Volume 66(1):75-84, 2022
Acta Biologica Szegediensis
http://abs.bibl.u-szeged.hu/index.php/abs
DOI:10.14232/abs.2022.1.75-84

MINIREVIEW

Origin, environmental presence and health effects of microplastics

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ABSTRACT Microplastics (MPs) – consisting of small plastic particles with size less than 5 mm – have become ubiquitous environmental contaminants. Even though plastics are mass produced and proved to be useful in many applications, they may have potentially negative impacts on environment and human health. Multiple sizes, shapes, and polymer types, and their various sources can influence the environmental and human health effects of MPs. Being present in oceans, freshwater, soils and air, MPs can cause human exposure via ingestion, inhalation, and dermal contact, resulting possibly in oxidative stress, inflammation, altered balance in metabolism and immune system, neurotoxicity, reproductive toxicity, and cancer risk. Also, MPs can act as vectors of toxicants or microorganisms. All the same, public awareness towards MPs is currently low, and a lot of studies related to MPs are still ongoing. Further research is needed for a better understanding of MPs' occurrence in environmental systems and their human health effects.
Acta Biol Szeged 66(1):75-84 (2022)

KEY WORDS
environment
health effects
microplastics
pollution

ARTICLE INFORMATION
Submitted
28 June 2022
Accepted
27 July 2022.
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Introduction

Since plastic products started to appear in the market at large scale in the 1950s, the global production of plastics increased dramatically from 0.5 million tons per year in 1960 to 348 million tons in 2017. Plastics have been playing an important role in the general improvement of human life conditions, thanks, e.g., to disposable medical equipment and increased food safety. On the other hand, wrong management of plastics may have undesired effects on human health and the environment. Most plastics are chemically stable and resistant to environmental impact, the huge amount of discarded plastic items is consequently a major environmental problem. Up to now, 8.3 billion tons of plastics have been manufactured, of which 6.3 billion tons are already waste, and ca. 80% of that ended up in landfills or in the free nature (Geyer et al. 2017).

However, despite all durability, many kinds of plastics suffer loss of material integrity when exposed to ultraviolet light and/or mechanical forces and become small debris. Fragments from 5 mm or less down to nano size are called microplastics (MPs). Because of slow further degradation, MPs tend to accumulate in the environment from various sources and have been widely reported in terrestrial and marine ecosystems. Plastic matter itself can contain harmful substances, and can, beyond that, act as carrier of toxicants such as endocrine disrupters (Wu et al. 2019).

MPs can be further classified into primary and secondary based on their sources. Primary MPs are intentionally produced for further processing into final commodities. These preproduction MPs, often called nurdles, are transported in large amounts also by sea, and shipping accidents may result in release of these nurdles into open sea or onto coasts. Plastic microbeads as additives in personal care products (hand and facial cleansers, toothpaste, cosmetics) are also primary MPs and end up typically in municipal wastewater. Secondary MPs are fragments degraded from larger plastic products (e.g., ropes, fishing nets, packaging, textiles).

Presence of MPs in the environment inevitably leads to human exposure, but knowledge on this newly recognized health hazard is still rather incomplete. In this paper, outcomes of a literature survey on the topic of MPs including origins, properties, and health and environmental effects, are summarized.

Methods

A literature search was performed, using web-based sources, such as PubMed, Scopus and Science Direct. The principal keyword was "microplastics" applied alone or combined with "human" "health", and "health effects".

During the search it became clear that most of the relevant papers were published in the last ten years, underlining the novelty of this subject. Fig. 1 shows the

