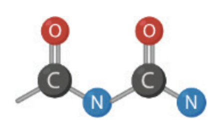
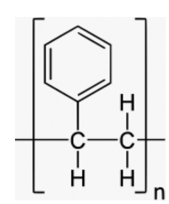
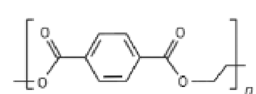
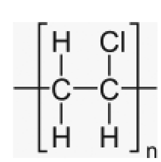
Table 3. Abundance of MPs in various types of soil.

	Species	MPs type	MPs abundance	MPs particle size	Exposure time (day)	Effect	References
1.	*Eisenia fetida*	LDPE	0.1, 0.25, 0.5, 1.0, 1.5 g kg^{-1}	<400 µm	28	When the concentration of MPs reached 1.0 g kg^{-1}, it caused surface damage to *Eisenia fetida*, triggered oxidative stress and stimulated neurotoxic reactions.	[189]
2.	*Eisenia andrei*	PE	1,000 mg kg^{-1}	180–212 µm, 250–300 µm	21	MPs had an effect on the activity of coelomocyte, and the damage to male reproductive organs was more serious than that of females.	[190]
3.	*Enchytraeus crypticus, Folsomia candida, Porcellio scaber*, and *Oppia nitens*	Polyester fiber	0.02%–1.5%	12 µm–2.87 mm, 4–24 mm	28	Polyester fibers had little effect on soil invertebrates	[191]
4.	*Eisenia fetida*	PE, PS	0%, 1%, 5%, 10%, 20%	<300 µm	14	When exposed to 20% of PE or PS particles, the activity of catalase and peroxidase in earthworms increased significantly, while the activity of superoxide dismutase was inhibited	[192]
5.	*Lumbricus terrestris*	Polyester	0%, 0.1%, 1.0%	361.6 µm	35	Ingestion of MFs has no fatal effect on earthworms, and earthworms showed no avoidance of MFs	[193]
6.	*Lumbricus terrestris*	LDPE	7%	<150 µm	60	Bacteria isolated from *L. terrestris* gut could degrade 60% of MPs and produce nanoplastics.	[194]
7.	*Eisenia fetida*	LDPE	62, 125, 250, 500, 1,000 mg kg^{-1}	250–1,000 µm	28	Exposure to MPs caused changes in earthworm oxidative stress and energy metabolism	[195]
8.	*Eisenia andrei*	PE	0, 62.5, 125, 250, 500, 1,000 mg kg^{-1}	250–1,000 µm	56	After 56 days of exposure, there was no significant difference in the average number of earthworm larvae under different MPs treatments	[196]
9.	*Eisenia fetida*	PS	0.25%–2%	58 µm	30	High concentrations (1% and 2% (w/w)) of MPs significantly inhibited the growth of earthworms and increased the mortality of earthworms	[197]
10.	*Lumbricus terrestris*	PE	7%, 28%, 45%, and 60%	<150 µm	60	The mortality of earthworms increased in 28%, 45%, and 60% MPs after 60 days of exposure, and the growth rate was significantly reduced	[198]
11.	*Caenorhabditis elegans*	PS	0–100 mg kg^{-1}	42 and 530 nm	1	Nematodes are more sensitive to large particles (530 nm) than small particles (42 nm).	[199]
12.	*Culex mosquito*	PS	0, 50, 100, and 200 MPs ml^{-1}	2 and 15 µm	12	The growth and mortality of *Culex* mosquitoes were not affected by MPs	[200]
13.	*Folsomia candida*	PE	0.5% and 1%	<500 µm	28	MPs inhibited the reproduction of earthworms and also significantly altered their gut microbial community and reduced bacterial diversity.	[201]
14.	*Caenorhabditis elegans*	PS	1 µg l^{-1}–86.8 mg l^{-1}	50 and 200 nm	1	Exposure to nano-PS particles could cause disturbances in metabolites related to energy metabolism and also led to toxic effects including inducing oxidative stress and reducing exercise and reproduction.	[202]
15.	*Caenorhabditis elegans*	PS		0.1–5 µm	3	At an exposure concentration of 1.0 mg l^{-1}, the 1.0 µm group had the lowest survival rate and the largest decrease in body length. In addition, it caused significant damage to cholinergic and GABAergic neurons.	[203]
16.	*Enchytraeus crypticus*	PS	0%, 0.025%, 0.5%, and 10%	0.05–0.1 µm	7	The body weight of animals exposed to 10% PS decreased significantly, and the reproduction of 0.025% animals increased.	[204]
17.	*Folsomia candida*	PVC	1 g kg^{-1}	80–250 µm	56	Exposure to MPs significantly increased the diversity of bacteria and changes the microbiota in the gut of springtails. In addition, the growth and reproduction of springtails were significantly inhibited.	
18.	*Achatina fulica*	PET	0.14–0.71 g kg^{-1}	1257.8 µm	28	The 0.71 g kg^{-1} MFs caused obvious villi damage in 40% of the snail gastrointestinal wall, and reduced liver glutathione peroxidase and total antioxidant capacity.	[205]

