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Review Paper

Entry Pathway and Potential Impacts of Microplastics in Air, Water, Soil and Human Health: A Review

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ABSTRACT

In this study, we discuss the existence and impact of microplastics (MPs) in different ecosystems, including water, soil, air, and the human body, as well as the absorption of pollutants into these microplastic particles. Airborne MPs have been detected in the atmosphere as well as indoors and outdoors. MPs in the air, in addition to inherent toxicity, may cause more risks to human health and the environment than virgin MPs through the absorption of pollutants and chemicals. Due to the widespread use of plastics around the world, the abundance of MPs in aquatic environments has increased. MPs can be ingested by a wide range of marine organisms, so it is possible that contaminated MPs cause mechanical damage to organisms and there is also the possibility of contamination being transmitted to marine organisms and the marine food web. Accumulation of MPs in the soil can cause them to be absorbed by plants and transport these MPs particles and pollutants absorbed by them along the food chain. Highly populated urban centers, industries or large-scale agriculture are the main causes of soil contamination by MPs. MPs can find their way into the food we eat, the water we drink, and even the air we breathe. Researchers were able to find MPs particles in all human tissues studied.

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Introduction

Plastics are synthetic organic polymers, light weight, high strength, low price and affordability are the reasons for their widespread use etc. are used [1]. During the past few years, plastic has become a widely used product with different chemical composition, properties and applications. In the past, people thought that plastics were harmless and ineffective, but over the years of disposing of plastics in the environment, the associated dangers have been realized. During the past few decades, plastic waste has caused widespread pollution of land, air and water ecosystems. They are known as a major environmental burden, especially in the aquatic environment [2]. The biophysical decomposition of plastics in aquatic environments requires a lot of time [3] and their negative effects on wildlife are undeniable and the options for removing plastics in aquatic environments are also very limited [4].

Larger plastic waste breaks down into smaller pieces due to weathering and ultraviolet rays, and those that reach a size of less than 5 mm during these destructive processes are called microplastics (MPs) [5]. The increasing abundance of MP particles in different environments, including air, water and soil, has caused an increase in concern about their impact. Humans can encounter MPs in different ways, MPs have been found in various food items such as sugar, table salt, bottled water and even house dust [6].

The presence of MPs in the environment can be proven through aquatic studies. For this purpose, we use the analysis of plankton, sand and mud sediments, as well as marine organisms. Through such methods, it has been proven that there are MPs from various sources in the environment of humans and animals [7]. In 2017, the International Union for Conservation of Nature (IUCN) reported that MPs account for 30% of Pacific Ocean debris, and in many developed countries, they can be a greater source of pollution than larger marine litter [8].

The toxic effects of MPs can occur through several mechanisms. First, toxicity can be caused directly by the polymeric materials used to manufacture plastic products. Polystyrene (PS) is a good example, which is widely used in protective packaging, containers, bottles and lids, but it has been found that it can be transported in the bloodstream and interfere with the reproduction of marine filter feeder such as many fishes and some sharks, bivalves, krill and sea sponges [9]. Secondly, the small size and sharp ends of MPs harm organisms and cause inflammation in them. It has been proven that consumption of MPs can cause malnutrition and changes in reproduction for some organisms [10].

Some review articles have been published regarding the impacts of MP on humans' health. But, unlike other review studies, this study examines the presence of MPs simultaneously in different environments of air, water, soil, and human body, thus enabling the comparison of the abundance and characteristics of MPs in air, water, and soil environments. In addition to receiving MPs through breathing and digestion, which are the more well-known routes, this study also deals with receiving these particles through intravenous injection and examines the presence of MPs in the air, separating indoor and outdoor air. Ways of entering MPs into marine environments and the impact of these particles on marine organisms have been discussed, and also ways of entering MPs into soil, its impact on organisms and soil structure, and their fate in this environment have been evaluated [11-14].

Adsorption of Pollutants to MPs

Organic materials

Absorption is a process in which chemicals are transferred from fluids (liquids and gases) to solids [15]. The results of various studies show that the interaction (adsorption and excretion) between chemicals in aquatic ecosystems, especially pollutants and MPs, is selective. There are two internal and external factors for this selective behavior. Intrinsic factors depend on the main properties of the two interacting substances. The type of MPs has an effect on the amount of pollutant absorbed by them, and even in one type of MP, the absorption effect of unrefined and old MPs is very different from virgin MPs. Polarity, which is the opposite of adsorption, is also a very influential factor in the interaction between chemicals in water and MPs. Studies have shown that the nature of most organic pollutants introduced into the aquatic environment is hydrophobic compounds. Therefore, specific pollutants and types of MPs were the two key factors that determined the adsorption capacity of MPs to hydrophobic organic compounds. It was also found that the external factors that affect the absorption and excretion of environmental chemicals on MPs include: The pH value and the salinity value of the water environment, as well as the strength of the background particles in the water environment [16].

The large surface area of MPs is the main factor in the absorption of organic pollutants from the environment [17]. In addition, previous studies have shown that nanoplastics have a larger surface area than MPs, and therefore their tendency to absorb organic pollutants from the environment is more [18]. In one study, the concentration of persistent organic pollutants (POPs) on the surface of MP particles was about six times higher than the concentration of this pollutant in the water surrounding MPs [19]. Therefore, when organisms ingest MP particles, it causes them to be more exposed to toxic pollutants and organic compounds. However, it seems that the attraction of organic pollutant to MPs is weaker than that of activated carbon. Organic compounds in aquatic environments have strong toxicity and long retention time. Both MPs and organic pollutants have undeniable negative effects on the environment, which necessitates the study of the interaction between MPs and organic pollution [20].