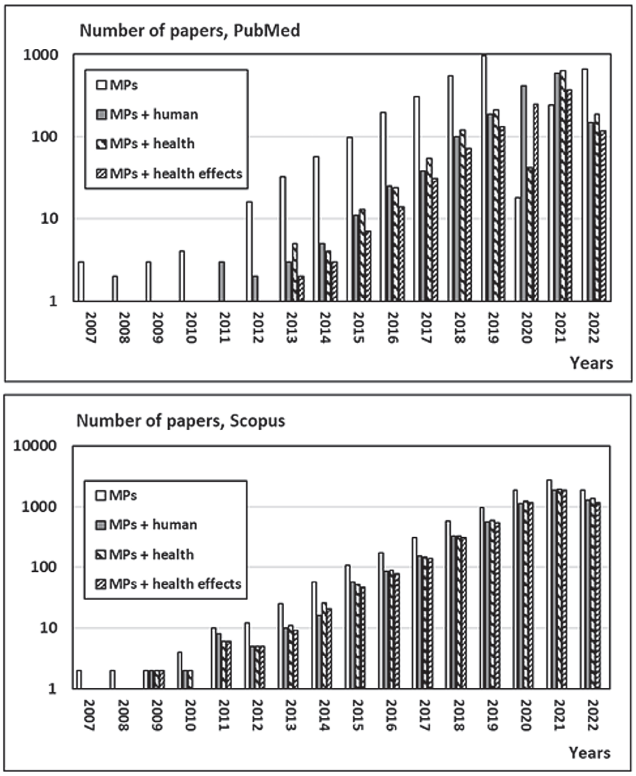

Figure 1. Number of papers returned by PubMed and by Scopus, with the keywords indicated.

distribution over the years of papers returned by PubMed and by Scopus, using the keywords indicated. From this ample source of information, the references for the purpose of this narrative review were selected by relevance to the aims defined above and by recency.

Occurrences, fate, and transport of microplastics in various environments

Microplastics, coming from a range of sources, interact with various constituents of the environment (seawater, freshwater, groundwater, sediments, soils), and are transported and transformed in a number of ways.

Presence of MPs in the oceans

Accumulation of MPs in the oceans has been detected worldwide. According to Wu et al. (2019), 94% of the plastic samples collected in the Northeast Atlantic are MPs and 89% of among them are less than 5 mm in length. Similarly, samples of the Pacific and Mediterranean surface waters contained MPs in 96% and 100%, respectively. MPs were found even in the polar areas of the Arctic Ocean (93-95%).

One of the major sources is accidental emission. When the container ship X-Press Pearl caught fire and sank in the Indian Ocean near Sri Lanka, in May 2021, 87 containers full of lentil-sized pre-production plastic pellets (nurdles) fell in the sea, and about 1,680 tons of the stuff were released. Nurdles are often mistaken as food by seabirds, fish and other wildlife, and were found so far in 470 turtles, 46 dolphins and eight whales washed ashore dead (UNEP 2022)

MPs released into aqueous environment will sink or float, depending on their density and whether they are in freshwater or saltwater, which leads to variations in distribution. Reisser et al. (2015) found in the North Atlantic Gyre that MPs of 0.5–1.0 mm size are more abundant in subsurface than surface water. The North Atlantic Gyre is a circular stream of ocean water in the Northern basin of the Atlantic, comprising, among others, the Gulf Stream; and the North Atlantic garbage patch, a huge collection of man-made marine debris, is found floating within it. The patch is estimated to be hundreds of kilometers wide, with a density of more than 200,000 pieces of debris per square kilometer. The specific surface area of such small MPs is large, which increases the adhesion of phytoplankton, organic debris, clays, and other particles, resulting in increased particle density (Claessens et al. 2013). This way, the MPs also act as “toxic sponges”. A lot of hydrophobic toxic molecules present in seawater (including persistent organic pollutants such as dioxins) will gather on the surface of MPs, to a concentration million times higher than in the water. After being consumed e.g., by fish, the toxicants can be transferred to and deposited in the animals’ tissues and can reach humans via sea food. By a similar mechanism, bacteria, including human pathogens, can be deposited on the MPs’ surface. To make it worse, MP particles covered by a rich biofilm are more attractive to marine animals seeking food.

The most common types of MPs in the seas are fibers and fragments. In the Mediterranean Sea, MPs in surface water were mostly fragments (87.7%-93.2%), and only 2% were pellets/granules (Cózar et al. 2015). The most frequently collected plastic particles in surface waters worldwide are polyethylene (PE), polypropylene (PP) and polystyrene (PS), which are also the most produced plastics globally (Hidalgo-Ruz et al. 2012). These polymers are floatable, so that they predominate in the surface layers. The variable composition of MPs in the ocean may indicate their sources, based on which an improved management of plastic waste could be achieved (Wu et al. 2019).