(Continued)

	Species	MPs type	MPs abundance	MPs particle size	Exposure time (day)	Effect	References
19.	*Lycopersicon esculentum*	PET, PE, PP	30,940 ± 8,589 particles kg^{-1}	0.4–2.6 mm	109	The soil containing MPs sludge promoted the growth of tomato plants but delayed and reduced fruit yield.	[206]
20.	*Lepidium sativum*	Green fluorescent plastic particles	10^3–10^7 particles ml^{-1}	50, 500 and 4,800 nm	3	MPs with different particle sizes had no significant difference in the germination rate after 24 h and the root growth after 48 h	[207]
21.	*Vigna radiata*	PS	0, 10 and 100 mg kg^{-1}	28 nm	10	Nanoplastics inhibited the growth of mung bean plant roots and caused the accumulation of nanoplastic particles in plant leaves.	[97]
22.	*Carrot*	PS	10 and 20 mg l^{-1}	0.1–5 µm	7	PS MPs with a size of 1 µm only accumulated in the intercellular layer of carrot roots, without entering the cells; those with a size of 0.2 µm could be transferred to the leaves.	[208]
23.	Lettuce	PE	0.25, 0.50, and 1.00 mg ml^{-1}	23 µm	28	MPs significantly reduced the growth rate, photosynthesis, and chlorophyll content of lettuce	[209]
24.	*Triticum aestivum*	LDPE and biodegradable plastic film	1%	50 µm–1 mm	120	The negative effect of biodegradable plastic mulch on wheat growth was stronger than that of PE.	[210]
25.	*Vicia faba*	PS	10, 50 and 100 mg l^{-1}	5 µm and 100 nm	2	The genetic toxicity and oxidative damage of 100 nm PS MPs to *Vicia faba* were higher than that of 5 µm PS MPs.	[96]

Table 4. Brief insight into the prominent MPs present within the soil ecosystem.

Polymer	Chemical formula	Density	Properties	Harmful effect on the soil	Chemical structure	References
PE	$(C_2H_4)_n$	0.88–0.96g/cm^3	Light weight, dielectric material, and insoluble in water	Decreases bulk density of soil and alters the function of soil particles		[95,73,211]
PP	$(C_3H_6)_n$	0.946 g/cm^3	Non-polar, partially crystalline, thermal polymer	Effects the dynamic of soil and plant growth as it emits greenhouse gases		[212,213,81]
Polyamide	(R—CO—NH—R')	1,140 kg/m^3	Polar, semi-crystalline, and water soluble	Alters the water dynamics and soil structure		[214,72] [215]
PS	$(C_8H_8)_n$	0.96–1.05 g/cm^3	Hard, clear, and thermoplastic polymer	Negatively affects the enzymes and microbes available in the soil.		[216-218]
PE terephthalate	$(C_{10}H_8O_4)_n$	1.38 g/cm^3	Semi-crystalline, thermoplastic polymer that is water-insoluble	It decreases water retention and stability of soil		[219,220]
Polyvinyl chloride	$(C_2H_3Cl)_n$	1.4 g/cm^3	Water-insoluble, white, amorphous polymer	Effects earthworm biomass with alternation in plant growth and development		[218,221,83]

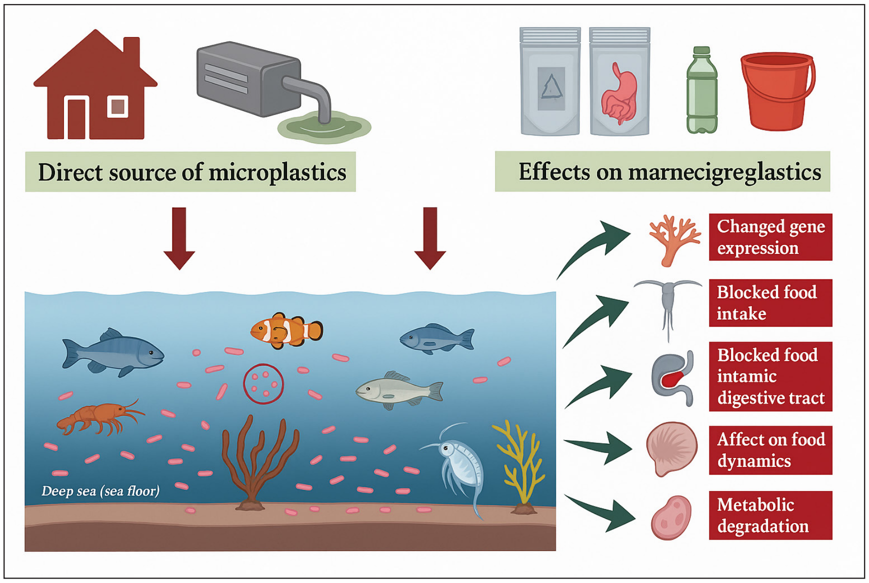


Figure 3. Sources of marine MPs.