Antibiotics

Antibiotics are a group of emerging contaminants, which are widely used due to their antimicrobial effects. The release of antibiotics in the environment is increasing day by day. China alone released 53,800 tons of antibiotics into the environment in 2013 [21]. MPs can absorb antibiotics, thereby causing their long-term migration and causing complex effects. According to Quan et al.'s research, tetracyclines, macrolides, fluoroquinolones, and sulfonamides are among the antibiotics that were found abundantly in the global aquatic environment. Quan et al. (2019) also proved the dangers of antibiotics remaining in water for aquatic organisms. If antibiotics are absorbed into MPs and ingested by aquatic organisms, the combined pollution of these two substances will be more toxic to organisms living in aquatic ecosystems [22].

The adsorption properties of five antibiotics on five different MPs were studied. The studies of Li et al. (2018) showed that the surface characteristics and degrees of crystal connections are different in different types of MPs. Therefore, different MPs have different absorption capacity for antibiotics. Polyamide (PA) has the highest absorption capacity for antibiotics among other polymers due to its porous structure and complex hydrogen bonds [21].

The results of the studies show that it is possible to transfer the heavy metal mercury from MPs to a small seawater crustacean called *Artemia nauplii*. This crustacean, which is the food of eels, can thus cause the transfer of mercury in the food chain [23]. Just as prey animals can ingest antibiotic-laden MPs and transfer them from lower-level organisms to higher-level organisms, heavy metals are also transferred through the food chain to amphibians, fish, corals, and ot`This not only endangers the entire organisms of aquatic ecosystems, but its consequences for organisms at the top of the food chain, such as humans, are undeniable.

To assess environmental risks in a variety of aquatic ecosystems, understanding the interactions between different types of MP polymers and different antibiotics is essential. A series of diagnostic tools were used to determine differences in specific surface area, pore size distribution, crystallinity, and other chemical and physical properties for different types of MPs. This was used to evaluate the difference in the absorption and loading capacity of antibiotics with different types of MPs [16].

Heavy metal

Heavy metals are non-degradable mineral pollutants that cause poisoning, cancer and chronic diseases for humans through bioaccumulation. Many sources can be the cause of heavy metal pollution in aquatic ecosystems. Human factors are increasingly affecting fresh water and sea water, while the natural environment is the main factor affecting irrigation water and clear water of streams. Despite the difference in the sources of heavy metal pollution in fresh water and sea water, there is a common source of heavy metal pollution between them, which is the use of anti-rust and anti-pollution paint for ports, docks and hulls. The reason is that these anti-rust and anti-moss paints contain many heavy metals. Similarly, there is a high concentration of MPs as a result of human activities in bays and estuaries [24-26]. The mechanism of metal adsorption on plastic may be diverse and complex [27].

During the last few decades, much attention has been paid to the interaction of heavy metals and different MPs. According to the studies of Brennecke et al. (2016), two types of MPs, polyvinyl chloride (PVC) and PS, have high absorption power for two heavy metals copper and zinc, these metals leak from anti-moss paint. In addition, the concentration of MPs as well as heavy metal pollution in water is strongly influenced by human activities [28].

Scientists like Almeida et al. (2019) compared the adsorption rate of copper and cadmium in various MPs, such as fishing hook fibers, plastic bag films, polyethylene microspheres and bottle cap fragments. As a re-

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sult, the researchers found that the aging of MPs and the absorption of metallic copper were not significantly changed by salinity [29]. In the cadmium absorption test, it was concluded that the type of environment as well as the type of MP affects the amount of cadmium absorption [30]. For example, the presence of C-O, N-H bonds in PA MPs leads to a high adsorption capacity for Cd compared to other MPs (i.e. PS, PVC, acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate [PET]) [31].

Heavy metals and MPs are pollutants with high abundance in aquatic ecosystems. A study by Tang et al. (2020) was conducted to evaluate the effect of contact time, pH, temperature, concentration of supporting electrolytes and folic acid on the absorption of lead metal in water by old nylon MPs. The results indicate the spontaneous and endothermic nature of lead uptake by old nylon MPs [32].

MPs in Environmental Health

Air

MPs have been detected not only in water and soil, but also in air, which is a potential source of exposure through inhalation, For example, Shruti et al. in 2020 detected MPs in public drinking water fountains in 42 different metro stations in Mexico City. These contaminated decorative/drinking public fountains can spray MPs into the air along with water, which may be a potential source, but its contribution to airborne MPs is underestimated [12]. Airborne MPs in terrestrial environments are the result of wind erosion, inhalation is the main route of exposure to airborne MPs [33]. As a result of inhaling airborne MPs, various problems may arise, including respiratory and cardiovascular diseases or even cancer [34].

Studies confirm that plastics involved in packaging applications such as PS, polyethylene (PE) and PET degrade and are capable of releasing MPs into the air at a much faster rate than water [35]. Therefore, the possibility of exposure to airborne MPs is very high for workers working in industries (mainly polymer, packaging, textile industries) [36], but the effectiveness of personal protective equipment used for them is not known. The risk factors associated with MPs increase with the weathering of plastic waste in exposure to environmental conditions. There are many differences between the weathering mechanisms and behavior of airborne MPs and terrestrial and aquatic MPs [37].