MPs in the ocean are frequently derived from fragmentation of larger plastic items. These can enter from rivers, runoff, disaster events, be moved by tides and winds, but can also originate in the seas (lost cargo, fishing and aquaculture equipment). Besides bundled fishing nets and ropes from marine origin, about 80%

of plastic debris in seas are derived from inland sources. For example, 530-1500 tons of plastic were transported by the Danube into the Black Sea annually (Lechner et al. 2014) while global plastic waste discharge from the rivers amounts to 1.15-2.41 million tons (Wu et al. 2019).

Identification of the way to oceans and original sources of MPs is difficult due to their small size, but further research on the properties of MPs (particle morphology and polymer types) may be helpful in identifying their origin. Resin pellets, such as PS, of about 2.5-5 mm diameter, are primary MPs (industrial feedstock of consumer plastic products) and reach the ocean through wastewater discharge from plastic-producing/processing plants to a river. However, due to the more efficient recapture of spilled pellets and better management in the plastic industry, the resin pellets' concentration decreased significantly between1986 and 2008. Therefore, fragments and fibers are the major types of MPs in the ocean in recent years (Reisser et al. 2015).

Secondary MPs are degraded from existing plastic items in the ocean by photochemical, oxidative and hydrolytic degradation. According to Morét-Ferguson et al. (2010) such MPs have characteristics marks of deterioration such as brittleness and rough edges/cracks. Microfibers are derived from the degradation of plastic items of shipping activities, fishing equipment, recreation, offshore industries, and, importantly, from laundering of synthetic textiles (Wu et al. 2019).

Presence of MPs in freshwater

Widespread occurrence of MPs is known also in freshwater environment, and constitute a major source of marine plastic debris.

In the American Great Lakes, the frequency of MPs occurrence was 100% in Lake Superior, 87.5% in Lake Huron and 100% in Lake Erie. The corresponding MP concentrations (in particles/km^2) were 5390 (Lake Superior), 2779 (Lake Huron), and 105,503 (Lake Erie; Eriksen et al. 2013). Several studies showed the occurrences of MPs in major rivers, in urban sections and in the estuaries.

In freshwater environment, the concentrations of MPs are highly dependent on human population density, economic and urban development, waste disposal, and hydrological conditions. In a highly urbanized river of Chicago, concentration of MPs in surface water was 6,698 thousand items/km^2, higher than in oceans and the Great Lakes. Also, research about Yangtze river of China revealed 3,407 to 13,617 thousand MPs/km^2 in the main stream, and 192 to 11,889 thousand MPs/km^2 in the estuarine areas of four tributaries. In general, the concentration of MPs in freshwater is higher at sites with higher population density. A counterexample is Lake Hovsgol in a mountain area in Mongolia, laden with 44 thousand MPs/km^2 because of improper waste management (Wu et al. 2019).

Also in Hungary's Tisza River, MPs' presence is on the increase (Féjja, 2021). Measurements by the University of Szeged, running for 3 years by now, found that the majority of 0.05 to 5 mm plastics came from fragmentation of macroplastic waste and only a little fraction originated from cosmetics. Most of the particles were plastic fibers, indicating their communal wastewater origin (laundering synthetic clothes). The authors hypothesized that populated areas with high population densities and improper waste management contribute the most to the direct input of MPs into Tisza and its tributaries and to development of local MP contamination hotspots (Kiss et al. 2021). In a yearly large voluntary action (called PET Kupa, that is, PET Cup) thousands of PET bottles and tons of other waste are being collected from the river and its banks (Petkupa.hu). It is also noteworthy that Tisza flows into Danube, the MP burden of which to the Black Sea was mentioned above.

Similarly to ocean environment, the most widely found MPs in freshwater are PP and PE, but differences vs. ocean water exist because of differences in pollution sources, location, and hydrodynamic conditions. Fragments and fibers are frequently dominant, but in some rivers, e.g. the Rhine, the MPs collected were dominated by spherules, pellets and microbeads (Mani et al. 2015). Spherical MPs are not well transported for long distance by water streams, so the bottom of rivers is potentially their major sink.

