



Microplastics in freshwater systems: A review of classification, sources, and environmental impacts

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ABSTRACT

The globally increasing contents of microplastics (MP) in ecosystems have become a serious environmental problem with far-reaching and at present unpredictable consequences for both aquatic life and human well-being. Until recently, most research on MP focused on marine ecosystems. Research on the occurrence of MP has lately started to focus on freshwater environments. This comprehensive and critical review examines the multifaceted problem of MP pollution in freshwater ecosystems, delving into its diverse sources, transport mechanisms, environmental impacts, detection methods, and mitigation strategies. The environmental impacts of MP pollution span a spectrum of impacts on aquatic life, food webs, and biodiversity in general. In addition, human health concerns have arisen due to potential exposures resulting from the consumption of contaminated freshwater and biological resources. The review summarizes analytical methods and technologies used to detect and quantify MP in freshwater samples, while recognizing the challenges and new innovations in this area. Mitigation and management strategies are explored, ranging from waste management and recycling initiatives to engineering solutions such as wastewater treatment and stormwater management. Legislative measures aimed at curbing MP pollution are also reviewed. Reviewed case studies highlight regional differences, and the unique challenges faced by different freshwater ecosystems. The review concludes by highlighting the urgent need for global awareness, further research, and coordinated action to address the growing problem of MP pollution in freshwater. As humanity faces this complex environmental challenge, interdisciplinary approaches, and international collaboration are essential for sustainable solutions and protection of freshwater ecosystems and health of the planet.

1. Introduction

Rivers, lakes, and groundwater supplies are examples of freshwater ecosystems, which are vital resources required to sustain life on Earth. Previously thought to be mainly a marine issue, microplastics (MP) are now known to be a major contaminant that is invading freshwater bodies worldwide. Their origins are diverse and linked to both industrial operations and the fragmentation of larger plastic waste streams. Questions about the transport of mp, their effects on aquatic life, and their potential health effects on humans are growing more urgent as they continue to influence the environment.

Since the 1940s, when plastics were first produced in large

quantities, the ecosystem's MP contamination has been an increasingly serious issue [1]. Global plastic output has nearly quadrupled over the previous three decades and is predicted to reach 33 billion metric tons by 2050 [2,3]. The amount of plastic produced annually rises despite increased awareness of plastic pollution and efforts to mitigate it. The manufacturing sector produces more than 280 million metric tons of plastic garbage per year [4–6]. The transport and fate of this total plastic load are still poorly understood and how the resulting MP streams are divided into different transport routes. The oceans and marine ecosystems, however, will be one of the major final sinks for much of the MP. Fig. 1 illustrates the proportion of worldwide aquatic plastic pollution that reaches the ecosystems according to recent estimates [7]. The

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amount of plastic waste generated and the degree of polluted water bodies in the world are generally reflected by industrial development, income level, population size, and environmental awareness. Consequently, a handful of the greatest polluted water bodies in the world are found in Africa, but most of the aquatic plastic pollution stems from Asia.

An estimated 4.8 to 12.7 million metric tons of plastic end up in the ocean each year, but a 2017 study found that 80% of the waste in the ocean come from just five Asian countries: China, Thailand, Vietnam, Indonesia, and the Philippines [7]. Also, according to statistics from worldpopulationreview.com, various aspects of the problem of global plastic pollution in 2024 have been revealed (Table 1) [8]. Table 1 contains various statistics related to global plastic pollution, allowing an assessment of the situation in different countries. The mismanaged waste index (MWI) is defined as the sum of uncollected and improperly managed plastic waste divided by the totally generated plastic waste amount. According to the MWI, countries such as India, Nigeria, and Indonesia fall into the “Very High” category, indicating significant challenges in managing plastic waste. The total production of plastic reflects the amount of plastic waste produced by each country. China leads the way with over 37.6 million tons of waste per year, while Niger generates significantly less at 37.3 thousand tons per year. The assessment of mismanaged waste, shows that the largest amounts of mismanaged plastic waste are in India and Indonesia, with approximately 7.3 million and 3.3 million tons per year, respectively [9]. Plastic Pollution Per Capita Plastic Consumption indicates the average level of plastic use per person per year. The United States has the highest level at 69 kg per person and year, while Ethiopia and Uganda have significantly lower levels at about 1.3 kg per person and year.

Microplastic Released into Waterways measures the amount of MP pollution in waterways. China releases about 517,699 tons of MP per year, while, e.g., Niger has a much lower figure. Pollution from chemical additives in plastic also varies, with the US reporting 12,152 tons per year, while countries such as Madagascar and Yemen have much lower figures. The data analysis shows that countries such as India, Indonesia, and Nigeria have serious problems with plastic waste management, as reflected by high MWI values and significant amounts of improperly disposed waste. At the same time, countries such as the US and Japan, despite having low MWI values, have high plastic consumption, indicating a mismatch between consumption and waste management efficiency. Moreover, countries with high plastic consumption also have a significant environmental impact through MP emissions and chemical additive pollution. These findings highlight the need for improved plastic waste management practices worldwide, especially in countries with high plastic consumption and poor waste management.

From the above, it is easy to understand the magnitude of MP

pollution problem. This is especially so since the comprehensive effects of MP pollution on human and ecosystem health is still not fully understood. Consequently, in the spirit to summarize existing knowledge on MP pollution, we performed this review on microplastics in freshwater systems regarding classification, sources, and environmental impacts. In the literature search we included MP and related keywords for published papers and textbooks indexed in the databases Web of Science, Scopus, and Google Scholar for SCI and SSCI indexed papers for the last 25 years. As well internet sources and sources of news until 2024 were used. The initial search was further expanded and finally about 200 significant written sources were included in the review. Accordingly, this review first gives an historical account and classification of MP. We then summarize examples of MP contents in some human food products, human blood, and human body parts and potential harmful effects. The following chapter deals with the transport and fate of MP. After this we summarize analysis techniques for water and wastewater samples and treatment. The potential risks for the environment involving MP are then reviewed. The paper is finalized by giving recommendations for the future and ways to reduce MP. Consequently, the review forms a basis for the present knowledge on MP in freshwater ecosystems and a critical summary of ways to classify, transport, fate, and environmental impacts of MP.

2. Results and discussion

2.1. Classification of MP

Synthetic polymers with malleability, or flexibility, that allow for shape-changing are called plastics [10]. Long chains of polymers made of carbon, oxygen, hydrogen, silicon, and chlorides make up plastic with polymers that are derived from coal, oil, and natural gas [11]. The most common synthetic polymers, making up 90% of plastic production worldwide, are polyethylene (PE), polyamide (PA), polypropylene (PP), polyester (PES), polyurethane (PU), acrylic (AC), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), high density polyethylene (HDPE), low-density polyethylene (LDPE), polyimide (PI), polymethyl methacrylate (PMMA), polytetrafluoroethylene (PFE), polyvinyl chloride (PVC), and high-density polyethylene (HDPE) [12, 13]. Plastic material is inexpensive and because of its low cost of manufacture, ease of use, strength, resistance to corrosion, strong electrical and thermal conductivity, and favorable chemical and physical characteristics, plastic has emerged as a crucial and adaptable material in every facet of our life.

Most MP are invisible to the human eye; however, particles range in size from nm scale to about 5 mm [14]. Various scholars have defined the word “microplastics” in different ways [15,16]. When using neuston

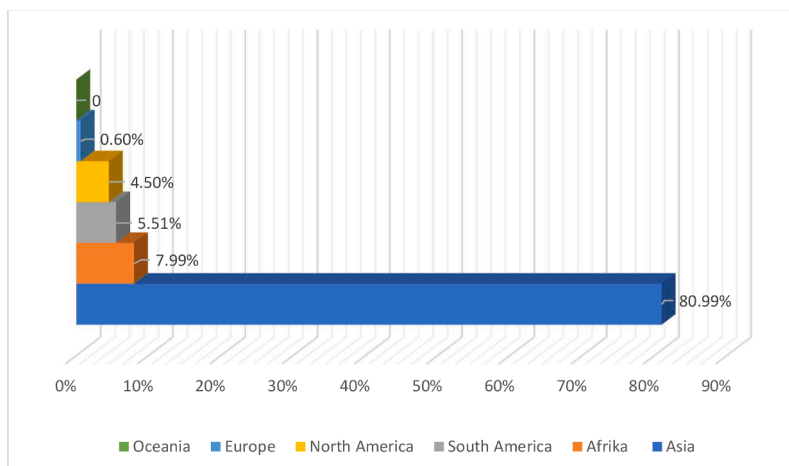


Fig. 1. Global ocean plastic pollution (over 1000 rivers, 80% from Asia) (adapted from [7]).

Table 1
Global plastic pollution metrics by country (2024): consumption, mismanagement, and environmental impact (Mismanaged Waste Index (MWI), adapted from [8].).