MPs that are exposed to environmental conditions such as UV rays and hydrological conditions (turbidity) are more dangerous to humans and the environment than fresh MPs due to weathering and aging [38]. Mao et al. (2020) investigated the processes of aging and long-term absorption of MPs in air, seawater and fresh water and observed the formation of carbonyl bonds (C=O) in aged airborne MPs at high temperature (75 °C). Since the bond (C=O) is highly reactive, it changes the surface texture and characteristics of MPs (pores, grooves), which can enhance their adsorption behavior [37].

MPs that have been exposed to air are able to adsorb copper and tetracycline more effectively than virgin MP particles (not exposed to air) [39]. Therefore, in addition to their inherent toxicity, aged airborne MPs may pose higher risks to human health and the environment than virgin MPs through the absorption of pollutants and chemicals [12].

MPs are capable of adsorbing and desorbing pollutants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), antibiotics as well as additives such as biphenyl A (BPA), phthalates and other endocrine disruptors in the environment [39].

The results of studies indicate the presence of airborne MPs in indoor and outdoor air. In 2019, a study indicated that MPs are transported in the atmosphere by wind to remote areas [40]. A study in 2017 showed indoor air microfiber concentrations between 1 and 60 microfibers per cubic meter (33% of which are MPs) [41].

Reports indicate much higher concentrations of synthetic fibers including MPs inside the building compared to the open space, and these MPs are mainly polypropylene (PP) and PET. Therefore, after these particles sit on the surfaces, It is possible for infants to swallow during normal oral behaviors [42]. Due to their long-term presence at home, the elderly can easily be exposed to these MPs particles for a long time and be affected by them [43]. Given that people in high-income countries spend about 90% of their time indoors, assessing indoor exposure through inhalation is critical to understanding the potential health effects of MPs. Although studies have proven that due to the excellent inhibitory properties of adult skin as well as the surface characteristics of plastic particles, the possibility of exposure to MPs and nanoplastics is low in this way, the degree of vulnerability of children's skin is not fully known. The skin barrier of adults is different from the skin barrier of babies and children. There is little evidence for transport of nanoplastics larger than 100 nm [44].

Table 1. Overview of the worldwide documentation studies on MPs in air

Country	Sampling Site	Forms of MPs	Abundance of Microplastics	Sampling Method	References
Australian (Southeast Queensland)	Seven different locations where people spend most of their time and the outdoor sample was taken outside the office	Mostly fibers	Concentration (indoor): 0.20 to 2.25 particles/m^3 Concentration (outdoor): 0.17±0.06	Active sampling technique	[56]
Korea (Seoul)	Five outdoor environments	Mostly fragments	Average number: 0.72 m^{-3}	Active sampling technique	[57]
Atmospheric MPs in the Northwestern Pacific Ocean	11 atmospheric samples	Mostly fibers	0.0046 to 0.064 particles/m^3	Intelligent high-flow atmospheric particulate sampling	[58]
India (Chennai, Tamilnadu)	Street dust (urban)	Mostly fragments	Abundance: 227.94±91.37/100 g	Passive sampling (street dust collectors)	[59]
Australia (Victoria)	Roadside dust (urban and rural)	Mostly fibers	Abundance: 20.6 - 529.3 items kg^{-1}	Street dust sampling	[60]
Iran (Asaluyeh City)	Street dust from 2 sampling stations (an industrial zone and an urban zone)	Mostly microfibers and filaments	Total concentration: 13,132 MPs and 3691 MRs from 15 samples	Particulate dust sampling (active sampling: Ambient filter)	[61]
Iran (Tehran)	Roadside dust from 10 sites in the central district	Microfibers and fragments (2649 particles)	Highest concentration: 605±10 particles/30 g dry dust	Street dust collection by gentle sweeping	[49]
France (Paris)	Indoor (2 apartments and an office room), outdoor (building roof) air	Mostly microfibers	Concentrations: 0.9 fibers m^{-3} (outdoor), 5.4 fibers m^{-3} (indoor)	Passive sampling (dust fall and deposition for 4 seasons)	[62]
Germany (Hamburg)	6 sampling sites in Hamburg City (selected based on population density)	Mostly fragments and fibers	Deposition rate: 275 particles m^{-2} day^{-1}	Passive sampling (atmospheric deposition)	[63]

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In a study conducted by Catarino et al. (2019), exposure to MPs through household airborne particles was higher compared to consumption of contaminated oysters [45]. In the urban environment of China, the daily exposure of children to PET through dust particles inside the building was estimated to be 17300 ng/kg of body weight [46]. Vianello et al. (2019) showed that exposure to natural microfibers (91%) was higher than synthetic (plastic) microfibers (4%) through a thermal manikin test with indoor breathing in 3 residential apartments (Denmark). Nevertheless, the results of this study indicate that fibrous MPs are smaller than natural fibers, which makes them easier to inhale [47].

In a study conducted on saliva, hair, and skin in Iran, PE, PET, and PP fibers (sourced from indoor and outdoor environments) were widely and consistently present in all collected human hair samples, indicating Exposure to a source of MP particles. This study concluded that human hair can absorb and trap MPs suspended in the air due to its high surface area and many twists that create an electrostatic charge in it. Among these MPs, we can mention the fibers released from clothes, furniture, etc. These entrapped MPs may enter the human body through the scalp, although this has not been proven [48].