body size, biomass, and the number of planktonic ciliates reduced sharply which they come across the feeding process of the species along with this MPs also alter the microbial loop around the region [88]. In the case of marine copepods, MPs act as carrier agents of OPs, such as chlorpyrifos, dibutyl phthalate, and triclosan, thereby enhancing the toxicity level inside copepods and consequently elevating the negative effect on the marine system. MPs hinder the digestive tract, block food intake, and develop physiological stress within copepods leading to a disturbed planktonic environment [89]. MPs polymers affect the life of marine environment which makes the microbial colonies susceptible to these minute particles. The interaction between the colonies and MPs has resulted in the degradation of the microbiomes present throughout the water system. Microbial degradation is fatherly affecting the aquatic ecosystems inherent balance [90]. Overall, the MPs degrade the aquatic bodies actual productivity [91]. Although the marine species digest these MPs, this is causing many side effects on entire marine bodies as it also affects not only direct consumer but also affect indirect consumer through the food chain. The limited or no use of plastic, along with the development of biodegradable plastic, is the only way of fighting MPs contamination in all water bodies (Table 5).

4.3 Aquatic Ecosystem

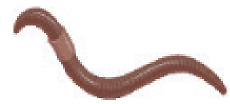
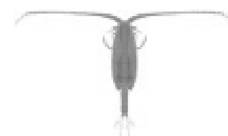
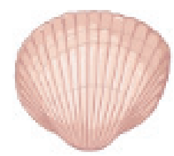
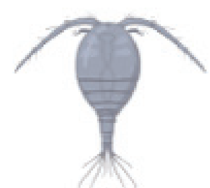
In aquatic environments, MPs have the ability to affect a wide variety of creatures, either directly or indirectly through the trophic chain. The majority of research focused on acquiring data regarding the consumption of MPs by various organisms and species, typically summarizing the quantity and primary features of the plastic particles identified in the examined species. An analysis of 46 species from the Amazon River on Brazil's north coast revealed that 30% of the species had consumed MP particles, the majority of which were pellets (97.4%) [92]. MPs accumulation has been observed in a wide range of aquatic life, including planktonic species, invertebrates, and vertebrates, according to ecotoxicology research [93]. However, compared to marine organisms, freshwater organisms have far less evidence of ingesting MPs, both in terms of the number of studies done and the variety of species examined. The most common techniques for determining if MPs are present in the various tissues and organs of aquatic species include Fourier-transformed infrared spectroscopy, Raman microscopy, optical microscopy, scanning electron microscopy, fluorescent microscopy, and fluorescent spectroscopy [94]. However, none offer a quick, precise, and quantitative way to figure out how quickly MPs bioaccumulate. There is also a dearth of knowledge regarding the mechanisms underlying the bioaccumulation of MPs, their translocation into organs, cellular transport channels, and elimination kinetics (Table 6).

4.4 Terrestrial Ecosystem

There is currently an absence of study on the possible effects of MPs on terrestrial plants, and our understanding of these effects is incomplete. Generally speaking, MPs in soil can cause modifications to its moisture content, density, structure, and nutrient content. These modifications can then affect the growth, nutrient uptake, and root characteristics of plants. Various studies have demonstrated that MPs impact on faba bean (*Vicia faba*) [95], spring onion (*Allium fistulosum*) de Souza [72], wheat (*Triticum aestivum*) [96], and cress (*Lepidium sativum*) [97]. These results suggest that plant responses are dependent on species, soil, and MPs properties. MPs development in plants can impede cellular connections or obstruct pore spaces in the cell wall, which limits the movement and uptake of vital nutrients. When PS MPs (about 100 nm) accumulated in roots, they caused growth retardation and genotoxic impairment to *Vicia faba* [95]. In a recent study, the germination rate of *Lepidium sativum* (cress) was found to be considerably reduced after 8 hours of exposure due to the buildup of MPs (~4.8 µm) on seed capsules [97]. The same study also found that after 24 hours of exposure to MPs, there was a substantial change in root growth. Research with conclusive data is still few, and the impacts of MPs on vascular plants are still unclear. MPs have been found to have significant effects on plants, including spring onions, *Allium fistulosum*.

According to de Souza Machado *et al*. [72], spring onions (*Allium fistulosum*) had different characteristics due to MPs (PES fibers, polyamide beads, PE, PES terephthalate, PP, and PS). These changes included total biomass, root and leaf traits, and leaf composition, which included nitrogen content and the carbon-to-nitrogen (C:N) ratio. They put forth a haphazard model to explain how MPs affect terrestrial ecosystems; they cause a series of

Table 5. A detailed study of various marine organisms which are affected by MPs.