Country	Plastic Pollution in MWI (%)	Plastic Pollution MWI Level	Total Plastic Waste Production (tons/year)	Plastic Pollution Mismanaged (tons/year)	Plastic Pollution Per Capita Plastic Consumption (kg/capita and year)	Plastic Pollution Waste Exported (tons/year)	Plastic Pollution Waste Imported (tons/year)	Plastic Pollution Microplastic ReleasedInto Waterways (tons/year)	Plastic Pollution from Chemical Additives (tons/year)
India	98.6	Very High	7,408,124	7,300,752	5.3	59,260	98,860	330,764	44,535
China	17.4	Low	37,606,230	6,546,264	26.7	496,480	1,273,710	517,699	39,932
United States	8.7	Very Low	22,867,246	1,992,144	69	380,350	264,760	254,667	12,152
Indonesia	98.4	Very High	3,366,941	3,313,742	12.4	26,940	79,080	80,414	20,214
Pakistan	91.5	Very High	790,123	723,213	3.5	6320	4790	58,487	4412
Nigeria	99.4	Very High	935,848	930,624	4.5	7490	960	27,685	5677
Brazil	98.0	Very High	4,911,580	4,811,936	23	39,290	1250	53,708	29,353
Bangladesh	98.5	Very High	579,920	571,453	3.5		2860	47,830	3486
Russia	97.8	Very High	3,164,038	3,094,976	22	25,310	12,180	47,987	18,879
Ethiopia	96.4	Very High	150,254	144,867	1.3	5260		13,381	884
Mexico	67.2	High	4,049,874	2,723,104	32.1	200,880	26,090	36,238	16,611
Japan	10.9	Very Low	3,806,805	413,770	30.2	675,660	2540	172,872	2524
Philippines	98.4	Very High	938,218	922,969	8.4	78,540	7950	31,807	5630
Egypt	89.4	Very High	834,699	745,985	7.8	70	950	31,451	4551
DR Congo	97.8	Very High	1,144,387	1,118,640	12.3	30		10,456	6824
Vietnam	32.0	Low	2,951,900	944,959	30.5	131,330	713,980	27,130	5764
Iran	84.4	Very High	1,305,605	1,102,093	15			19,684	6723
Turkey	48.0	Medium	938,490	450,803	11.2	9580	429,770	19,827	2750
Germany	8.3	Very Low	3,568,313	297,559	42.9	428,860	294,020	74,309	1815
Thailand	98.5	Very High	3,355,763	3,304,945	46.9	132,630	179,080	26,463	20,160
Tanzania	99.6	Very High	126,931	126,432	2.1	3030	200	7298	771
United Kingdom	12.3	Very Low	2,085,254	256,610	31.1	149,230	45,720	59,546	1565
France	5.1	Very Low	2,680,095	136,239	39.7	314,320	101,040	60,757	831
South Africa	81.8	Very High	1,013,303	828,949	17.2	8110	5600	12,765	5057
Italy	22.0	Low	3,335,851	734,733	56.1	156,940	141,810	55,704	4482
Kenya	99.0	Very High	270,850	267,861	5.2	2170	50	7512	1634
Myanmar	99.2	Very High	498,431	494,335	9.3	6120	30,490	14,348	3015
Colombia	62.4	High	769,331	480,247	15.1	6150	100	12,425	2930
Uganda	99.7	Very High	59,786	59,613	1.3	510	30	4758	364
Sudan	80.5	Very High	359,574	289,580	8.1			6722	1766
Spain	16.9	Low	1,580,823	267,425	33.4	57,160	141,750	42,735	1631
Iraq	98.4	Very High	695,106	683,664	16.3		480	8950	4170
Algeria	12.8	Very Low	2,092,007	268,285	48.1			13,747	1637
Argentina	40.8	Medium	1,236,184	503,987	27.2	9890		23,641	3074
Afghanistan	98.1	Very High	447,766	439,097	11.5		850	9101	2678
Poland	13.5	Very Low	1315	177,365	34.7	130,100	214,850	35,388	1082
Canada	2.6	Very Low	2,106,603	54,061	55.4	386,440	426,440	29,422	330
Morocco	74.4	High	548,160	407,884	14.9	4390	2530	5980	2488
Ukraine	59.4	Medium	1,066,942	633,696	24.2	8540	37,140	32,866	3866
Angola	94.4	Very High	568,842	536,821	17	4550		8184	3275
Saudi Arabia	70.2	High	2,105,362	1,478,568	58.5	43,530	30	26,737	9019
Uzbekistan	98.2	Very High	100,000	98,225	2.9	800	14,400	8212	599
Yemen	97.8	Very High	384,783	376,318	11.9			3581	2296
Mozambique	99.9	Very High	105,235	105,074	3.4	860	640	3671	641
Ghana	88.0	Very High	141,531	124,522	4.4	1130	910	4026	760
Peru	94.5	Very High	597,668	564,722	17.9	4780	5230	8251	3445
Malaysia	76.4	High	1,371,397	1,047,735	41.3	25,650	589,970	11,789	6391
Nepal	93.8	Very High	267,823	251,325	9.1	2140		8995	1533
Madagascar	99.8	Very High	299,816	299,232	10.6	2400		3349	1825
Ivory Coast	98.0	Very High	473,230	463,511	17.7	3790	3210	7102	2827
Venezuela	53.2	Medium	1,200,487	638,790	42.1			8029	3897
Cameroon	87.5	Very High	107,930	94,400	4.1		30	7425	576
Niger	98.2	Very High	37,313	36,656	1.5			1304	224
Australia	9.3	Very Low	1,160,779	107,851	45.2	165,690	17,020	33,117	658
Syria	94.6	Very High	315,000	297,944	15.2			2679	1817
Mali	97.1	Very High	38,747	37,626	1.8	2740	60	2133	230
Taiwan	4.5	Very Low	1,484,073	66,635	62			32,765	406
Burkina Faso	94.1	Very High	231,773	217,974	10.8	1850	170	4140	1330
Sri Lanka	92.1	Very High	184,216	169,645	8.4	1470		10,369	1035
Malawi	97.2	Very High	103,247	100,392	5.3	830	140	2255	612
Zambia	94.0	Very High	277,947	261,284	14.7	2840	50	2630	1594
Kazakhstan	94.1	Very High	1,164,935	1,096,651	62.1	9320	10	58,878	6690

nets for sampling, 333 nm seems to be a reasonable lower limit. Though, seawater often contains plastic particles that range in size from a few to about 500 nm [17,18]. Mesoplastics refer to larger particles, including primary resin granules. Furthermore, small plastic pieces are created when macroplastics break down, and MP are tiny plastic granules that

are utilized as air purifiers and scrubbers in cosmetics [19–21]. Because they are so small, they slowly find their way into aquatic systems where they are pushed into drainage channels without being adsorbed. These meso- and MP ensnare persistent organic pollutants (POPs), which are found in small amounts in fresh and marine water systems all over the

world. POPs are more concentrated in meso-MP litter than in the general fresh and marine ecosystem, which is partly due to their hydrophobicity [22,23]. When aquatic species consume these tainted plastics, it presents a significant risk since POPs might infiltrate the water food chain. MP are invisible to the unaided eye, in contrast to macroplastics; even mesoplastic resin grains mixed with sand can be challenging to identify. Naturally, smaller MP are not collected by net sampling, and there is not any recognized standard method for counting them in sand or water [24]. Primary and secondary MP are the two categories into which MP are separated based on where they come from. Primary MP are man-made polymers that are so small that they are released into the environment as individual microscopic particles. Chemical formulations, abrasive surroundings, petrochemical and chemical cleaning, and the production of synthetic garments are just a few of the processes in which they find application as exfoliants. They can as well be added to goods like shower gels and other hygiene and beauty cleaning products [25–27]. In addition, they may result from the abrasion of sizable plastic items during manufacture, usage, or upkeep, e.g., tire erosion when driving or abrasion of synthetic fabrics while washing. Microbeads are a type of virgin plastic, used in cosmetic and medical items, that are about 2 mm in size and made of granules of polyethylene, polypropylene, and polystyrene [28].

When larger plastic goods degrade into tiny plastic secondary fragments in the water environment, recycled MP are produced. It occurs because of environmental changes brought by photocatalysis, microbial decomposition, thermal decomposition, high temperature decomposition, hydrolysis, and other weathering processes connected to careless discharge like discarded plastic bags, or unanticipated losses like fishing gear. MP in water can sink and stored into the bed sediments or circulate (Table 2) [29–32].

When evaluating threats to the environment and human health, it is important to consider the irregular shapes of MP, which might include spherical, rod-like, and cubic forms, depending on their morphological characteristics [33,34]. Sharp MP particles have the potential to be harmful because they physically stimulate human tissue. Additionally, depending on the final use, different chemicals are used in the manufacture of plastic polymers, the majority of which are harmful to essential human organs. MP contamination of drinking water is a major environmental and public health concern, with biodegradable microplastics emerging as a potential alternative to conventional plastics. Despite their promise, biodegradable MP also contribute to water pollution, creating complex problems [35]. MP, including biodegradable variants, have been found in drinking water supplies around the world. The most contaminated areas with biodegradable MP tend to coincide with regions heavily affected by traditional MP. Large urban centers and coastal regions in countries such as China, India, Indonesia, and the Philippines report high levels of MP contamination in water supplies. For example, studies have found significant MP contamination

in the Ganges River in India and the Yangtze River in China, both major sources of drinking water [36].

Biodegradable MP are designed to decompose more quickly than conventional plastic. The main types include polylactic acid (PLA), used in packaging and single-use products. PLA is made from renewable resources such as corn starch. Polyhydroxyalkanoates (PHAs) are produced by microbial fermentation and are used in medical and packaging applications. Starch-based plastics are commonly used in single-use items such as bags and are derived from natural starches. Cellulose-based plastics are made from plant cellulose and are used in films and coatings [37].

While biodegradable MP are designed to decompose more quickly, they have several disadvantages such as incomplete degradation in natural environments, especially in water. Biodegradable MP may not completely decompose, leading to persistent MP pollution. A study conducted at the University of Plymouth found that biodegradable plastic bags remained intact after three years in the marine environment. As biodegradable plastics decompose, they may release harmful additives or byproducts into the water [38]. For example, PLA can release lactic acid, which can alter the pH of bodies of water, potentially harming aquatic life. The breakdown process of biodegradable plastics may still result in the formation of microscopic particles that persist in the environment, similar to traditional microplastics [39].