Another study investigated MPs in the street dust of Tehran and found 2649 MPs particles in 10 street dust samples. The frequency of MPs in the samples varied from 83 particles to 605 particles (±10) per 30.0 grams of dust [49]. MPs were also found in snow samples [50] and in clean high altitude air at great distances from their source [51]. However, as with freshwater and soil ecosystems, further studies are needed to understand the impact and significance of airborne MPs [52]. Figure 1 shows airborne MPs at indoor air.

Hair follicles, sweat glands or damaged skin are all entryways for MPs [53]. In addition, studies have shown that it is possible for particles below 100 nm to pass through the skin barrier and they can penetrate the human

Figure 1. Entry of MPs particles into indoor

body through the skin [33]. Chemicals used in cosmetics and personal care products and their fragmentation may lead to hazardous nanoplastics [54]. Furthermore, Kuo et al. (2009) proved that chemical enhancers, such as oleic acid and ethanol, can enhance the transport of nanoplastics through the skin [55]. In Table 1, several studies of airborne MPs around the world are shown in terms of abundance, sampling method and sampling location.

Water

MPs in water environments such as ponds, reservoirs, lakes, and rivers are formed as a result of the destruction of large plastics by wind, rain, sunlight, and hydraulic turbulence [64].

As a result of the increasing use of plastic materials, the abundance of MPs in aquatic environments has increased. For example, MPs can be found in sandy beaches, surface waters, in the water column, and deep sea sediments. They were also found in many other types of marine particles such as dead biological material (tissues and shells) and some soil particles that are blown into the water by the wind and transported to the ocean by rivers [65, 66]. Population density and proximity to urban centers are considered to be the main factors affecting the abundance of MPs in the environment. Figure 2 shows the entry of MPs from different environments and their effects on aquatic organisms.

In one study, MPs were found at an abundance of 96 particles in a sample of East Antarctic ice in 2009. These MPs were of 14 different chemical compositions. Plastic pollution has previously been documented in Antarctic surface water and sediments, as well as in Arctic sea ice, but this is believed to be the first time plastic has been found in Antarctic sea ice [67].

The widespread presence of MPs in aquatic environments around the world is evident in various studies [68]. The first study on MPs in freshwater ecosystems was published in 2011, which showed an average of 37.8 pieces/m^2 of Lake Huron sediment samples. Furthermore, studies have shown that MPs are present in all Great Lakes with an average concentration of 43,000 particles/Km^2 [69]. MPs have also been detected in freshwater ecosystems outside of the United States. In a three-year study in Canada, the average abundance of MPs was 193,420 particles/Km^2 of Lake Winnipeg. MP pellets were not found in the studied samples, and most of the MPs were fibers from the breakdown of larger particles, synthetic textiles, MPs atmospheric fallout [70]. The highest detected concentration of MPs in freshwater ecosystems belongs to the Rhine River with an abundance of 4000 particles/kg [71].

Global estimates of the occurrence of plastic waste, including MPs that end up in seawater, show that rivers are one of the main sources of plastic pollution, carrying more than 2 million tons of MPs per year [72]. In addition, it has been reported that river transport of plastic waste accounts for 80% of the release from land to marine environments [73].

MPs can be ingested by a wide range of marine organisms, so it is possible that contaminated MPs cause mechanical damage to organisms [74], and there is also the possibility of contamination being transmitted to marine organisms and the marine food web [75]. Studies have proven that bottom feeder fish in a tropical estuary lo-

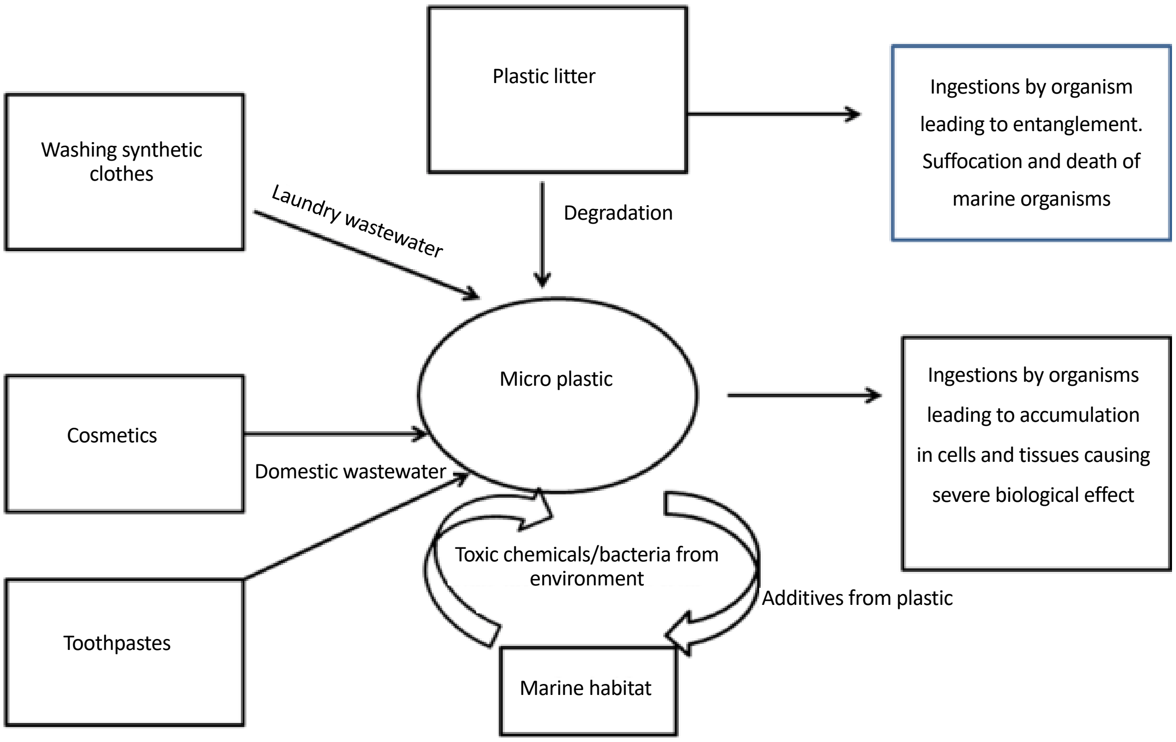

Figure 2. The arrival of MPs from different sources and its negative impact on aquatic organisms