Effected marine organism	Source of MPs contamination	Impact on the marine ecosystem	Large-scale impact	Image of the species	References
Coral reef	Ingestion of PP	changed gene expression, feeding impairment	Effects the microbiome available in the coral reef		[80]
Lugworms	MPs like polyvinyl chloride and PE	Deteriorate benthic species	Causing an unbalanced aqueous environment		[87]
Microzooplaktons	Ingestion of polymers during the feeding process	Reduces body side, biomass, and number of planktonic ciliates	Affects the larger species dependent on zooplanktons		[222]
Benthic invertebrates	polychaetes-MPs	Effecting the feeding dynamics of the species although they can act as bioindicators	Disturbance in the biota of the region		[88]
Copepod	MPs act as carrier agents of OPs	hinder the digestive tract, block food intake, and develop physiological stress	Disturbance in the zooplankton biomass		[86]
Microbial colonies	Oil spillage and industrial waste containing polymers like PE, polyamide, etc.	Metabolic degradation of biota	Unbalanced marine ecosystem		[89]

changes in the biophysical environment of soil that impact onion development. In contrast, Jiang *et al*. [95] found no appreciable adverse impacts on the emergence of seedlings or the generation of wheat biomass from the addition of MPs (HDPE, PET, and PVC). These findings suggest that more investigation is needed to evaluate the effects of MPs on plants and how they interact with soil ecosystems. Another study found that the type of plastic mulch film had a significant impact on wheat growth; MPs from starch-based plastic mulch films (37.1% pullulan, 44.6% PET, and 18.3% polybutylene terephthalate) showed strong negative effects on wheat during both vegetative and reproductive stages, in contrast to those derived from LDPE [96]. MPs' effects on plants and in vivo transport have only been documented in a few number of research [98]. It is still mostly unknown how soils, plants, and MPs properties (type, concentration, and source) interact. Therefore, in order to fill in the knowledge gaps regarding the effects of MPs on plants, more research is required to comprehend the response mechanisms of different crops. Furthermore, trophic transfer from the accumulation of MPs in plants to terrestrial organisms can be hazardous [99]. Thus, it is critical to concentrate future studies on the effects of MPs contamination on regional food webs.

4.5 Atmospheric Ecosystem

Environmental MPs can be consumed by a variety of creatures, including species that are frequently found in human diets. Recent research on air MPs demonstrates the wide spatiotemporal ranges of the mechanisms influencing the origins, destiny, and transportation of MPs as well as their impacts on the ecosystem and all of its inhabitants, including humans [100]. According to epidemiologic research, air pollution from ambient atmospheric particles has a negative impact on the heart and lungs. Dust intake poses a risk of exposure even if the visible MP threads are allegedly too big to breathe in, especially for small children [101]. Previous research found plastic and cellulose fibers in human lung biopsies and removed lung tumors, as well as in lung biopsies and health issues as occupational asthma, wheezing, coughing, and dyspnea [102]. It has also been shown that MP particles (larger than 100 μm) can pass through the epithelium of the gastrointestinal tract and remain biopersistent. The concentration of MPs in the atmosphere may be used to estimate human exposure to MPs, particularly through dust consumption. A pollutant delivery medium for additional hazardous substances such as DDT and hexachlorobenzene is MPs [103].

Table 6. Summary of abundance of MPs in aquatic organisms.

Studied organism	MPs type	MPs size	MPs concentration	Ecotoxicological effects	References
Zooplankton taxa	PS	0.4–30.6 µm	3,000 beads/ml (7.3 µm); 2,240 beads/ml (20.6 µm); 635 beads/ml (30.6 µm)	Ingestion rates decreased	[90]
Pacific oyster larvae	Fluorescent PS, animated PS (PS-NH_2), carboxylated PS (PS-COOH)	0.07, 0.16, 0.87, 1.84, 4.1, 7.3, 10.2, and 20.3 µm fluorescent PS0.99 µm PS-NH_2,0.94 µm PS-COOH	1, 10, 100, or 1,000 particles/ml	Ingestion rates decreased (1 µm PS)	[223]
Palaemonetes pugio	PS, PP, PE	30,75 µm PS34, 93 µm PP35, 59, 83, 116, 165 µm PE	50,000 particles/l	20%-55% mortality	[224]
Mytilus edulis L.	HDPE	<80 µm	2.5 g/l	Granulocytomas formation increased, lysosomal membrane stability decreased	[225]
Dreissena polymorpha	PS	10 µm and 1 µm	50 mg/l	Significant modulation of CAT and GPx activities, significant increase of DOP level	[226]
M. edulis L.	PS	2, 3 and 9.6 µm	0.51 g/l	No significant biological effects	[227]
Xenopus tropicalis	PS	10 µm and 1 µm	10, 10^3 and 10^5 particles/ml (1 µm);0.1, 10 and 10^3 particles/ml (10 µm)	-	[33]
Danio rerio	PS	5 and 20 µm	20 mg/l	Inflammation, oxidative stress, and alterations of metabolic profiles in the liver, disturbed the lipid and energy metabolism	[228]
Brachionus koreanus	PS	0.05, 0.5, and 6 µm	10 mg/l	Oxidative stress and lipid peroxidation	[229]
Paracentrotus lividus	PS	40 nm PS-COOH50 nm PS-NH_2	2.5, 5, 10, 25 and 50 µg/ml PS-COOH ;1, 2.5, 3, 5, 10 and 50 µg/ml PS-NH_2	Malformation of embryos, modulation of gene expression	[230]
Euphausia superba	PE	27–32 µm	29 beads/ml or 400 ng/ml	No mortality and weight loss	[231]
Daphnia magna	PE	1–5 µm	10^4 particles/ml	Delevated mortality, increased inter-brood period, decreased reproduction and food intake	[232]