2.2. MP effects on organisms

It is critical to comprehend the pathways through which people are impacted by MP. Oral consumption, inhalation, and skin contact are common ones, but oral consumption is the primary method of exposure among them. Humans frequently encounter MP in many contexts. Human exposure risk is increased by the mobility of MP [40].

Our everyday necessities, including milk, tea bags, seafood, bottled water, salt, and sugar, contain MP [41–44]. Due to consumption of shellfish that filter mp, Europeans are exposed to around 11,000 MP particles annually [40]. Depending on what they eat and drink, humans can consume between 39,000 and 52,000 particles of plastic annually. Additionally, MP may be widely distributed in soil, particularly in agricultural systems [45]. They can enter the plant's water and nutrient transport system and then travel to the roots, stems, leaves, and fruits, especially if they have a negative charge [46]. Food contamination results from the introduction of MP into agricultural systems through sewage sludge [47], composting, and plastic mulching, all of which raise the possibility of human exposure [48].

There is increasing evidence that our food and water are contaminated with MP. A 2020 study conducted in Italy discovered that MP are common in fruits and vegetables. Laboratory experiments have shown that wheat and lettuce plants can absorb MP particles, likely through soil contaminated with these particles, which is how they end up in our food (Fig. 2) [49]. MP are present in takeout containers, which are frequently constructed of traditional polymeric materials [47,50]. It has been estimated that 10–200 pieces of MP may be consumed through containers by those who eat takeout four to seven times a week [51]. Furthermore, studies indicate that the process of steam sterilizing silicone rubber cribs damages their surface, causing the discharge of MP particles into the surrounding air. It is predicted that throughout a year of regular bottle feeding, an infant may consume up to 0.66 million MP particles [52].

Most of the particles and fibers of polyethylene, polystyrene, and polypropylene that are present in the air are MP, and their diameters range from 10 to 8000 μm [53]. Roads and traffic wear account for the majority of MP in the atmosphere (84%). According to reports, the average concentration of MP fibers in Paris city air is 5.4 fibers/ m^3 outdoors and 0.9 fibers/ m^3 indoors [54]. Shanghai's outdoor air has an average concentration of 1.4 particles/ m^3 of MP, with a size range of 23–5000 μm [55]. The yearly intake of MP, accounting for both ingestion and inhalation, is estimated to be between 74,000 and 121,000

Table 2

Classification of primary and secondary MP according to their size, shape, and type.

MP		
Primary	Secondary	
Granules, microballs, glitter from cosmetics, and personal care products	- Wear and tear from normal use of plastic - Airborne dust - Decomposition of larger plastic products	
And Size	Shape	Type
mp ≥ 5 mm	Granules,	- High density MP (PET, PVC) - Low density MP (PS, HDPE, LDPE, PP)
Nanoplastic ≥ 1 μm	microbeads, cubes, rod, foam, fiber, film, fragment, and microfiber	

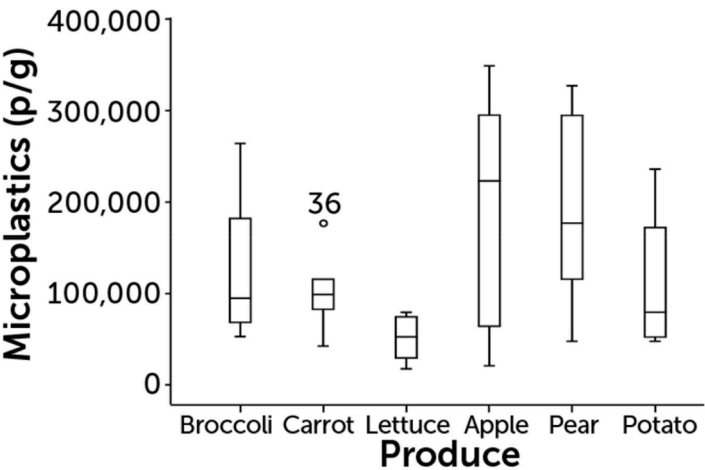


Fig. 2. Boxplots of MP particles found in produce samples (adapted after [49]).

particles. Human lungs were discovered to contain MP fibers (8.1–16.8 mm) mostly composed of polyethylene and polypropylene, as well as MP particles smaller than 5.5 μm . Lung tissue contains MP that are smaller than those in the atmosphere. This highlights the possible damage to the human body and reaffirms the likelihood of MP exposure by inhalation [56–58].

Although MP are generally thought to not pass the skin barrier, they may nevertheless increase the risk of exposure by being deposited on the skin. For instance, using consumer products that contain MP (like face cream and facial cleanser) increases the risk of exposure to polyethylene. Children may encounter MP on the ground when they crawl or play. Common plastic additives that can be absorbed during skin exposure to MP include bisphenols (BP), triclosan (TCS), and phthalates [59–61].

It is widely acknowledged that MP are eliminated from the human body through the biliary and digestive systems. On the other hand, scientists are finding that human blood contains MP [59]. The dangers that MP represent to human health are starting to become seriously

investigated. According to a recent analysis, MP are carried throughout the body via the bloodstream and have been detected in 15 different human biological components, including the lungs, spleen, liver, colon, feces, placenta, and breast milk [59,62] (Fig. 3). Fig. 3 shows the typical presence of MP in various parts of the human body, indicating the potential for human exposure to these particles. The most common kinds of MP found include PC, PVC, PS, PP, PET, and PE. Infants and pregnant women are vulnerable groups that are exposed to MP [58].

Leslie et al. discovered MP in blood samples from 17 out of 22 healthy adult volunteers in the Netherlands. These findings confirm a long-standing suspicion among scientists: MP can indeed be absorbed into the human bloodstream [63]. The types of polymers detected varied among the participants, as did the concentrations. Donors 11, 12, and 13 provided two samples each, both containing MP, while for many others (indicated with a star in Fig. 4), one sample showed the presence of MP, and the other did not (Fig. 4).

In addition to being hazardous in and of itself, MP also carries a

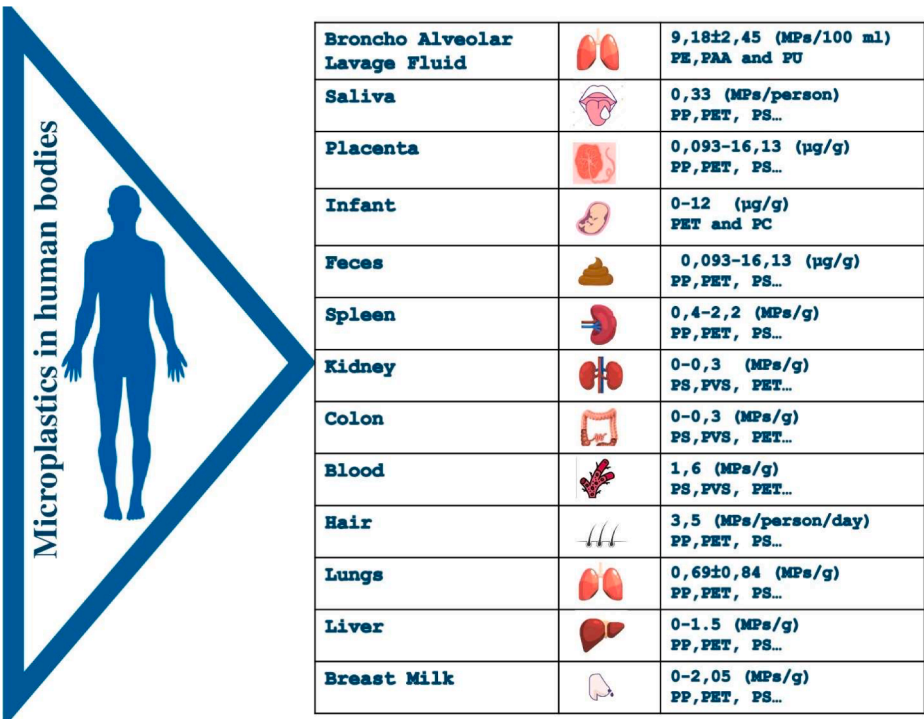


Fig. 3. MP typically found in the human body (adapted after [67]).

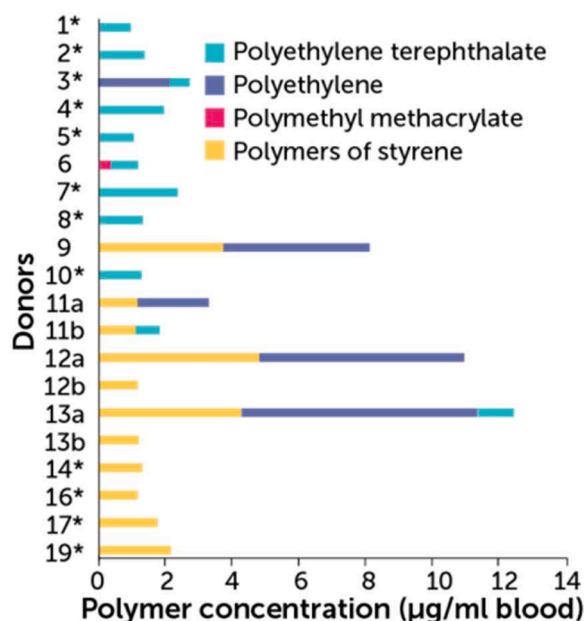


Fig. 4. Levels of MP detected in human blood samples [63].

variety of contaminants that infiltrate biological tissues and organs. The broncho alveolar lavage fluid contains 9.18 ± 2.45 pcs of MP per 100 mL [64]. The MP found in this fluid have been found to be constituted by PE, PAA (polyacrylic acid), and PU. Infants may have MP ranging from 0 to 12 µg/g [65]. The MP found in infants can be made of PET and PC (polycarbonate). Feces may contain MP ranging from 0.093 to 16.1 mg/g [66]. The MP found in feces have been found to be made of PP, PET, and PS. The spleen may contain MP ranging from 0.4 to 2.2 pcs of MP/g [67]. The MP found in the spleen may be constituted by PP, PET, and PS. Human blood may contain 1.6 pcs of MP/g [68]. The MP found in the blood have been found to be made of PS, PVS, and PET. Finally, hair may contain 3.5 pcs of MP per person and day. The MP found in hair were constituted by PP, PET, and PS.