With their vicinity to sources of pollution and with smaller water bodies, MP content of freshwaters is more influenced by local sources than in case of the oceans (Mani et al. 2015). Urban watershed and MP concentrations are highly correlated. In the Rhine and Danube, the major type of MPs is spherules. PS spherules possibly come from plastic processing plants with industrial wastewater, while the PE spherules (microbeads) occur in personal care products and so in municipal wastewater. Due to resistance of classic plastics to biodegradation, MPs are not decomposed during standard wastewater treatment, but may be removed. Grease removal, solid skimming, sludge settling, and similar mechanical methods can transfer MPs into sewage sludge efficiently, but MPs in the sludge, in case it is deposited openly, may be resuspended and become airborne, spreading to terrestrial ecosystems. Fibers and pellets in freshwater also frequently originate from wastewater discharges. In the Chicago North Shore Channel, MP concentration at the sampling site downstream of a wastewater treatment plant was 9.2 times higher than that at the upstream site (Wu et al. 2019).

Non-point source of MPs is associated with surface runoffs (uncontrolled flow of excess rainwater), accidental spillages, as well as with poor management of wastewater and solid waste in underdeveloped regions. As reported by Baldwin et al. (2016) the 29 tributaries of the Great Lakes had higher MP concentrations during runoff events than under normal conditions.

Presence of MPs in sediments (bottom sediments, beach sediments) and soils

MPs are likely to sink and accumulate in bottom sediments when they lose buoyancy. This takes place mainly in coastal shallow regions of seas, such as subtidal or continental shelf areas, but MPs up to 2000 particles per m^2 have been detected even in distant deep-sea sediments. In areas near the shore, observed MP concentrations were e.g., 20-3320 items/L in Sweden, 97.2 items/kg dry sediment in Belgium, 672-2175 items/kg dry sediment in Italy, and 10 items/kg sediment in Portugal (Wu et al. 2019).

MP accumulation in freshwater sediments, with high and widely varying concentrations, has also been reported. In a study on occurrence of MPs in the subalpine Lake Garda in Italy, 108 (south shore) to 1108 (north shore) particles/m^2 were observed (Wu et al. 2019).

The factors that influence MPs in sediments are still largely unknown. A positive relationship between MP concentration and human population density is, however, obvious, and has been in fact described (Naji et al. 2017) since the majority of MPs in sediments originate from settlements.

Regarding beach sediments, Browne et al. (2011) reported that among 18 beaches in six continents, the MP concentrations at 1 cm depth ranged from 2 fibers/L in Australia to 160 fibers/L in the United Kingdom and Portugal. Examining the Belgian coast, Van Cauwenberghe et al. (2015) reported that MP concentrations in coastal harbor, beach and sublittoral areas were significantly different due to factors including freshwater inputs, urban discharges, human population density, urbanization, industrialization, aquaculture farming, and monitoring methods.

The major shapes of MPs in sediment samples are microbeads/pellets, fragments and fibers, and the polymers, PP, PE, and PS. The likely sources include coastal industrial and municipal wastewater discharges and direct plastic disposals (Martin et al. 2017).

Soil contamination with MPs is largely due to solid waste landfilling and dumping, and sludge fertilizing. In a soil treated with organic wastewater sludge for 15 years, plastic fibers were detected (Zubris and Richards, 2005). Nizzetto et al. (2016) reported that approximately 63 000 to 430 000 and 44 000 to 300 000 tons of MPs may enter farmland soils annually through sludge application in Europe and North America, respectively. The presence of MPs may influence soil physical properties, such as aggregate structure. Liu et al. (2017) found that addition of MPs can enhance microbial enzymatic activity to activate organic C, N, and P pools, and therefore promote their presence in the dissolved phase and accessibility to plants.

Primary MPs found is soils come mainly from application of sewage sludge on farm soils. Secondary MPs in soils originate from decay of agricultural plastics, such as soil covers (plastic mulch) and plastic tunnels, or from incidental plastic debris, at soil surfaces or inside the soil profile. Very small particles or fibers can be distributed further by airborne deposition onto soils. Since it is technically complicated to isolate MPs from a complex organic soil matrix for analysis, it is difficult to fully characterize and quantify MPs.