Research on MPs bioaccumulation in the environment is still in its infancy; not much is known about it in freshwater, marine, or terrestrial settings, and it has not been looked into in connection to the atmosphere yet [104]. Phthalates and other plastic constituents have been shown in previous study to have deleterious effects on human health, including endocrine disruption from bisphenol A (BPA) and altered gene expression, shorter gestation lengths, and lower birth weights from DEHP [105]. Additionally, there is proof that phthalates, such as BPA, are present in the environment in significant amounts as aerosols (up to 174,000 pg m^{-3}) [106]. Although the impact of air MPs, their chemical constituents, and the contaminants they have absorbed on human and ecological health is unclear, the possibility that micro- and nanoplastics will have an impact on this is concerning [107]. MPs interactions with metals and other OPs in the atmosphere, as well as their effects on human health, the environment, and ecosystem health, are mostly unknown and require further research.

5. ANALYSIS METHODS OF MPS

Monitoring work employs a wide range of methodologies to better understand the effects of MPs on the ecosystem. Three steps make up a thorough examination of MPs: MPs recovery, identification, and quantification, as well as MPs collection [108].

5.1 Collection of MPs

5.1.1 Water samples

MPs typically float on the water surface or suspend in it due to their density. Water column sampling and manta trawls are hence often utilized tools. The mesh size of the sample equipment has a direct impact on the amounts of MPs that are retrieved from the aqueous matrix. The use of sampling instruments with varying mesh sizes complicates the comparison of the available monitoring data. The sample instruments range in mesh size from tens of microns to millimeters, with 300 to 333 µm being the most commonly used aperture sizes. Half of the trawl was submerged in water to guarantee the highest possible collection of MPs at the surface [109]. The local wind speed and trawling time had an impact on the collection efficiency as well. Researchers made the decision to periodically gather samples equally and at varying wind speeds in order to lessen the impact of wind speed on the collection process. The wind usually dictates the direction of the sampled trawl [110]. Furthermore, if the trawling duration was excessively prolonged, trawls would be obstructed, which could cause the measured abundance to be lower than the actual one. The water collector device had a cylindrical main form with an in-outlet at both ends. Recently, a better water collector composed of metal components was implemented. This one's ability to acquire volume sets it apart from the previous one. The new one can gather about 100 l of material in a run, which explains why samples include so many MPs. Water samples are filtered directly beneath the pump's operating mechanism via a metal filter with a mesh size of 300 μm that is positioned in the middle between the inlet and the pump. Lastly, collecting the filter membrane is also simple. One of the benefits of this equipment is that it lowers shipping costs [111], but this approach has certain drawbacks. Keeping the pump running continuously without running out of power was a challenging task. Afterward, high-frequency replacement of the filter membrane was necessary due to frequent blocking. Following the final stage of sampling, samples were treated with 5% formaldehyde or ethanol and kept in a low-temperature storage area until testing.

5.1.2 Soil samples

Obtaining representative samples of soil is made more challenging by the ease with which human activity can alter the samples. It is advised to employ composite sampling, which combines and homogenizes samples from several distinct sites within the same sampling area into a single sample [112]. The most widely used procedures use small sampling units (1 × 1 m, 15 × 15 cm, and 20 × 20 cm) [111,113]. Stratified samplings should be used to determine the depth of pollution [109]. Soil sampling tools include shovels, metal grabs, box corers, and stainless steel corers [114,115]. Typically, non-plastic bags, such as glass bottles or aluminum foil bags, are used to hold soil samples. Prior to examination, the soil samples were allowed to naturally dry by air at 4°C.