Due to their large surface area and strong hydrophobicity, MP can efficiently adsorb environmental pollutants, including organic pollutants, heavy metals, and pathogenic microorganisms, potentially leading to serious health risks. As well, MP can enhance the bioaccumulation and toxicity of organic pollutants in organisms. For example, PS-MP have been shown to increase the sorption of pollutants like 6:2 chlorinated polyfluorinated ether sulfonate, leading to oxidative stress and inflammation in zebrafish [69]. Co-exposure with other pollutants, such as polybrominated diphenyl ethers, can further aggravate developmental and thyroid toxicities [70]. MP can act as carriers for heavy metals like arsenic, cadmium, chromium, copper, and lead, significantly increasing their health risks. Studies have shown that PS-MP have a high capacity for adsorbing heavy metals, such as chromium and arsenic, leading to enhanced toxicity [71]. MP can transport pathogenic microorganisms, increasing the risk of infections. For instance, MP have been found to facilitate the binding and transport of SARS-CoV-2, potentially increasing infection rates [72]. Similarly, MPs mixed with *Helicobacter pylori* can accelerate infections and worsen gastrointestinal inflammation [73].

Oxidative stress, caused by an imbalance between reactive oxygen species (ROS) and the antioxidant system, plays a key role in MP-induced toxicity. MP have been shown to increase ROS levels, leading to inflammation, apoptosis, and cellular damage. For example, PS-NPs induce oxidative stress in various organisms, which is linked to toxic effects like cardiotoxicity, memory deficits, and mitochondrial dysfunction [74]. MP also disrupt signaling pathways such as Nrf2/HO-1 and MAPK, exacerbating oxidative stress and contributing to

cellular damage Mitochondrial injury, resulting from MP exposure, further amplifies ROS production, leading to severe cellular dysfunction [75].

2.3. Transport and fate of MP

Most studies on the properties and prevalence of MP among different aquatic habitats have been performed for saltwater. Investigations of MP in freshwater, wastewater, and groundwater have generally been done more recently [76]. Water quality deterioration by MP appears to be related to intensive economic development, and the association between high MP concentrations and poor water quality has led to the hypothesis that economic activity influences MP concentrations [77]. The association between MP and population density suggests that plastic particles mainly originate from land sources, even if some may have moved in the atmosphere from far-off places. Specifically, densely populated areas with rapid economic expansion appear to have the largest concentration of MP [78]. Nonetheless, the periphery of industrialized centers has as well substantial amounts of MP also in locations with low population densities [79]. Pollution levels often decline with increasing distance from the mouth to the open sea. For instance, when the distance from the Yangtze River mouth increased, the concentration of MP dropped. On the other hand, the number of floating MP rose by increasing distance from the coast on the Italian Tuscan coast. The spatial variability of MP was linked to coastal currents, according to research on the seasonal distribution patterns of MP at six beaches in Qingdao, China [80]. Six beaches showed a rise in MP from east to west, in line with the direction of the ocean currents.

The amount of MP is also influenced by various environmental conditions, including typhoons, precipitation, snowfall, and melting. Autumn had the largest concentration of MP in the Marmara Sea of Turkey, whereas summer had the lowest concentration [81]. Nonetheless, there is a growing body of study on the behavior and distribution of MP in freshwater. Because inland freshwater bodies usually are exposed to discharge from cities and urban areas, they contain mp, which is why they are found in and surrounding plastic producing locations. To learn more about how the environment affects freshwater, studies of MP in sediments are conducted according to location and season. China's largest textile manufacturing zone was shown to be home to more than twice as many MP (13.3 pcs/L) than the control area. High amounts of MP pollution were discovered in the adjacent waters and sediments because of the production and trade operations of the textile sector. Pellets made up 73.1% of MP found in the surface waters of Nigeria's Lake Oxbow. It was proposed that the high concentration of beads was probably caused by the traditional bead-making tradition and the usage of beads as fishing gear [82–84]. Lake Taihu showed comparatively high amounts of MP (3.4–25.8 pcs/L). Cellophane, which is categorized as a common semi-synthetic substance, was the most prevalent particle [69].

Table 3 provides information on observations of MP in freshwater environments at various locations. In Argentina (Patagonia): sampling methods involved using a net with a mesh size of 38 µm. The MP were observed using a stereomicroscope and µ-Raman. The composition of MP included Indigo Blue (44.1%), PET (38.3%), PU (11.8%), PS (2.9%), and PP (2.9%). The concentration of MP was 0.9 ± 0.6 particles/m³ (ranging from 0.3 to 1.9 particles/m³). Australia (Cooks River): Sampling method involved using a 0.014 m³ metal bucket through a 37 µm plankton net. The MP were observed using a microscope. The concentration of MP ranged from 400 to 17,400 particles/m³. Australia (Goulburn River): Grab sampling was done using 5 L food-grade blue PP jars. The MP were observed using a stereomicroscope and ATR-µFTIR. The composition of MP included PES (30.6%), PA (12.9%), and rayon (8.1%). The concentration of MP was 0.0004 ± 0.00027 particles/m³. Australia (Gold Coast): A sampling device consisting of four removable stainless-steel mesh screens (25, 100, 190, and 500 µm) was used. The MP were observed using a dissecting microscope and ATR-µFTIR. The composition of MP included polystyrene-co-ethylacrylate (black

Table 3

Freshwater observations of MP (adapted after [45]).