Presence of MPs in air

MPs can be blown out from surfaces of poorly managed landfills or untidy streets, and stay airborne. The atmospheric deposition of MPs in an urban and a suburban site of Paris (France) was between 2 and 355 particles/m^2/day, consisting mainly of fibers (Dris et al. 2016). In a subsequent study (Dris et al. 2017), they found MPs in both indoor and outdoor air and indoor settled dust. MPs concentrations were 1.0 to 60.0 fibers/m^3 indoors, and 0.3 to 1.5 fibers/m^3 outdoors. Deposition rate of MPs in indoor environments was 1 to 11 thousand fibers/day/m^2. About 33% of MP fibers in the indoor environment were synthetic, mostly PP. These results suggest that the residential atmosphere contains MPs that can lead to human exposure and possibly to health risk.

Final fate of environmental MPs

In general, once MPs reach a water body, they will end up in the ocean. About 70% of marine trash are estimated to settle down to the bottom of ocean as sediment, 15% floats on the surface, and the remaining 15% is present in coastal areas. If MPs are ingested by organisms, they may either be excreted as waste or retained in/translocated to tissues. Along the food chain, trophic transfer and accumulation in organisms at higher levels can take place. Moreover, MPs may enhance the transport of persistent, bio-accumulative, and toxic substances, added to the plastic matter during manufacturing or adsorbed later on MPs' surfaces.

Human exposure and health effects of microplastics

MPs may act on human health by causing oxidative stress, cytotoxicity and inflammatory changes, by altering metabolism, by translocating to distant organs, possibly resulting in neurotoxicity, reproductive system toxicity, and carcinogenesis. In addition, as an indirect effect, MPs may release chemicals, from their matrix or adsorbed from the environment, or act as vectors for dangerous microorganisms.

Routes of exposure

The main routes of human exposure by MPs are ingestion of contaminated food (e.g. table salt, seafood such as shellfish) and water, inhalation (both indoor and outdoor air), and by direct dermal contact to the particles through personal care products, clothes, cosmetics or indoor dust. The chance of internalization is higher for very small, microscopic or submicroscopic particles, while bigger particles mostly do not cross the external or internal boundaries of the body and remain in the intestinal contents or within the airways.

Ingestion

The number one route of human exposure to MPs is ingestion of contaminated food and water. Estimated intake of MPs is 39 000 to 52 000 particles per person per year (Prata et al. 2020). The levels of MP consumption vary between different sex and age groups, due to differences in diets and lifestyles. With inhalation included, estimated yearly MP intake values increase to 74 000 to 121 000 particles per person (Rahman et al. 2021).

Drinking water treatment is an effective barrier to a wide range of waterborne particles, but it may contribute to MPs in drinking water because some plastic components of treatment plants and distribution networks may erode or degrade. In drinking water, MP concentrations range from zero to several ten thousands particles/L, the predominant types being fragments and fibers (WHO, 2019).

Similarly, bottles and caps of most bottled waters are made of plastic, which are possible primary sources of MPs. In the study of Mason et al. (2018) eleven brands of bottled water, purchased at 19 locations in nine countries, were tested for MPs. From the 259 bottles, 93% showed presence of MPs, with an average level of 10.4 particles/L of >100 μm size. The major type of MPs was fragments (66%) followed by fibers, and the most common polymer was PP (54%), the material of bottle caps. A study by Rahman et al. (2021) indicated that persons who only consumed bottled water to meet their recommended fluid intake were ingesting an additional 90 000 particles, in contrast to only 4000 particles for those who consumed tap water only.

Items of solid food in which MPs are likely reported include sea food (such as mussels and commercial fish) table salt, and sugar. A comprehensive review by the European Food Safety Authority in 2016 included 10 studies that measured MP concentrations in marine fish and shellfish. Typical concentrations of MPs were 1 to 7 particles per fish and up to 10 particles/g of shellfish. Particle sizes ranged from 130–5000 μm and 5–25 μm in fish and shellfish, respectively. This also meant very small consumed amounts of polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and bisphenol A (BPA; WHO, 2019). Van Cauwenberghe and Janssen (2014) showed that exposure of Europeans via consumption of bivalves is approximately 11,000 MPs per person per year. Since mussels (*Mytilus* spp.) contained the highest median MP count of 4 particles/g and since they are eaten without removing their digestive tract, mussels can serve as a conservative (pessimistic) model for all fish and other seafood. The European Food Safety Authority estimated an intake of 7 μg of MPs associated with an intake of a 225 g portion of mussels. Bivalves (mussels, oysters, etc.) obtain nutrition by passing water through their bodies and filtering out plankton, organic particles, but also suspended MPs, which explains the high particle count in edible bivalves and the resulting human exposure.