cated in northeastern Brazil were contaminated with MP particles, and the stomach was the organ most affected by the harmful effects of MPs [76]. In the central gyre of the North Pacific Ocean, pollution of plankton-eating fishes with plastic fragments has been proven. The main route of exposure to MPs is ingestion mistaken for bait. Accumulation of MPs (less than 5 mm) in the gut of fish leads to starvation and malnutrition of the fish and eventually leads to death [77]. The results of studies indicate that the length of time that MPs with a larger size (5 mm) remain in the gut of fish is longer compared to smaller beads (2 mm) [78]. This study shows that MPs with a larger size compared to small MPs, it poses a greater risk to marine fish communities because smaller MPs can be excreted through natural feces. The risk of MPs to marine environments is shown in Figure 3.

The presence of plastics, especially MPs, in the food chain is increasing. In the 1960s, MPs were discovered in the guts of seabirds and have since been found in increasing concentrations [79]. Seabirds such as albatross, shearwaters, petrels, and northern fulmar on the surface of the sea, and ingested MPs accumulate in their stomachs. Plastics in the form of industrial pellets were found in approximately 30-35% of seabirds [80].

The impact of various environmental processes, including sunlight, thermal aging, the growth of biological layers and oxidation on plastics in marine and coastal environments, leads to the degradation and fragmentation of plastic polymers [81]. Degradation refers to the breaking of the structure of plastic polymers as a result of a series of chemical reactions and often includes optical degradation, thermal degradation, biodegradation and thermo-oxidative degradation. As a result of the degradation process, secondary MPs are created from the fragmentation of large plastic waste, and these secondary MPs finally enter the environment [82].

In recent years, MPs in aquatic ecosystems have been raised as an important environmental problem. The situation is exacerbated by the fact that even if plastic waste is prevented from ent ring the marine environment, it is likely that the abundance of MPs will increase as a result of the degradation of plastics that are currently in the world's oceans [83]. The mass production of plastic has led to the release of 4.8 to 12.7 million tons of plastic waste in the ocean [84].

The US Environmental Protection Agency (EPA) launched its "litter free waters" initiative in 2013 to prevent single-use plastic waste from entering waterways and ultimately the oceans [85]. EPA is working with

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Figure 3. Dangers of MPs for the marine environment

the United Nations Environment Program (UNEP), the Caribbean Environment Program (CEP) and the Peace Corps to reduce as well as eliminate litter in the Caribbean [86]. Among the various projects that EPA has funded in the San Francisco Bay area is one aimed at reducing the use of single-use plastics such as disposable cups, spoons, and straws [87]. In addition, there are many organizations that work in the field of dealing with MPs and they consider spreading awareness about MPs as one of the basic measures in this regard. One such group is the Florida MPs awareness project (FMAP), which consists of a group of volunteers who look for MPs in coastal water samples [88].

The common chemical composition of MPs in aquatic ecosystems is mainly PP, PE, PS, PET and PVC [89]. The chemical composition of MPs affects their environmental behavior. Those composed mainly of PET and PVC are more likely to settle, while PP, PE and PS float more easily. The chemical composition of MPs affects their environmental behavior. Those composed mainly of PET and PVC are more likely to settle, while PP, PE and PS float more easily [90]. Table 2 shows some studies related to the abundance, type and shape of MPs as well as their extraction method in aquatic environments.

Soil

Accumulation of MPs in the soil can cause them to be absorbed by plants and transport these MP particles and pollutants absorbed by them along the food chain. Urban and agricultural soils, in particular, are considered vulnerable to MPs contamination because they are exposed to MPs due to being in contact with artificial activities. Although there is abundant evidence of MPs in soils, our knowledge of MPs in soil is still incomplete.

MPs have been increasingly studied in soil over the past few years due to their threats to terrestrial ecosystems. Highly populated urban centers, industries or large-scale agriculture are the main causes of soil contamination by MPs [103]. However, studies indicate the presence of MPs in the soils of areas far from development, including pastures [104], where it is believed that the main cause of pollution is the airborne transport of MP particles with air masses [105].

The concentration of soil MPs is increasing significantly and is widely distributed around the world [106]. Korea had the largest annual consumption of plastic worldwide as of 2016. Therefore, the investigation of soil MPs around the world, including Korea, leads to the improvement of knowledge about the sources, abundance and effects of MPs in soil [107]. As a result of the deposition of MPs in the soil, there is a possibility that many of them will eventually enter the aquatic ecosystems.