Location (country)	Sampling	Prior treatment	Analysis method	Results		Reference
				Composition	Concentration	
Argentina (Rio de la Plata Estuary)	Bucket, plankton net (36 µm)	Fe (II) 0.05 M and 30% H ₂ O ₂ , NaCl (5 M)	Stereomicroscope	–	139 particles/m ³	[85]
Argentina (Patagonia)	Net of 38 µm mesh size	30 % H ₂ O ₂	Stereomicroscope, µ-Raman	Indigo Blue (44.1%), PET (38.3%), PU (11.8%), PS (2.9%) and PP (2.9%)	0.9 ± 0.6 particles/m ³ (0.3–1.9 particles/m ³)	[86]
Australia (Cooks River)	14 L metal bucket through 37 µm plankton net	NaCl solution (1.2 kg L ⁻¹ , 30% KOH: NaClO, Nile red	Microscope	–	400–17,400 particles/m ³	[87]
Australia (Goulburn River)	Grab sampling (5 L food-grade blue PP jars)	Sodium hydroxide (NaOH)	Stereo-microscope, ATR-µFTIR	PES (30.6%), PA (12.9%), rayon (8.1%)	0.0004 ± 0.00027 particles/m ³	[87]
Australia (Gold Coast)	Sampling device consisted of four removable stainless-steel mesh screens (25, 100, 190, and 500 µm)	30% H ₂ O ₂ , NaI with a Density of 1.59 g/mL	Dissecting microscope, ATR-µFTIR	Polystyrene-co-ethylacrylate (black fragments) followed by PP, nylon, and PES	Inlet: 0.0009 ± 0.0003 particles/m ³ Outlet: 0.004 ± 0.0024 particles/m ³	[88]
Canada (Lake Ontario)	Stainless steel bucket with PP rope	Saturated calcium chloride solution (CaCl ₂ , ρ = 1.4 g L ⁻¹)	Stereomicroscope, µ-Raman	Cellulose, unknown, anthropogenic (dye-based, unknown), PET, PE, PVC, and PVC additive	0.0133 ± 0.0155 particles/m ³ in wastewater effluent 0.0009 ± 0.0013 particles/m ³ in agricultural runoff, 0.0154 ± 0.0079 particles/m ³ in stormwater runoff, 0.0008 ± 0.0007 particles/m ³ in the lake	[89]
China (Taihu Lake)	Steel sampler	H ₂ O ₂ (30%, v/v)	Stereomicroscope, µ-FT-IR microscopy, SEM/EDS	cellophane	× 10 ⁶ – 6.8 × 10 ⁶ particles/km ² in plankton net samples, 0.0034–0.0258 particles/m ³ in surface water	[90]
China (Suzhou River and Huangpu River)	Metal pail (nylon filters of 20 µm pore size), air lift pump	KOH solution (10% w/v)	Stereomicroscope, ATR-µFTIR	fibrous PES (27.7%), rayon (14.4%), PP (8.7%)	0.00008 – 0.0074 particles/m ³	[91]
China (Tibetan Plateau)	2 L stainless steel bottle	0.05 M Fe (II) solution and 30% H ₂ O ₂	Stereomicroscope, Raman	PP (32.7%), PE (29.8%), PS (13.5%) and PET (9.6%)	277.3 ± 95.4 particles/m ³ (66.7 – 733.3 particles/m ³)	[92]
China (China textile city stream)	Metal nail	H ₂ O ₂ (30%, v/v), NaCl	Stereomicroscope, µ-FT-IR	PES (65.7%), rayon (6.7%), PP (6.5%), non-plastic (10.5%)	0.0068 particles/m ³ in surface water (0.0021–0.071.0 particles/m ³)	[93]
China (Yellow River)	Stainless steel bucket	NaCl solution (1.3 g/mL), H ₂ O ₂ (30%)	Optical electron microscope, ATR-FT-IR	PE, PP, PS	Wet season: 0.497 (0.380–0.582) particles/m ³ dry season: 0.930 particles/m ³ (0.623–1.392 particles/m ³)	[94]
Denmark (ponds)	Filtering device (10 µm stainless-steel mesh)	30% H ₂ O ₂ with catalyst, followed by an enzyme treatment (Cellubrix, Viscozyme, Alcalase), NaOH, ZnCl ₂ solution (1.7 g/cm ³)	µFT-IR microscope	number concentrations PP (71.5%), PE (9.1%), PVC (7.4%), PES (5.5%) and PS (2.2%) mass concentration PP (48.9%), PVC (39.1%), PES (5.0%), PE (3.9%), and PS (2.2%)	490–22,894 particles/m ³ /85–1143 µg/m ³ (1409 particles/m ³ /231 µg/m ³)	[95]
Europe (Carpathian basin)	Developed mobile sampling system. (P pump, PVC hose, filter (2 mm, 300 µm, 100 µm), flowmeter)	30 % H ₂ O ₂	ATR-FT-IR	PP, PE	13.8 ± 9.26 particles/m ³ (3.52–32.05 particles/m ³)	[96]
India (Netravathi River)	stainless steel bucket of 10-liter volume	H ₂ O ₂ (30%) in the presence of ferrous solution (Fe (II); 0.05 M), ZnCl ₂	Stereo zoom microscope ATR-FTIR	PE (58.3%) and PET (28.6%), PVC	288 particles/m ³ (56–2328 particles/m ³)	[97]
Italy (Ofanto River)	Plankton nets (333 µm)	30% H ₂ O ₂ in the presence of an iron (II) catalyst, NaCl solution (1.2 g/cm ³)	Digital microscope, Py-GC/MS	PE (76%), PS (12%), PP (10%), PVC (0.7%) and TDI-PUR (0.35%)	0.9 ± 0.4 – 13 ± 5 particles/m ³	[98]
Korea (Nakdong River)	Stainless steel beaker, Submersible pump	35% H ₂ O ₂ and Fe (II) solution, lithium meta-tungstate solution (1.6 g/cm ³)	ATR-FT-IR	PP (41.8%), PES (23.1%)	293 ± 83 particles/m ³ (upstream, February 2017)– 4760 ± 5242 particles/m ³ downstream, (August 2017)	[99]
Netherlands (Rhine and Meuse Rivers)	Glass jars	–	FT-IR	–	100 particles/m ³ (48–187 particles/m ³)	[100]
Nigeria (Ox-Bow Lake)	Clean Teflon pump (stainless-steel mesh)	H ₂ O ₂ (30%, v/v)	Micro-FT-IR	Dry season (water, sediment): PET (72.63%) and Plasticised PVC (10.9%)	Dry season: 1004–8329 particles/m ³	[101]

(continued on next page)

Table 3 (continued)

Location (country)	Sampling	Prior treatment	Analysis method	Results		Reference
				Composition	Concentration	
Taiwan (Fengshan River)	Hemp sling with a stainless-steel bucket hanging (50 μm , 297 μm , and 5.000 μm)	ZnCl ₂ solution (density: 1.8 g/cm ³)	ATR-FT-IR, gas chromatograph/mass spectrometer	Rainy season: Plasticised PVC (81.5%) and low-density polyethylene (LDPE; 4.2%) PE, PET, PA, and PES	Rainy season: 201–8369 particles/m ³ Water: 334–1058 particles/m ³	[102]
Turkey (Urban Crater Lake)	Glass bottles (0.045 mm)	–	μ -Raman, SEM	PE, PP	–	[103]
United Kingdom (Trent catchment)	Metal bucket on a telescopic pole	30 % H ₂ O ₂	Dissection microscope, ATR-FT-IR	PE (12), PP (3), PS (2), PVA (2), UA (1)	178 particles/m ³	[104]
United States (Gallatin River watershed)	Grab sample (average of 1.3 L)	–	Stereomicroscope, μ FT-IR	Semi-synthetic cellulose (30%), PES (20%), PET (13%), Cotton (5%), PP (4%), PA (4%), Urethane (4%), etc.	0.012 particles/m ³ (0–0.675 particles/m ³)	[105]
United States (Hillsborough River)	Neuston net (500 μm)	–	μ -Raman	PE (51%), PP (24.7%) and PS (5.9%), other polymers (10.5%) including PET (1%) and false positives (7%)	Surface samples: mean concentration 2.36 mg/m ³ and 2.36 mg/m ³ water column: mean 0.94 mg/m ³ and 0.34 mg/m ³ Bottom sample: July (2.71 mg/m ³), August (2.08 mg/m ³); July (3.42 mg/m ³), August (2.1 mg/m ³ and 14.1 mg/m ³) 0.44–9.7 particles/m ³	[106]
United States (Lake Mead)	mp net (100 μm)	30% H ₂ O ₂ and an iron catalase, lithium metatungstate (1.6 g/mL)	Stereoscope	–	–	[107]

fragments), followed by PP, nylon, and PES. The concentration of MP at the inlet was 0.0009 ± 0.0003 particles/m³, and at the outlet, it was 0.004 ± 0.0024 particles/m³. Europe (Carpathian basin): A developed mobile sampling system was used, including a pump, PVC hose, filter (2 mm, 300 μm , 100 μm), and flowmeter. The concentration of MP was 13.8 ± 9.26 particles/m³ (ranging from 3.52 to 32.05 particles/m³).

The amount of MP in ponds in the European Carpathian Basin (Hungary) was consistently lower near the pond's exit than at its entry, based on an examination of water and bottom sediment samples. Presumably, the pond acted as a sink for MP [96,108]. MP can move by wind and in water through catchments basins towards water bodies, i.e., movement from land towards larger freshwater systems. Thus, one of the most significant processes affecting the quantity and distribution of MP is the hydrological. In China, the lower portions of the Suzhou and Huangpu rivers tended to contain more MP while metropolitan areas and estuaries had smaller concentrations of MP pollution. In contrast, from tiny urban bodies of water to the sea, the number of fiber-like MP tended to decrease [109–111].

The number and distribution of MP in freshwater systems are subject to variation based on both intrinsic characteristics and external causes. Due to the characteristics of MP, results from actual environmental samples taken from stormwater ponds in Denmark verified that tiny particles are more prevalent than big particles. Large particles tend to either float on the water's surface or sink to the bottom of the pond since the particle's ultimate velocity is proportional to the square of its diameter [112]. Large plastic particles were identified in sediments, but numerous small ones were present in water samples from Indonesia's Chiwalengke River [106]. Plastic particle sedimentation may be influenced by the polymer's density as well as the terminal velocity, which is established by the size of the MP particles. mp were abundant in floating particulate matter in the Rhine and Meuse rivers in the Netherlands. Moreover, a significant amount of MP was discovered in estuarine sediments [96]. Over time, low-density MP frequently settle in sediments together with high-density MP. This is because MP interact with feces, aggregates, and biofouling, which can enhance sedimentation by decreasing MP buoyancy and raising particle density [113,114].

Sediments underneath the Nakdong River in Korea had 2830 times more MP than the top layer [99]. Larger and rougher-surfaced particles are more prone to biofilm formation and breakdown [106]. MP are not dispersed equally throughout the water system due to their characteristics and interactions with surrounding materials. The varying distribution of MP in soil and water samples taken from Lake Taihu, China, using plankton nets provides evidence in favor of this [111,115,116].

Anthropogenic and hydrodynamic variables are the main environmental influences on the spread of MP. Nine lakes in Patagonia, Argentina were reported to contain MP, primarily from fishing, textiles, and urban areas. Metropolitan areas have a critical role in the generation of MP, as evidenced by the correlation between the presence of MP in Lake Ontario, Canada, and the proximity to metropolitan centers [89].

The plastic industry, landfills, highways, wastewater, and other chemical compositions including cellulose, polyethylene, PET, and PVC are some of the sources of anthropogenic dye-based chemicals. Cigarette butts from abandoned commercial cigarettes are a source of cellulose acetate, a substance that may especially reinforce the effect of metropolitan areas. Supporting evidence for this was discovered in the Suzhou and Huangpu rivers in China, where the spatial distribution of MP revealed an increasing tendency in urban areas and estuary waterways [76,117]. At locations of direct and indirect usage and application, there were considerable concentrations of MP in Lake Mead, United States. It is common knowledge that fresh water is immediately impacted by wastewater, which represents every aspect of a metropolis. Nevertheless, MP concentrations in wastewater treatment plant effluents from three rivers in the UK's Trent basin did not significantly rise, indicating that there could be variations in effluent composition [107]. Residential and highway areas generate less MP than commercial and industrial sectors. Significantly, polyethylene was found on China's Tibetan Plateau and was shown to come from sheets that were used to mulch the surface of cultivated soils for agricultural cultivation [92]. It has been proposed that while studying MP, surrounding land use should be taken into consideration because the composition of MP might vary based on land use around freshwater [118–120].