5.1.3 *Atmospheric samples*

Dust [116], atmospheric fallout [117], and suspended atmospheric MPs (SAMPs) [118] are the main types of air samples among studies. MPs in the air are sampled using active samplers and passive atmospheric deposition. Passive atmospheric deposition is always associated with dust and atmospheric fallout. In order to prevent plastic contamination, samples of street dust were gathered by carefully sweeping the study area with a local antistatic hardwood brush made from dried plant stems and a steel pan [116]. A glass bottle and a fixed support were attached to a sample equipment, which was used to collect the fallout [117]. A 20-l glass bottle was positioned at the bottom of the funnel to collect the water, and a stainless-steel funnel was used to collect fallout. To make it easier to collect particles stuck to the funnel, water was used to rinse the funnel. For unobstructed sampling locations such as squares and building roofs, passive atmospheric deposition is always appropriate. This technique enables investigators to move and carefully preserve samples on a regular basis while also enabling long-term continuous collection in distant places without power assistance [119]. SAMPs are often collected using an active sampler system, which consists of a filter-equipped device and a pump. Over the course of an hour, SAMPs were gathered using an intelligent middle flow total suspended particle sampler, model KB-120 F, with an intake flow rate of 100 ± 0.1 l/min, in triplicate. For each sample, this apparatus has a 6 m^3 filtering capacity. In order to replicate human inhalation, the filtering device was positioned horizontally between 1.2 and 1.7 m above the ground [120]. In contrast to the passive sampling method, this approach may quickly complete the collection and modify the flow rate and time in accordance with various needs [121]. In particular, it is important to document the weather during the sample procedure in order to have a deeper understanding of how variations in the weather affect the quantity of MPs. In conclusion, depending on the goals of the study, sample locations, height, time of day, weather, and sampling techniques must be taken into account.

6. MPS STATUS IN INDIA

India needs to make coordinated efforts in waste management, recycling infrastructure development, and public awareness initiatives to combat MPs pollution. Improving wastewater treatment infrastructure, promoting eco-friendly alternatives, and fostering sustainable purchasing habits are essential measures in reducing the harm MPs in India cause to the environment and to people's health. According to India, MPs come from a variety of sources including plastic waste generated by business businesses, households, and other public spaces. Inadequate waste management practices, such as insufficient garbage collection, disposal, and recycling, cause an environmental buildup of plastic waste. MPs may also be released during the washing of synthetic textiles as well as during the breakdown of larger plastic products such as bags and packaging.

India with its numerous rivers, lakes, and coastal areas in aquatic ecosystems that are vulnerable to MPs pollution [122,123]. Sources of MPs in aquatic ecosystem include the discharge of inadequately or improperly treated wastewater containing MPs, the disposal of plastic waste in water bodies, and the use of plastic mulch films in agriculture. Aquatic organisms can consume these MPs, potentially introducing them into the food chain [123]. India's atmosphere contains MPs as airborne particles [8]. MPs' air pollution is particularly common in urban areas with large population densities, industrial activity, and transportation congestion. MPs are present in the air due to wind dispersion from open landfills, burning of plastic debris, and vehicles [124]. MPs threaten India's various ecosystems, which have a negative impact on ecosystem health. They can affect marine and freshwater organisms in aquatic habitats, including fish, shellfish, and other aquatic flora [13]. The consumption of MPs by these species has the potential to hurt them physically, obstruct their digestive systems, and maybe move MPs up the food chain. The influence of MPs on soil health, nutrient cycling, and potential consequences on terrestrial species are also raised by the presence of MPs in soil [125].

The plastics sector in India is rapidly expanding. Of the regions that consume plastics, Western India accounts for the highest share (47%) and is mostly concentrated in the states of Gujarat, Maharashtra, Madhya Pradesh, Daman and Diu, Chhattisgarh, and Dadra and Nagar Haveli. As a significant consumer, India produces over 26 million metric tonnes of plastic garbage annually from its average annual use of 11 kg of plastic per person [14]. Increased adherence to the plastic surface causes other species to be recruited or lost from the biofilm, and eventually this competition or the combined impacts of various bacteria forms a mature biofilm. Plastic waste is likely to endanger public health and reduce diversity while devaluing the aesthetic value of the aquatic environment [126].

The Indian government has taken action to address plastic pollution, particularly MPs. The "Plastic Waste Management Rules," published by the Ministry of Environment, Forest, and Climate Change in 2018 aim to regulate the production, distribution, and use of plastic products. The "Swachh Bharat Abhiyan" (Clean India Mission), and among other initiatives, has been undertaken by the government to encourage the cleanliness and ethical trash disposal [127]. India is increasingly recognizing the pollution caused by MPs. Studies are being conducted by academics and environmental groups to determine the scope and effects of MPs pollution in various parts of the country.

7. MPS POLLUTION AND INTERNATIONAL RESPONSE

Public awareness and responsive activities have increased due to concerns about the effects of plastic and MPs pollution. Schools have implemented plastics education programmers, non-governmental organizations have started campaigns, and some businesses have promised to reduce their use of plastic [24]. The USA passed the Microbead-Free Waters Act in 2015 as part of a global response to the worsening MPs issue, outlawing the use of plastic microbeads in the production of personal hygiene products [128]. Furthermore, a number of nations, particularly those in the European Union, have begun to phase out the use of plastic microbeads in a variety of items, including cosmetics [129]. In 2018, Europe promoted the recycling of plastic products by adopting the "European Strategy for Plastics in a Circular Economy" and putting additional environmental protection programs such as "Zero Plastics to Landfill" into action [130].