Table 2. Overview of the worldwide documentation studies on MPs in aquatic environment

Region	Average Microplastics Concentration/Range	Sample Types	Polymer Types	Shape of Microplastics	Sampling Method	References
Zarjub River, Iran	66,730 particle/m^3	Surface water	PA, PP, PE, PS, PVC	Fiber, fragment, films, pellets	Using 45 micrometer stainless steel sieve, density separation using NaCl followed by H_2O_2, Whatman glass filter (47 mm)	[91]
Gohar Rood River, Iran	83,520 particle/m^3	Surface water	PA, PP, PE, PS, PVC	Fiber, fragment, films, pellets	Using 45 micrometer stainless steel sieve, density separation using NaCl followed by H_2O_2, Whatman glass filter (47 mm)	[92]
Ergene River, Turkey	4.65±2.06 items L−1	Surface water	Mostly PET, PA	Mostly fiber	-	[93]
Ergene River, Turkey	97.90±71.72 items kg−1	Sediment	PS Mostly	Mostly fiber	-	[93]
Los Angeles River, USA San Gabriel	13.7 particle L−1	Surface water	PS	Fragment, foam, pellet, film, line	Manta Trawl (333 µm)	[94]
Seine River, France	108 particle m−3	Surface water	Not detected	Fiber	Plankton net (80 µm)/30% H_2O_2 and density separation using $ZnCl_2$	[95]
Pearl River, China	19,860 particle m−3	Surface wate	PE, PA, PP, PVC, VAC	Film, granule, fiber	Using 45 µm mesh; 30% H_2O_2	[89]
Minjiang Estuary, China	1245.8±531.5 items/m^3	Surface water	PP, PE, PTFE, PVC	Fibers, granules	Using 333 µm mesh; filtered through a Sartorius filter 1.2-mm pore size	[96]
Vembanad Lake, India	252.80±25.76 items/m^2	Sediment	HDPE, LDPE, PS, PP	Fragments, films, foam, fiber, pellets	Van Veen grab	[97]
Lake Superior, USA	30,000 items/km^2	Surface waters	PE, PP, PEST, PA, PS	Fibers, fragments, films, foams, pellets	Neuston nets with mesh size 0.500 mm, H_2O_2, Fe(II) solution for digestion organic material	[98]
Bay of Calvi, Mediterranean Sea	0.062 items/m^2	Surface water	–	–	Neuston samples, Separation of plastic particles from zooplankton using gravity	[99]
Iskenderun Bay, Turkey	0.2254 item/m^2	Surface water	–	Filaments, granules, foam, films, fragments	Manta Trawl net with mesh size of 333 µm, 30% H_2O_2, Fe(II) solution for digestion organic material	[100]
Chabahar Bay, Iran	218±17 item/L	Surface water	PE, PET, nylon	Fibers, Fragments, Films, Pellets	48 micrometer stainless steel sieve, 10 ml of H_2O_2, A glass microfiber filter (1.2 mm)	[101]
Chabahar Bay, Iran	262±17 item /kg	Sediment	PE, PET, nylon	Fibers, fragments, films, pellets	Sediment sampling using a metal frame (1 x 1 m), flotation using Nacl, 10 mL of H_2O_2	[101]
Mid-west Pacific Ocean	34,039±25101 item/km^2	Surface water	PP, PMMA, PE, PET	Fibers, fragments	Manta Trawl net with mesh size of 333, 30% H_2O_2 and $FeSO_4$	[102]

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Figure 4. Use of plastic mulch in agriculture

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As a result of the vertical transfer of soil MPs to the subsoil over time, these MPs eventually end up in groundwater. Plastic mulch and sewage sludge are the main contributors of MPs in the soil of rainfed agricultural lands (e.g. potato fields) [108]. Plastic mulch is often used in planting crops to prevent the growth of weeds, and it is also very effective in maintaining soil moisture and optimal soil temperature. The application of plastic mulch is shown in Figure 4.

Sewage sludge can be considered an organic fertilizer that is widely used for wheat growth [109]. The most influential factor of MPs pollution in Korean agricultural land is greenhouses, which is different from other regions of the world. In addition to the use of plastic mulch and wastewater sludge in agricultural lands, improper disposal of municipal waste, wear and tear of tires, and littering are other main sources of MPs in the soil. In terrestrial environments, including natural forests, the only major natural source of MPs is MPs deposited from the atmosphere [110, 111]. Microbeads used in textiles, cosmetics, washing industries and personal care products are a common source of MPs in water and soil environments [112]. They release 94,500 fine particles into the environment [113].

Studies indicate that a significant part of MPs ends up in soils, but the number of studies that investigate soil outside of aquatic environments is not high. In wetland environments, MP concentrations show a negative correlation with vegetation and stem density [68]. The fate and effects of MPs in soil are shown in Figure 5.

The conversion of plastic waste into MPs by soil geophagous fauna, such as earthworms, mites and collembolans through digestive processes, can increase secondary MPs in soil. However, more research is needed. There are specific data linking the use of organic waste materials to synthetic fibers in soil. But most studies investigating plastic in soil simply report its presence and do not examine its origin or abundance [114].

MPs cause changes in soil biophysical properties and do this by affecting pH, soil structure, fertility, soil nutrients, soil microbes and water-stable soil grains [115]. MPs gradually penetrate into the structure of soil grains and establish loose or strong bonds with soil grains in different ways, and in this way they will have the possibility to influence the stability of soil grains [116].

Soil grains are the main unit of soil structure and play an undeniable role in forming the habitat of soil organisms. In addition, they are also very effective in creating porosity in the soil, as a result, the movement of gas and water and the activities of related microbial communities depend on them. When MPs are present, soil bulk density is low, which will have completely different indirect effects on the entire soil system. The information available so far about the impact of MPs and the reaction of plants to these tiny plastic particles is very limited [117].