Depending on where the samples were taken, the distribution of MP

along the Argentina's Rio de la Plata estuary varied considerably. The most urbanized regions had higher wastewater discharge and turbidity, which are associated with higher quantities of MP. These findings demonstrated that anthropogenic activities have an impact on MP and that there is a strong relationship between MP and habitat quality. The studied environmental parameters (temperature, pH, turbidity, conductivity, salinity, dissolved oxygen, total dissolved solids (TDS), and wind strength) did not, however, show any association [85]. MP concentration in sediment and water in Taiwan's Fengshan River was strongly connected with water quality parameters, including kind of polymer, flow rate, chemical oxygen demand (COD), and river pollution index [87]. Further study is required since the association between MP and water quality measures is not fully understood.

In addition to the inherent characteristics of MP and environmental conditions, one of the things that can have a big impact on their spread is the weather conditions. Following a storm, the level of MP in Australia's Crooks River surged 40-fold. After two days of intense rain, MP concentration peaked and then quickly decreased over the following five days [121]. High flow rates induced a first flush of suspended pollutants and conveyed MP deposited in the riverbed. Heavy rainfall and runoff mobilize contaminants, including terrestrial MP, into the river [122]. MP composition is also influenced by precipitation. Tire and road wear particles made up 22% of the particles identified in stormwater, according to research done in three rivers in the UK's Trent area. MP are effectively transported by sediment, which finds their way into the environment, water, and soil. According to research done in the Korean Nakdong River, 92% of the MP traveled through the water column and 70–80% of the yearly load migrated during the wet season [99,123,124].

It has been stressed that stormwater runoff must be included in the MP major transport routes as freshwater can carry MP from land to the sea [125]. MP are now mostly transported via agricultural irrigation from rivers into soil on China's Tibetan Plateau [92]. The dynamics of flows and tidal exchanges control the geographical distribution of MP in water and bottom sediments. Furthermore, the distribution of MP is determined by human emissions and MP density. Furthermore, rain and wind carry MP across great distances. Small fragments of MP were discovered in five different places at Turkey's 2380 m high Urban Crater Lake, distant from agricultural land. Less dense MP were carried to the sea by streams and rivers. It has been demonstrated that wind may carry MP to different locations [103]. The discovery of tire fragments in a pond next to a roadway further supported the theory that air deposition was occurring. Stormwater management techniques are crucial to reducing the amount of MP that enter the aquatic ecosystem since aquatic animals are susceptible to these long-distance migratory MP particles [126].

Advection flows were 10 times larger than lateral and vertical flows in a study measuring flow variations under various flow conditions in the Hillsborough River in Tampa, USA; in turbulent conditions, lateral and vertical plastic flows increased by up to 3–10 times [99,129]. Regardless of the density of the MP, turbulence and mixing brought on by typhoons or heavy rain can alter the concentration of MP in the water column and sediment. Turbulence is more likely to occur in plastic particles that are larger and have irregular shapes. Water levels and the amount of MP present in the Netravati River in India were found to be strongly correlated. This suggests that MP originating from the land move into freshwater ecosystems by showing a correlation between MP content and water volume [107,127]. MP from land enter freshwater systems due to weather and environmental factors, which impacts aquatic life. The bioavailability of MP can be determined by other water quality characteristics such as electric conductivity and pH. This was shown to impact, e.g., the quantity of MP in fish residing in Taiwan's Fengshan River [102,128,129].

2.4. MP in water; analysis and techniques for water and wastewater sampling and treatment

To collect wastewater samples, usually electric pumps are used, along with a glass storage container for MP analysis and a metal filter device (such as aluminum or stainless steel) [130–132]. The filter size may differ depending on type of MP that is investigated (11, 37, 125, 333, 500 μm , and 1 mm). Smaller MP may be removed from the analysis if a sample tool with a reasonably high pore size is utilized, such a 333 μm Manta mesh. Owing to the high concentration of organic matter in wastewater, the pre-treatment stage requires an oxidation procedure. Density separation is then used to extract MP from the intricate web of organic matter. Potassium hydroxide (KOH) or hydrogen peroxide (H_2O_2) may be used for this purpose. However, either enzyme cellulase is employed in a biological process or iron (II) sulfate is introduced for the Fenton reaction to achieve effective oxidation. Although the hydrogen peroxide oxidation procedure works well, if pretreatment is left for too long, bacteria may proliferate, and filtering may not be the best option [133]. Reagents having densities of more than 1 g/mL, such as zinc chloride (density: 1.6 g/mL), calcium chloride (density: 1.3 g/mL), and sodium chloride (density: 1.2 g/mL), are used for density separation [134,135].

High-density MP are often eliminated from content analyses because they cannot be separated using a comparatively low-density solution like NaCl (1.2 g/mL), such as PVC (density: 1.14–1.56 g/mL) or PET (density: 1.32–1.41 g/mL) [137]. Samples free of MP are used for pre-treatment and sampling to verify the MP extraction process' quality [136,137]. Establishing a uniform sampling and pretreatment procedure is necessary as it is challenging to compare results between studies due to variations in wastewater collection and pretreatment procedures for MP analysis.

Because freshwater environments have different characteristics than saltwater, it is challenging to employ a plankton net, which is routinely used to collect MP from that environment. Plankton nets cannot be used in small ponds that do not fit the troll. Facilities like boats and bridges are also required. Furthermore, even when a flow meter is used to measure the filtration value, it may still be erroneous [138]. Because sampling is often restricted to small freshwater bodies, the dredging technique was employed in three rivers in the Trent watershed in the UK in place of the Manta and Neuston nets [17]. In any case, it is important to choose a sample strategy that works well in the freshwater sampling environment.

One of the key considerations when selecting a sample technique is the particle size. When 333 μm mesh plankton nets were employed for sampling in the Ofanto River in Italy, tiny particles passed through the net, underestimating the amounts of mp. Research on how the mesh size affects the quantity of MP particles found that employing an 80 μm mesh may detect up to 100,000 times more MP particles than using a 450 μm mesh [139,140]. Care must be given while choosing the right mesh size since it can affect the concentrations of MP in the field.

Organic matter has previously been extracted from samples by digestion using acidic and basic solutions; however, since they break down polymers and are inefficient in extracting some organic matter, an alternate technique utilizing oxidative digestion has been suggested [141,142]. Organic debris is successfully removed by wet peroxidation (also known as the Fenton reaction or mpO), which has no discernible effect on polymers. However, some polymers, like PA and PE, melt or lose weight because of the high temperature (60–100 $^{\circ}\text{C}$) that happens during the oxidation process [143,144]. MP can become discolored because of the oxidation reaction of MPO and environmental weathering conditions, which causes transparent particles to be detected during MP analysis [145,146]. To ensure that the temperature stays below 60 $^{\circ}\text{C}$, the influence of an oxidant on temperature increase should be considered when choosing one for the removal of organic materials. Additionally, more studies must be performed to investigate effects of the discoloration of MP.

Denser solutions are more effective in eliminating MP from samples, but there are several things to consider, including expense and toxicity. Despite having a density of 1.7 g/cm^3 , zinc chloride is poisonous and prone to corrosion. Both sodium polystramate ($3\text{Na}_2\text{WO}_4 \cdot 9\text{H}_2\text{O}$) and sodium tungstate dihydrate ($\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$) are costly but include barite and have a high density of $1.4\text{--}1.6 \text{ g/cm}^3$. NaCl has a density of $1.0\text{--}1.2 \text{ g/cm}^3$ and is difficult to separate high-density MP, but is inexpensive, highly soluble, and low toxic. NaCl has been the density separation solution of choice in several investigations because of this. Creating a suitable density separation procedure is essential for the efficient separation of MP [136,147].

Several analytical instruments have been developed to analyze MP in aquatic environments. The detection range of scanning electron microscopy (SEM) is undefined as it is unable to study many forms of mp, but it can assess their surfaces at the nanoscale. MP are measured with a microscope or the unaided eye at the start of the investigation. The use of infrared analysis tools to qualitatively evaluate various kinds of MP and sizes has been developed. Furthermore, an attenuated total reflection mode can be utilized, and further analyses such as X-ray computed tomography (XCT) or scanning electron microscopy (SEM)-energy dispersive spectroscopy (EDS) are carried out. Compared to infrared-based analytical techniques, Raman spectrometry has recently been used that has a lower detection limit for mp. Nevertheless, because spectroscopic analysis is still limited in its ability to detect MP at the nanoscale, pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) is suggested as an alternative.

There are two types of MP analysis methods for MP in wastewater: heat analysis and spectrometric analysis. While hundreds of μm in size may be examined with an optical microscope, MP ranging in size from 1 to 5 mm can be identified with the unaided eye. The two primary techniques for analyzing MP with sizes in the tens of micrometers are FTIR and Raman spectroscopy. For nano-sized particles, thermal analysis methods as Py-GC-MS or thermal extraction, desorption, gas chromatography-mass spectrometry (TED-GC-MS) are advised [148–150].

To detect MP by using thermal analysis, larger quantities of MP are needed than in spectrometry, which examines each particle in detail. Because each particle thought to be an MP must be examined, spectroscopy takes a long time. Because they are difficult to identify, translucent particles or threads with black pigmentation are frequently underestimated [151,152]. The fact that non-MP particles might occasionally be mistaken for MP or that MP particles can fragment into smaller particles upon identification could lead to an overestimation of MP content [153]. MP can either be dyed using the Rose-Bengal technique [154], using enhanced identification and digestion procedures, or apply a bleaching reagent to eliminate any organic materials adhered to the surface to clearly separate MP from non-MP particles [155].