Further studies reported moderate presence of MPs in honey – 0.166 fibers/g (size range 40 to 9000 μm) and 0.009 fragments/g (size range 10 to 20 μm); and in beer – 0.025 fibers/mL and 0.033 fragments/mL. Another study about table salt found the highest concentration of MPs, at 0.550 to 0.681 particles/g (size 45 to 4300 μm) in sea salt (WHO, 2019). Besides presence in food itself, there is also a possibility of MP contamination on plates during mealtime due to dust, or due to packaging foodstuffs e.g. in plastic containers (Prata et al. 2020).

MPs reach the gastrointestinal system with contaminated food or through the mucociliary clearance after inhalation. This may result in inflammatory response, increased permeability, and changes in gut microbe composition and metabolism. After ingestion, MP particles could be phagocyted in the intestine by M cells of intestinal lymphoid tissue (Peyer's patches), or directly absorbed, depending on adherence to the gastrointestinal mucosa. Another possible way of absorption, paracellular transfer of particles through the intestinal epithelium, has also been mentioned. In rats, MPs after oral administration were found to pass through to the circulatory and lymphoid system. Generally, small size (micrometers or less) and attachment of the organism's own proteins to the MPs' surface promote absorption (Prata et al. 2020). The absorbed MPs can be translocated to blood and lymph circulation, causing systemic exposure and accumulation in different organs and tissues including liver, kidney, and brain (Vethaak and Legler, 2021).

Inhalation

MPs are released to the air from various sources, including synthetic textiles, abrasion of materials (e.g. car tires), and waste management (landfilling). In contrast to waterborne MPs that can be of several mm size, airborne MPs as constituents of settling or suspended dust are typically microscopic or even nanometer sized.

Sewage sludge, degradation of plastic sheeting and other construction materials, clothes drying, wear and tear of textiles, and the resuspension of polymer fragments in urban dust are all possible sources of airborne MPs (WHO, 2019). All the same, less than 1% of fine particulates ($PM_{2.5}$) in urban air samples (in London, Los Angeles or Tokyo) are plastics.

As previously mentioned, Dris et al. (2017) observed outdoor concentrations of 0.3–1.5 particles/m^3 and indoor concentrations of 0.4–56.5 particles/m^3. Estimation by Prata et al. (2020) showed an individual inhalation of 26–130 airborne MPs per day, depending on sampling methods as well as space use factors such as cleaning schedule, activities, furniture materials and season. Size and density of MPs will influence their deposition within the respiratory system, with less dense and smaller particles reaching deeper in the lungs. In a study using 114 lung specimens from patients undergoing lung resection for removal of a tumor, 87% were observed to contain cellulosic or plastic fibers, suggesting that these small fibers are respirable and accumulate in lung tissue (Pauly et al. 1998).

In human lungs, the alveolar tissue barrier is less than 1 μm, which can be easily permeated by very small particles (Lehner et al. 2019). After deposition in the respiratory system, microscopic or submicroscopic MPs are phagocyted by macrophages and then possibly migrated to the circulatory or lymphatic system. In addition, the large surface area of small particles in the respiratory system may induce a release of proinflammatory chemotactic factors, resulting in chronic inflammation (Prata et al. 2020).

Occupational exposure to airborne MPs in workers of the synthetic textile and flock industries, and in production of polyvinyl chloride, was found to induce respiratory symptoms associated with the development of airway and interstitial lung disease. Depending on exposure level and individual susceptibility, inhalation of MPs may contribute to immediate asthma-like bronchial reactions, and to inflammatory and granulomatous changes in bronchial tissues ending up in chronic pneumonitis or extrinsic allergic alveolitis. This synthetic microfiber-related health problem had been reported long before MPs as an environmental issue were recognized (Pimentel et al. 1975).

Dermal contact

Dermal exposure by MPs is considered a less significant route, although nanoplastics (<100 nm) could penetrate the dermal barrier (Prata et al. 2020). According to the Federal Institute for Risk Assessment of Germany, dermal route is often included with personal care products such as hand cleansers, face washes, face masks and toothpastes, representing a potential risk of skin damage due to local inflammation and cytotoxicity (Rahman et al. 2021).