In a study by Souza Machado et al. (2019), the results indicate that the physical parameters of the soil change due to the addition of MPs, and as a result, it affects the hydrodynamics and microbial activity, and on the other hand, the effect of MPs on the soil depends on the shape and size of the MPs particles. The results of this study proved that despite the decrease in the apparent density of the soil after adding high density PE, the density of the soil in the rhizosphere (root) is increasing. Plant root traits, plant leaf traits, and total biomass have also changed [115].

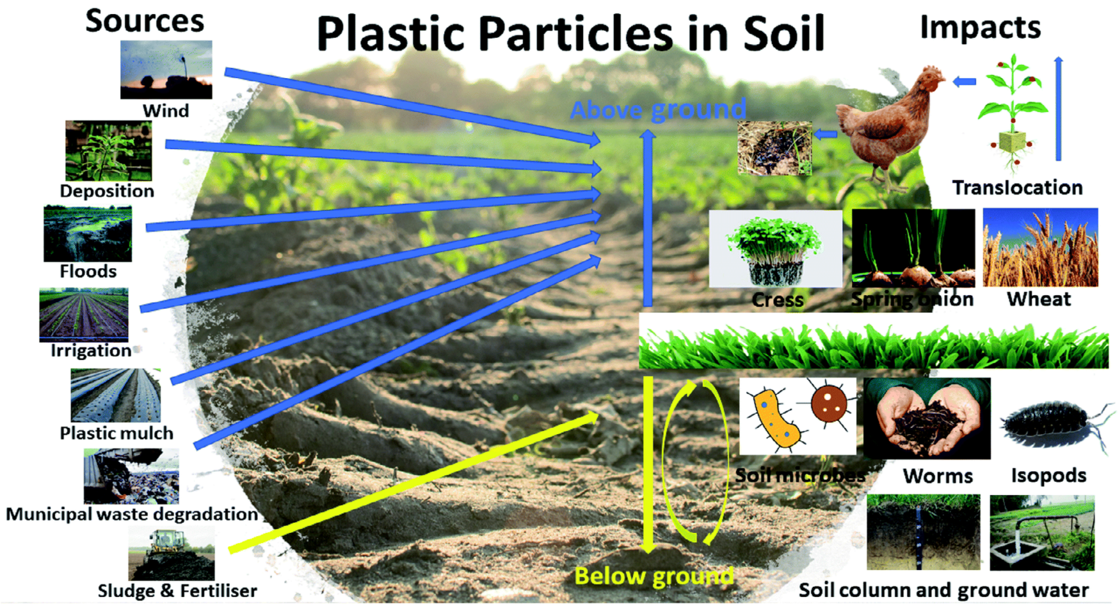

Figure 5. Fate and effects of MPs in soil

Wan et al. (2019) proved that MPs accelerate the evaporation of soil water by creating channels for water movement, and this phenomenon increases with increasing concentration of MPs [118]. The accumulation of MPs can also destroy the structural integrity of the soil and cause cracking on the soil surface. The accumulation of MPs can also destroy the structural integrity of the soil and cause cracking on the soil surface [119]. In Table 3, we review several studies related to soil MPs, taking into account the abundance and shape of MPs, the type of polymer and the type of land use.

Table 3. Overview of the worldwide documentation studies on MPs in soil

Region	Sites	Land Use	Vicinity	Polymer Types	mg kg $^{-1}$ dw mv±sd Median (Min–Max)	Items kg $^{-1}$ dw mv±sd Median (Min–Max)	Size Span [µm]	Shape of MPs	Reference
Köln (Germany)	1	_	Munici-pal	PE	915±63	_	_	_	[120]
Shanxī Province (China)	9	Agriculture	Munici-pal	PE, PET, PP, PS, PVC	_	2131±371	<5000	Fiber	[121]
Sydney (Australia)	1	_	Industrial	PE, PS, PVC	2400	_	<1000	_	[122]
Yucatan Peninsula (Mexico)	10	Horticulture	Rural	_	_	870±1900	<2000	_	[123]
Austria/Southern Germany	11	_	Munici-pal	_	_	11×10^6	5–1000	_	[124]
Denmark	1	Agriculture	_	PP	5.8	71000	20–500	_	[125]
Mittelfranken (Germany)	1	Agriculture	Rural	PE, PP, PS	_	0.3 (0.0–1.3)	1000–5000	Film>fragment> others	[126]
Hangzhou Bay (China)	60	Agriculture	Munici-pal	Diverse	_	310 (0–2760)	>60 mainly 500–3000	Fragment, Fiber>film	[127]
Tiānjīn China)	1	_	Munici-pal	PP	_	95	<3200	Fragment	[128]