Dimensions from the mesh of a plankton net, which is used to gather MP from a wide region rich in organic matter, to the mesh of a filter, which is used to gather samples for tiny MP analysis, the sampling mesh is progressively decreased. However, the rate of false positive findings may rise with decreasing particle size in spectroscopic analysis, which can verify the form, size, and composition of MP particles [156]. Using spectroscopy, 83% of the MP particles larger than $100 \mu\text{m}$ were visually recognized as plastic, but only 63% of the particles smaller than $50 \mu\text{m}$ were confirmed to be plastic [157]. Under a microscope, a fibrous black material discovered in the Rhine and Meuse rivers in the Netherlands was recognized as mp; however, Fourier transform infrared spectroscopy did not reveal its identity [158,159]. For polymer identification using Attenuated Total Reflection Fourier Transform and Infrared Spectroscopy, the usual MP size is (ATR-FTIR) $> 500 \mu\text{m}$ [160–162]. Due to the limits of analytical equipment, even the effective recovery of MP from freshwater habitats might present difficulties in their interpretation. This means that tiny MP might be overrepresented; therefore, care needs to be taken when drawing conclusions based on MP size [163].

2.5. Possible environmental risks from MP

The number of fragmented MP grows exponentially as size decreases, and MP in marine settings often fragment gradually due to physical abrasion, UV irradiation, and biodegradation. MP in samples from surface waters in Greenland and the Northern Seas were flaky and worn. The surface of the MP, which was in the shape of a film, cracked like onion peels, and the broken MP showed unequal cracks. MP discovered in saltwater samples after a typhoon had higher wear, folds, and fractures than when the weather was not stormy [164,165]. These surface alterations supported the theory that MP age due to weathering from UV radiation and mechanical forces from wind and waves. Another element affecting the fragmentation of MP is flow rate. It is believed that the intense hydrological processes that occur during the flood season, with high flow rates, further encourages the fragmentation of MP [166,167].

The size of fragmenting and aging MP appears to gradually decrease. The size of MP determines its toxicity: marine zooplankton is more susceptible to harm from small MP than from big ones [168]. It was shown that MP smaller than $20 \mu\text{m}$ have the highest potential to damage marine ecosystems using MP detected in coastal surface waters of the subtropical island of Okinawa, Japan [169]. MP or nanoparticles smaller than $1.5 \mu\text{m}$ can directly harm cells, while particles smaller than $20 \mu\text{m}$ can cross cell membranes. Furthermore, a study using energy dispersive spectroscopy and scanning electron microscopy revealed that MP with a lot of weathered and exfoliated patches can absorb heavy metals [170, 171]. Studies have evaluated the hazards plastic polymers pose to the environment and human health based on their chemical makeup. Based on monomers, fifty-five plastic polymers were graded and assessed. The polymer families that include the most hazardous polymers are polyurethanes (PUR), polyacrylonitrile, PVC, epoxy, and styrene copolymers. These polymers are derived from monomers that are categorized as mutagenic or carcinogenic [5,172]. To enhance plastic goods, additives are supplemented to synthetic polymers throughout the production process [173,174]. These additives can be hazardous and have negative consequences if consumed, breathed, or come into touch with the product.

Utilizing the plastic polymer hazard ratings from an earlier investigation and the proportion of different MP polymer types collected at each sample site, a MP risk assessment was carried out for surface waters in the Changjiang River Estuary, China [175,176]. The research region was deemed to be a high risk due to the presence of PVC with high hazard ratings. Due to the release of internal plasticizers and carcinogenic monomers, PVC leaks into the marine environment have the potential to kill marine life. Additionally, PVC's surface can easily adsorb pollutants like persistent organic pollutants (POPs), which have complex toxic effects [142,177]. MP tend to absorb heavy metals and POPs in the marine environment [178]. A sample from the North Sea, Greenland, had a trace quantity of zinc bound to MP [179]. Fish can be exposed to dangerous substances through plastics, which can stress their livers and change their endocrine systems. When mixed with other contaminants, MP can have a major negative effect on coral reefs [180,181]. Plastics' toxicity is influenced by their shape in addition to their harmful chemical content and composition. According to research on the bioaccumulation and toxicity of MP consumed by fish, fiber-based MP accumulation is more harmful than fragment- or microbead-based MP accumulation. Large volumes of organic compounds are absorbed by aged polymers in granular form [182,183].

2.6. Recommendations to reduce MP

Seawater is the destination of inland waterways and is exposed to marine industry, whereas freshwater, which is closest to land, is mostly exposed to waste from land-based activities. Wastewater is a byproduct of human activity. Any aquatic habitat is hence significant. Every day, significant volumes of plastic garbage are produced and released into aquatic environments without the proper waste treatment procedures in

place. Plastic garbage thrown into the environment influences both environmental and anthropogenic elements in the surrounding region.

When plastics are discharged into the environment, they are usually not in their industrial form and are susceptible to corrosion and fragmentation from external sources. High amounts of organic compounds are absorbed by aged MP. Therefore, aged MP rather than industrial plastics should be used for toxicity studies. It is necessary to do more research on the toxicity of dangerous compounds like POPs and heavy metals, which are readily absorbed by outdated MP.

The paucity of studies on plastic debris in sediments is one of the biggest obstacles to the field of MP study. UNEP research states that only around 30% of marine debris is discovered floating in the ocean or on beaches, with the bulk of rubbish falling into sediments [184,185]. Because it may be harmful, marine garbage that settles in sediment is difficult to remove and threatens marine ecosystems. Benthic animals may readily consume plastic debris that is present on the seafloor. Plastic garbage is liberated and transferred when there is a shift in the ocean current or a meteorological event that causes vertical mixing of the seawater layer [186].

Since water systems are where MP end up, it is important to control industrial polluters and all plastic items that are made and disposed of on land to mitigate the quantity of plastic waste that ends up in water systems. Better control of drainage systems on land and efficient waste management are required. Regulations in one or two nations will not be enough to address this issue; but a worldwide coalition and regulations would be necessary for a reduction in MP. Furthermore, technologies for eliminating MP need to be created specifically for each type of aquatic ecosystem [187,188].

There are two categories of factors that affect the amount and distribution of MP in aquatic ecosystems. These include biological interactions in the aquatic environment, climatic events, and industrial locations close to the water system, in addition to the intrinsic characteristics of MP, such as hydrophobicity, specific gravity, and size. When plastic debris is exposed to strong UV rays, waves, and wind in the environment, it ages and fragments, dispersing into tiny pieces across the planet. It is possible for MP to travel through the atmosphere.

Because MP are easily carried by wind, they have also been discovered in Antarctica and the Alps [189,190]. Excrement, biofilms, and aggregates can all interact to deposit low-density MP. Furthermore, meteorological patterns cause deposited MP to resuscitate and spread throughout the aquatic ecosystem. Due to improper waste management at industrial locations close to the sample site, plastic garbage occasionally finds its way into the water supply.

Despite the apparent establishment of a relationship between MP in aquatic habitats and their sources, inconsistent outcomes are seen because of unpredictable weather fluctuations. Notably, the horizontal distribution brought about by environmental variables and the vertical distribution, which is impacted by the specific gravity and biological interactions of MP, enhance the variability of MP because of weather variations. An important consideration when researching MP in aquatic habitats is weather and climate. It is challenging to determine the distribution of MP in a research region by single-sample methods. Accurate MP analysis necessitates long-term monitoring [191].

The largest problem, aside from these environmental factors, is still the grid size for sampling, which varies between different studies. Furthermore, the interpretation of the data is limited due to the differences in the sampling and preprocessing techniques. The development of sampling and pretreatment techniques for MP analysis need to be the top focus. However, it is advised to create a pretreatment technique for each polymer under analysis and an ideal methodology based on the polymer, as the effects of the density separation solution and digesting reagent may vary depending on the polymer [192].

The primary driver for the increasing significance of this field of study is the uncontrolled negative effects of MP on the environment. Despite the continuous production and recycling of plastics, appropriate waste management is lacking. Small species at the base of the food chain

consume small fragments of disintegrated plastic trash thrown into the environment, which might be harmful to human health [193].

Even though the toxicity of MP has been extensively studied, toxicity evaluations are challenging due to the tiny size of the particles. Apart from the unfavorable consequences resulting from the intrinsic physical and chemical characteristics of MP, the environment's hazardous materials that readily adhere to MP constitute an even bigger risk. Plastic materials have been employed in most investigations to regulate experimental conditions. However, a variety of environmental conditions can alter the chemical characteristics of aged MP [194]. More research is required on plastics whose chemical characteristics have altered because of environmental aging.

Once discharged into the environment, plastic garbage keeps breaking down and endangering life as we know it. A thorough waste management system must be created to stop the careless disposal of garbage into the environment to stop the problem from getting worse. Defining sample and pretreatment procedures is the first step towards conducting accurate investigations of MP. Next, a technique for detecting MP at the nanoscale must be developed (Fig. 5). MP come from many sources, such as home garbage, industrial processes, and the deterioration of larger plastic objects. It is essential to comprehend these sources to create solutions that effectively reduce their environmental impact. A variety of international agreements and organizations, national laws and regulations, corporate and non-governmental initiatives, technical and engineering solutions, and national laws and regulations have all been involved in the global effort to prevent plastic pollution. Marine pollution, especially MP, is an objective of the Sustainable Development Goals (SDGs) of the United Nations, particularly SDG 14 [195]. In addition, the United Nations Environment Programme (UNEP) has been instrumental in promoting international action to mitigate plastic pollution and increasing public awareness of the issue [196].