In medicine, plastic products used in surgical procedures and prosthetic body parts are known to induce low inflammatory reactions, and a foreign body reaction with fibrous encapsulation. In mice, *in vivo* subcutaneous introduction of <10 mm plastic disks induced minimal inflammation after 98 days (Rahman et al. 2021). All the same, Schirinzi et al. (2017) reported that both micro- and nanoplastics induce oxidative stress in human epithelial cells. Therefore, such particles could cause damage through dermal contact in susceptible individuals, and further investigations are needed.

Toxic mechanisms involved in the effects of MPs

Oxidative stress and cytotoxicity

MPs could cause oxidative stress by releasing oxidizing chemicals (such as metals) adsorbed to their surface. The host organism's inflammatory response on the presence of MPs also results in reactive oxygen species (ROS). ROS present directly in MPs can be products of polymerization and processing, and interaction with UV light or occurrence of reactive metals significantly increase their presence (Rahman et al. 2021).

Acute toxicants and free radicals due to acute inflammation were found in limb and joint prostheses containing MPs, and the latter could cause degradation of the polymer. ROS production causes risk of rejection of plastic prosthesis from the body (Rahman et al. 2021).

The cytotoxicity of MPs is a result of oxidative stress and inflammation. MPs can be absorbed by macrophages and interact with the intracellular organelles which potentially lead to injury. Schirinzi et al. (2017) showed *in vitro* that MPs at 0.05 to 10 μg/mL exposure level increased ROS concentration in human cerebral and epithelial cells *in vitro*, leading to cytotoxicity. Chiu et al. 2015 stated that *in vitro* exposure of macrophages and lung epithelial cells to submicroscopic MPs increased the level of ROS, which induced aggregation of misfolded proteins in the endoplasmic reticulum, ending up in cytolysis. Therefore, exposure to MPs can potentially result in oxidative stress and cytotoxicity also in humans (Rahman et al. 2021)

Altered metabolism and energy balance

MPs were found to diminish energy intake by reducing food intake in crabs, clams, and marine worms, by reducing predatory activities in fish (possibly due to neurotoxicity), and by decreasing the animals' digestive capacity via modulation of digestive enzyme activities, leading finally to malnutrition (Prata et al. 2020). Metabolism is disturbed by MPs directly by influencing metabolic enzymes, or indirectly by disrupting energy balance. Exposure to MPs was found to lead to increased lactate dehydrogenase activity in fish and mice, indicating increased anaerobic metabolism. In fish that ingested nano plastic particles, breakdown of lipids was induced, potentially interfering with mobilization of energy reserves.

Deng et al. (2017) treated mice with PS particles of 5 and 20 µm diameter orally for 1 to 28 days. Deposition of the MPs of both sizes was found in the gut wall, liver, and kidney. The liver samples showed inflammation and presence of lipid droplets. ATP level was decreased, as was total cholesterol and triglycerides, but lactate dehydrogenase activity was increased in the treated mice's livers. Oxidative stress was signalized by increased glutathione peroxidase and superoxide dismutase activities. Liver acetylcholinesterase activity, and levels of molecules involved in neurotransmitter metabolism, were also affected. MPs may cause similar metabolic effects in humans as well, by increasing or decreasing energy expenditure, lowering nutrient intake, and/or modulating metabolic enzymes – but such effects have not yet been reported (Rahman et al. 2021).

Disruption of immune functions

MPs may induce local or systemic immune responses depending on their dissemination in the host organism and the response of the latter. In genetically susceptible individuals, environmental exposure to MPs may be enough to induce manifest autoimmune disease or immunosuppression (Prata et al. 2020). Mechanisms such as cellular oxidative stress, release of immune modulators, and inappropriate activation of immune cells can be involved, resulting in production of autoantibodies. Diseases linked to MP exposures might include systemic lupus erythematosus and autoimmune rheumatic disease, but direct connection between human MP exposure and immune disorders has not been reported yet.