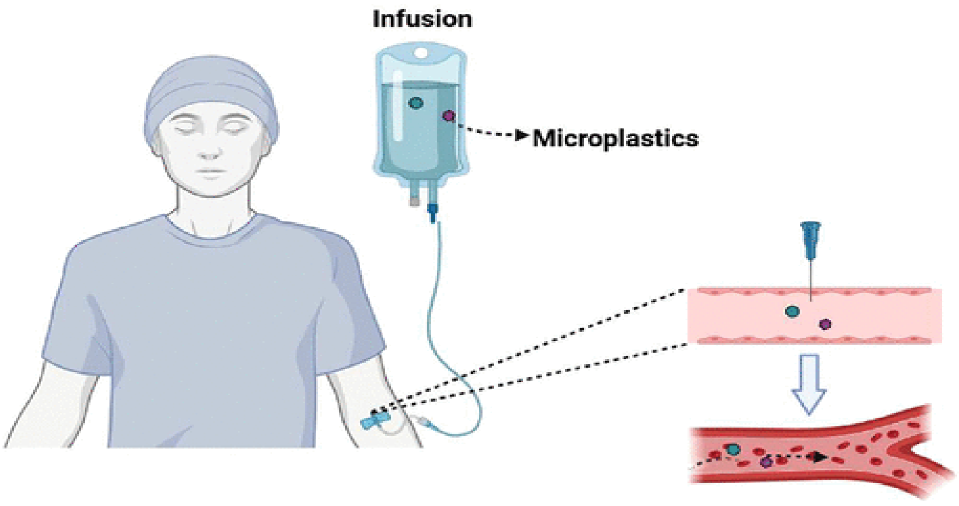

Figure 6. Exposure to MPs through intravenous injection

The human body

MPs can find their way into the food we eat, the water we drink, and even the air we breathe. According to recent research, people consume more than 50,000 plastic particles per year, and this amount is much higher when inhalation is considered [129]. Graduate students at Arizona State University were able to find MP particles in all human tissues studied [130]. A study published in March 2022 clearly showed that MPs were found in 80% of 22 unidentified blood samples. This means that they are able to transfer throughout the human body, and the question arises whether they can reach the brain as well [131].

The German Federal Institute for Risk Assessment (BfR) conducted an assessment of health risks from the use of face washes, hand cleaners, toothpaste and dental care products containing MP particles. Their results showed that the MP particles used in facial exfoliation and bath products are larger than 1 micrometer, and during long-term human use of them, it leads to the absorption of PE and PP particles into tissues, which ultimately ends in skin damage. There is a possibility of swallowing these toothpaste MPs unconsciously and absorbing them through the digestive system [132]. Ingestion of MPs can block the digestive tract, slow growth, stop enzyme production, reduce steroid hormone levels, affect reproduction, and cause absorption of toxins [74].

In December 2020, for the first time, MP particles were found in the placenta of unborn babies [133, 134]. In June 2022, MP particles were found in breast milk for the first time [131]. In July 2022, scientists found MP particles in the lungs of 11 of 13 samples, supporting the hypothesis that we can inhale MPs and Also swallow them [135]. According to research conducted by the Medical University of Vienna, an average of five grams of plastic particles enter the digestive tract of each person per week. That's about the weight of a credit card. According to another recent estimate, a person who eats seafood ingests 11,000 MP particles per year, even tiny MPs have been detected in human blood [136]. A recent study showed that one kilo of sugar contains 440 MPs, one kilo of salt contains 110 MPs, and one liter of bottled water contains 94 MPs [136, 137].

Using plastic bottles, bags, and injection syringes may directly introduce plastic particles into the bloodstream. Here, we hypothesize that if the infusion solution contains MP particles, they can enter the bloodstream during IV treatment. Due to their indestructibility, MPs remain in the human bloodstream for a lifetime. Injection solutions are injected into the blood through an injection tube with an in-line filter. More than 90% of particles with a diameter greater than 5 micrometers, including MPs whose size is greater than 5 micrometers, can be trapped by in-line filters. Therefore, there is a possibility that MPs with a diameter of less than 5 micrometers will pass through the filter and end up in the bloodstream. These tiny plastic particles may accumulate in the vascular walls and cause disruption or even obstruction of blood flow, as reported by Wu et al [138]. Despite the high filter capacity, in-line filters cannot completely trap all particles, and it is possible for some MPs larger than 10 micrometers to pass into the bloodstream. Therefore, patients receiving frequent IV therapy may be exposed to more MP particles compared to other individuals. It should be noted that plastic is widely used in the construction of various tools and pipelines in pharmaceutical factories, and avoiding the use of plastic during production is impossible. In addition, the quality control system that is currently used for the production of injectable solutions in pharmaceutical factories does not consider MP as one of the health indicators of control. It also does not develop a standard to control MP contamination in injectable solutions and related medical products. The up-to-date quality control system should guarantee human health by considering MP as an emerging pollutant [139]. Figure 6 shows human exposure to MPs through intravenous injection.

Conclusion

Studies confirm that plastics involved in packaging applications such as PS, PE and PET degrade and are capable of releasing MPs into the air at a much faster rate than water. MPs in the air, in addition to inherent toxicity, may cause more risks to human health and the environment than virgin MPs through the absorption of pollutants and chemicals. MPs have been increasingly studied in soil over the past few years due to their threats to terrestrial ecosystems. The conversion of plastic waste into MPs by soil geophagous fauna, such as earthworms, mites and collembolans through digestive processes, can increase secondary MPs in soil. While some of these MPs may be transferred vertically under the soil over time and eventually enter the groundwater. In recent years, MPs in aquatic ecosystems have been raised as an important environmental problem. The situation is exacerbated by the fact that even if plastic waste is prevented from entering the marine environment, it is likely that the abundance of MPs will increase as a result of the degradation of plastics that are currently in the world's oceans.

Ethical Considerations

Compliance with ethical guidelines

This article is review with no human or animal sample.

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Authors' contributions

Conceptualization and supervision: Jalil Jaafari; Methodology: Aran Akbari; Investigation, and writing: All authors.

Conflict of interest

The authors declared no conflict of interest.

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