To improve global plastic waste management and decrease the transport of plastic waste, particularly from developed to less developed countries, the Basel Convention on the Control of Transboundary Movements of Wastes and Their Disposal has been amended to include plastic waste [197]. Addressing plastic pollution has also greatly benefited from national laws and regulations. The Single-Use Plastics Directive (2019) of the European Union seeks to outlaw specific single-use plastics, support recycling, and stimulate the development of sustainable substitutes. In an effort to limit the amount of plastics that enter the environment, this regulation has had a substantial influence on the manufacture and disposal of plastics inside the EU [198].

The Ocean Cleanup and other non-profit groups are spearheading initiatives to eradicate plastic debris from rivers and seas [199]. These initiatives include involve encouraging improved waste management techniques and increasing public awareness of the causes of plastic pollution. There are still obstacles in the way of properly tackling MP, despite these enormous efforts. For instance, the issue is still exacerbated by the environmental persistence of legacy plastics and the partial decomposition of some biodegradable polymers. Furthermore, stricter laws and improved enforcement are required, especially in areas with heavy plastic usage and inadequate waste disposal facilities. MP sources must be taken into account, as well as current international initiatives to lessen their occurrence in freshwater systems. More extensive and co-ordinated worldwide action is needed, even if national laws, international agreements, business initiatives, and technical advancements have made progress in reducing plastic pollution. Subsequent investigations ought to concentrate on enhancing the efficiency of current protocols, creating novel technologies for the handling of plastic trash, and comprehending the enduring consequences of microplastics on human well-being and ecosystems.

In view of the above, further research is required to determine the toxicity of MP and related pollutants as well as any environmental variables that may have an impact on MP. Ultimately, it is critical to study how MP behave, manage their entry point into the water body, and reduce the amount of discharged MP. Research on the allowable

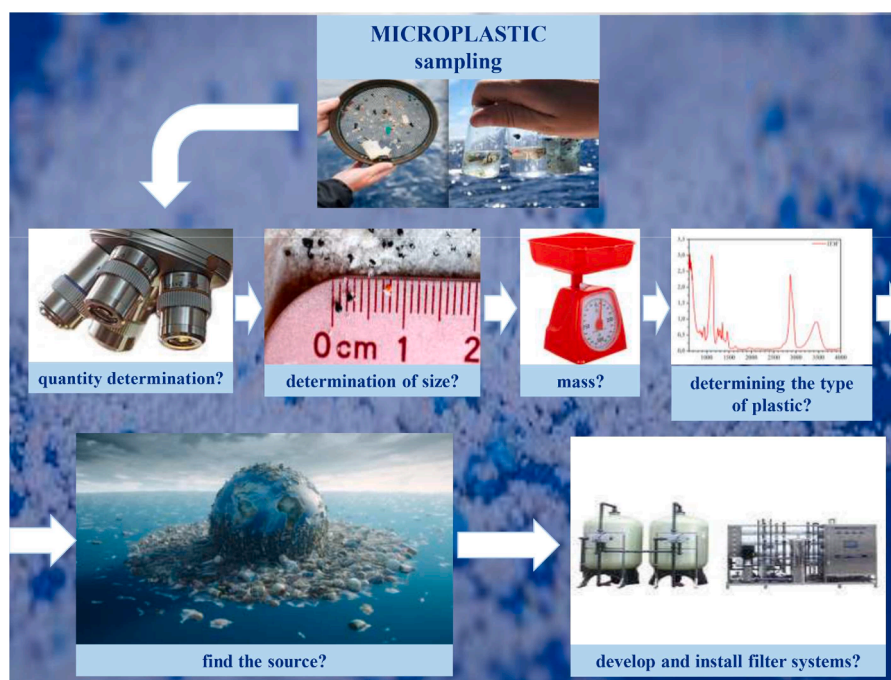


Fig. 5. MP in drinking water, from methods to results.

level of MP in the human body without endangering health suggests that plastic waste is not properly managed.

Effective management of MP pollution necessitates the development of specialized strategies tailored to the specific conditions and pollution levels of each region. Drawing on current scientific data and literature, well-founded recommendations can be made for management strategies and detection methods across different areas. In countries with high pollution levels, such as China, Indonesia, India, and the Philippines, where a significant amount of plastic waste is generated, much of which enters aquatic systems as MP, strategic measures must be implemented to reduce this pollution and prevent further environmental degradation.

Recommended management strategies include intensive monitoring and water quality control, which involve establishing comprehensive monitoring systems, regularly surveying water bodies using modern analytical techniques to detect and quantify MP and developing and upgrading infrastructure for plastic waste processing and disposal, including the installation of specialized filters at treatment facilities. Another key element is the introduction of regulatory and legislative initiatives to limit the use of single-use plastics and promote the transition to more environmentally sustainable materials.

For detecting MP in these regions, methods such as Raman spectroscopy, which is highly effective for the rapid and precise identification of MP ranging from 0.5 to 20 μm in size, and pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS), used for analyzing nanoscale MP and identifying hazardous chemical additives, are recommended. Additionally, a combined microscopic and chemical analysis approach, involving the use of stereomicroscopy together with FT-IR spectroscopy, can reliably identify MP of various sizes and chemical compositions.

In regions with moderate pollution levels, such as Brazil, Mexico, and Turkey, a balanced approach is required, combining systematic MP monitoring with educational initiatives and technological solutions aimed at reducing pollution. This might involve developing national monitoring infrastructure, launching educational programs to raise public awareness about the dangers of MP, and promoting plastic waste recycling and sustainable technologies. Detection methods suited for these regions include Fourier-transform infrared (FT-IR) spectroscopy, which provides accurate analysis of microplastics ranging from 10 to

500 μm in size, and thermal analysis, which is applied to identify MP between 50 and 100 μm and assess their thermodynamic properties.

In regions with low pollution levels, such as Ethiopia, Uganda, and Niger, the focus should be on preventive measures and early detection of potential increases in MP levels. This includes the implementation of pollution prevention programs, such as limiting the import of plastic products and transitioning to alternative materials, establishing local monitoring systems for timely detection of changes in MP concentrations in water bodies, and initiating agricultural programs aimed at preventing water contamination through agricultural runoff.

Detection methods such as stereomicroscopy, which is suitable for quick and straightforward identification of large MP particles ranging from 20 μm to 5 mm, and microscopic analysis using ATR- μFTIR , which ensures qualitative analysis of MP in water and sediments, will help monitor the situation in these regions. Thus, successful management of MP pollution requires individualized strategies that consider the unique ecological and social conditions of each region. The implementation of advanced MP detection and analysis methods, along with the development of regulatory, educational, and infrastructural initiatives, will significantly reduce pollution levels and minimize its adverse effects on ecosystems and human health.

3. Conclusions

Concern over the effects of plastic debris, particularly MP, on freshwater ecosystems has grown in recent years. MP, which are microscopic plastic particles smaller than 5 mm, can find their way into freshwater bodies through several routes, including air deposition, agricultural runoff, and sewage treatment facilities.

The amount of plastic garbage entering the environment has significantly increased over the past several decades due to the mass manufacture of plastics. Plastic manufacturing increases despite initiatives to cut plastic usage and enhance waste management techniques. As a result, large volumes of plastic debris have found their way into freshwater environments, endangering aquatic life, and perhaps having an impact on human health.

Studies have indicated that the manufacturing sector alone generates around 280 million tons of plastic garbage annually. This garbage may

find its way into groundwater supplies, rivers, lakes, and ultimately the seas. The global distribution of plastic pollution in the oceans is seen in Fig. 1, with Asia accounting for most of the contamination.

Different synthetic polymers generated from coal, petroleum, and natural gas are the building blocks of plastics. The most widely used plastics are polyester, polyvinyl chloride, polyethylene, and polypropylene. These materials are frequently utilized because they are durable, adaptable, and are cheap in production. Nonetheless, there is a significant issue with their pollution status in the ecosystem.

Although research on MP effects on freshwater ecosystems is ongoing, preliminary findings indicate that they may be harmful to aquatic life. Fish, birds, and other species can consume MP, which can lead to bodily injury, decreased reproductive success, and even death. Furthermore, other contaminants like heavy metals and organic compounds, which may build up in the food chain and endanger human health and animals, can be carried by MP.

A diverse strategy is needed to address the issue of MP contamination in freshwater environments. It is imperative to try to decrease the usage of plastic and encourage sustainable substitutes. Enhancing waste management procedures is essential to keeping plastic debris out of freshwater bodies. This includes recycling and disposing of it properly. Furthermore, the development of sophisticated filtering technologies at wastewater treatment facilities can aid in the removal of MP prior to their release into lakes and rivers.

In conclusion, there is a major risk to human health and the environment posed by the growing amount of MP in freshwater environments. Rivers, lakes, and groundwater sources are now contaminated due to the mass manufacturing and inappropriate disposal of plastic garbage. Reducing plastic usage, enhancing waste management procedures, and creating creative ways to lessen the consequences of MP contamination are all urgently required. The preservation of freshwater habitats is crucial for the welfare of wildlife and humans alike, and it calls for the combined efforts of organizations, businesses, and private citizens to engage in this urgent problem.

CRediT authorship contribution statement

K. Bexeitova: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **A. Baimenov:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **E.A. Varol:** Writing – review & editing, Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **K. Kudaibergenov:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **U. Zhantikeev:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis. **Y. Sailaukhanuly:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **K. Toshtay:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Z. Tauanov:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation. **S. Azat:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **R. Berndtsson:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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