A study Du *et al.* [131] documented that the USA leads the world in plastic garbage production (42 million metric tonnes yearly), followed by the European Union, India, China, Brazil, Indonesia, the Russian Federation, Germany, and other nations. Beginning in 2020, China promoted "Opinions on Further Strengthening the Control of Plastic Pollution" at the level of the Far East nations [132]. It follows that most nations definitely want to phase out plastics and look for sustainable substitutes. Over 150 countries' environment ministers made a commitment to significantly reduce the use of single-use plastic products (SUPs) by 2030 during the fourth United Nations Environment Assembly in March 2019 [131]. Following an earlier assembly resolution emphasizing the need for long-term ocean MPs cleanup, this step was taken. Furthermore, in May 2019, governments decided to amend the Basel Convention by formally requesting the importing nations' approval for contaminated plastic waste, as agreed upon 3 years prior [133]. Furthermore, in an effort to reduce the manufacture of these plastic materials, numerous nations across the world are now imposing fees on plastics that cannot be recycled [134].

8. CURRENT KNOWLEDGE AND AWARENESS OF MPS POLLUTIONS

There are many interconnected environmental challenges in the world today, such as the link between biodiversity loss, climate change, and MPs pollution [135]. The association is readily explained by the significant amount of GHGs produced during the production of products based on MPs that need fossil fuels. As a result, after utilizing these goods, their waste products are discharged into the aquatic environment, where they negatively impact all living things, including top consumers, phytoplankton, and zooplankton [136]. This causes the ecosystem as a whole to become disturbed, leading to the irreversible loss of species and ecological diversity.

It is important to note that one of the main strategies and necessary first steps in addressing and managing all of these concerns is for the public to have a thorough understanding of environmental challenges, including its origins, effects, and mitigation strategies. However, the process of mitigating environmental challenges, notably MPs pollution, is hampered by a lack of fundamental understanding, unclear facts, and unambiguous information [137]. The problem is further compounded by widespread misconceptions among the general population, especially educated people, regarding the differences between plastics and MPs and the challenges associated with recognizing specific products made of MPs. This can be addressed by putting in place a number of measures, which will be covered in detail in this part, to raise public awareness of the issues surrounding MPs and encourage the creation of workable solutions.

Ensuring that all facets of MPs issues, including their many sources, types, effects, destinies, and other relevant elements, are taught in curricula at schools and universities is the first step toward MPs control. Students and young people can learn about this topic as early as possible by being introduced to it. This strategy might be put into practice by having students learn about the problem of MPs through a variety of topics, as recently shown at US high schools in the San Diego region [138]. Students should also be encouraged to write scientific papers and take part in research projects in order to gain a strong understanding of the subject and provide workable solutions for MPs problems. The American Chemical Society has provided a perfect example of this kind of strategy by introducing new rules to the plastics and polymer industry as well as cutting-edge research approaches to bachelor's students in the USA [139].

In many nations, including the UK, the public's knowledge of MPs has increased thanks to the media. For instance, the British Broadcasting Corporation has created a number of television programmers and documentaries that encourage people to refrain from using SUPs by presenting the problem of plastic pollution in an approachable and straightforward manner. By these initiatives, the media has encouraged individuals to use less plastic and assisted in educating the public about the effects of MPs on the environment [140]. The media is in charge of educating the public, disseminating guidelines, and assisting political parties, constitutional authorities, and legislators in reaching just choices and practical solutions for a number of pressing environmental challenges [141]. Furthermore, the internet and its various social media platforms have emerged as a potent resource for comprehensive and broad scientific information regarding MPs [142].

The public's view of consumerism is another strategy. Due to the industrial revolution that began in the 18th century and, more notably, the substantial economic growth and affluence that followed World War II, excessive consumerism became the norm in the majority of countries [142]. People began to live a lavish lifestyle as a result, and they began to place greater importance on purchases and those who made larger ones. One of the primary causes of the substantial growth in trash production was this social conception, which extended beyond MPs to include other waste products including food, medicine and cosmetics, clothing, and electronic devices such as computers and phones [143]. While it may not be an easy challenge to change the way people behave in society, it is imperative to help governments manage the growing problem of MPs and limit the massive amounts of waste materials released into the environment.

It is important to note that government initiatives have successfully decreased the use of plastic in several nations. For instance, several nations have imposed price increases, tariffs, or bans on plastic carrier bags in an effort to encourage people to use reusable bags and drastically cut down on plastic usage. After a plastic bag ban was implemented in China, the country's consumption of plastic bags fell by 49% [144].

After a plastic bag tax was implemented in Washington, the state saw an 80% decline in the use of plastic bags [145] and the UK experienced 8%–85% decreases following the introduction of a plastic bag fee. These instances highlight the major influence that laws and regulations may have on cutting down on plastic usage and addressing the problem of MPs in the environment. The policies' implementation was not without its difficulties, considering the many advantages that plastic carrying bags provide, including durability, longevity, and water resistance. Nonetheless, the positive outcomes showed how well limits, international collaboration between various countries, and most importantly raising public awareness may reduce the use of plastics and MPs.

9. LIMITATIONS AND FUTURE PERSPECTIVES

The majority of MPs pollution in ecosystems is released by human-caused activities such as daily living, business, transportation, and agriculture. Currently, there are problems with MPs pollution linked to hazardous substances that have a negative impact on the ecosystem [146]. It has been found that MPs live in an environment where dangerous substances can act as a vector for their movement throughout ecosystems. The presence and dispersion of MPs in ecosystems may have an impact on human food supplies as well as fresh and marine habitats [147]. Because MPs are unable to break down, they build up in plants and animals throughout the food chain and seriously harm both the creatures and humans.

It is possible to suggest important prospective tactics to address these problems, such as implementing technical standards and laws, raising awareness, and developing engineering solutions It has been found that microorganisms (such as bacteria and fungi) obtained from biota facilitate the biodegradation of MPs aging [148]. It was also investigated how highly efficient cutting-edge technology, such as membrane bioreactors, maybe, with clearance rates of up to 99%. The aging process of MP can be effectively accelerated by applying advanced oxidation processes and photo catalytic technology to eliminate MP contamination.

MP particles linked to chemical toxicity and microbiological toxins may have an impact on human health. It draws attention to the in-depth knowledge research deficit and makes fundamental research recommendations for scientists and policymakers [149]. Future studies that clarify MPs function as important sources of hydrophobic organic contaminants and HMs in the environmental media are crucial. MP debris can travel infinitely through the atmosphere and soils, and its impact on both terrestrial and aquatic environments must be carefully considered [150]. Evaluating transport mechanisms, MP contamination fate and pathways, and ecological sinks is crucial.

The carbon cycle, wildlife, human health, and biodiversity are all seriously threatened by the presence and behavior of MPs in freshwater and marine sediments [151]. To fully comprehend MP contamination sources and explore the ecological impacts of MPs in various ecosystems, more research is required. Developing a database on the distribution and travel behavior of MPs is crucial in order to investigate the environmental risks that MP-conveying OPs pose as well as their effects on ecosystems. Effective management methods can be created to mitigate MPs contamination and its associated ecological effects by carrying out comprehensive research and effect evaluations [152].

The ability of biological technologies to directly degrade MPs is restricted. Consequently, it is necessary to look at laboratory-accelerated testing that can replicate various aging processes and variables [153]. Additionally, microbial remediation presents a viable alternative for MP breakdown; nonetheless, additional effective microbial strains have to be obtained and fostered [154]. Their efficiency of degradation can be paired with cutting-edge treatment methods. As an alternate strategy to raise environmental consciousness and protect the environment, commercial plastic items made from natural resources should be taken into consideration. By reducing their carbon footprint, bio-derived polymers can help accomplish the circular economy and the Sustainable Development Goals by removing SUPs. The properties of MP polymers and dangerous micropollutants must be incorporated with the ecological effect evaluation or exploration. Specifically, it is important to understand how MPs could affect the (eco) toxicity of PAHs in their natural environments.

10. CONCLUSIONS

Plastic items are widely utilized and difficult to break down; thus, it is certain that plastic pollution will have an ongoing negative impact on the ecological environment for a very long time. The consequences of MPs on the environment have been brought to light recently. A glaring example of the magnitude of the plastic problem is the quantity of plastic that has ended up in the environment, including the land, ocean, and even the air. The ecosystem's balance will be upset and the animal population will be impacted by MP's pollution. If management operations are not handled well, this will happen. The eco-toxicology of MPs, their source distribution, migration, and transformation, as well as enhanced analytical techniques for sampling, classification, and identification, and the ecological health risk assessment system for MPs pollution should all be further investigated in the future. More research is required to understand the toxicological mechanism and influencing factors of MPs. To prevent harm to human health, pay attention to the transfer effect of MPs in the food chain, as well as their transfer path and control measures. Scientific innovation would have to receive more attention since it would facilitate the production of environmentally suitable substitutes for plastics. Furthermore, the present review would indicate MPs are a global issue and all nations should encourage their monitoring strategies collectively in order to estimate MP abundances globally. Additionally, lawmakers and the government should enact laws with force, impose “zero tolerance” on the use of megaplastics and MPs, and require corporations to substitute biodegradable components for non-biodegradable components. To address the issues and reduce plastic pollution, governments, businesses, international organizations, and consumers must work together.

11. CONFLICT OF INTEREST

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This study does not involve experiments on animals or human subjects.

14. PUBLISHER’S NOTE

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The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

16. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

17. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

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