Neurotoxicity

MP exposures may lead to neurotoxicity and neurodegenerative diseases, due to the activation of immune cells in the brain, and to oxidative stress. These could be induced by direct contact with translocated particles or be consequences of circulating proinflammatory cytokines, resulting in permanent neuronal damage (Prata et al. 2020). In a fish species (European sea bass) MP exposure resulted in decrease of acetylcholinesterase activity, initiation of oxidative stress, increase in lipid peroxidation, and induction of anaerobic energy production. Deteriorated swimming performance indicated complex nervous system damage. In the work of Deng et al. (2017), cited above, exposure to microscopic MPs induced neurochemical alterations. However, very little information regarding neurotoxicity of MPs is at present available (Rahman et al. 2021).

Reproductive toxicity

If MPs exert reproductive toxicity, it is typically related to (sub)microscopic particles. The reproductive function of *Daphnia magna* was decreased by treatment with 70 nm microbeads for 21 days. The number of oocytes of oysters, and their sperm velocity, were significantly reduced on exposure to MPs of a few µm size. In *Caenorhabditis elegans*, accumulation of nano plastic particles in the gonad, causing decreased reproductive activity due to oxidative stress and disturbed energy metabolism, was found (Rahman et al. 2021).

Carcinogenicity

Relationships between exposure to plastic products and tumors in animals have been discussed for decades. Chronic inflammation and irritation caused by MP exposure might contribute to cancer due to DNA damage. Oxidative stress and chronic irritation exerted by nanosized MPs induced release of proinflammatory mediators, leading to angiogenesis, and finally to formation of malignancies (Rahman et al. 2021).

Indirect effects of MPs acting as vectors of harmful chemicals and microorganisms

Within, or attached to, MPs several chemicals (dyes, BPA, phthalates, etc.) were found, which interfere with endocrine regulation even at low concentration. Phthalates are given as plasticizers to soften PVC, and polybrominated diphenyl ethers, as flame retardants. Phthalates might contribute to congenital defects, abnormal sexual development, and cancer risk. In food and beverage containers made of polycarbonate, BPA is present as a constituent monomer (Rahman et al. 2021). Additives not chemically bound in the matrix of MPs may leach, so pollutants released from MPs on contact with body surfaces may reach the underlying tissue. Ossmann et al. (2018) reported that MPs containing BPA were detected in polycarbonate bottles, commonly used in infant feeding. Early life exposure to BPA via MPs may enhance the risk of cancer, liver function alteration, insulin resistance, and decreased reproductive and brain function in later life (Acevedo et al. (2013). From the environmental medium (typically water) various persistent organic pollutants, such as dioxins and polyarenes, can attach to the surface of MPs, and cause exposure in case of ingestion or dermal contact. Although the contribution of MPs to exposure to toxic chemicals might be minor compared to the daily intake from food and dust, multiple exposures may increase their concentrations and health effects.

The extensive surface area makes MPs prone to act as vectors to microorganisms. MPs carry the attached microorganisms, such as *Vibrio* spp., to the target tissues, protect them from the immune system, induce proinflammatory responses, and cause tissue damage that might lead to infection. Moreover, MPs altered and increased the diversity of the gut microbiome in soil organisms, and this effect could happen also in humans if high amount of MPs are ingested. Alterations in the gut microbiome could result in adverse effects, including proliferation of harmful species, increase in intestinal permeability, and endotoxemia. Actual health consequences depend strongly on what molecules or germs and in what number are attached to the ingested particles, on the migration and clearance time of the vector MPs, on the release rate of the contaminant and its translocation and noxious effects in human tissues (Prata et al. 2020).

Public attitude towards microplastics

MPs have possible impacts and threats to the environment and human health, but there is currently no effective technology to tackle and eliminate MPs from the environment. Therefore, public attitudes are an important factor in reducing MP emissions.

Deng et al. (2020) investigated the public's perceptions and attitudes towards MPs in Shanghai by random face-to-face interviews yielding 437 valid questionnaires. The researchers at first briefly introduced the definition and generation of MPs because not many of the respondents were familiar with the concept. Then, the researchers asked about the respondents' knowledge and perception of plastics and MPs, and their behaviors using and disposing plastic bags, in order to compare the public's attitudes towards plastics issues. Finally, the respondents were asked about their behavioral preferences for MPs, and their willingness to reduce emissions.

Only 26% of the respondents heard of MPs before the interview, and the majority were relatively unfamiliar with this issue. Although the public's knowledge of MPs was low compared to that of other substances, 75% of respondents became worried or even overly worried about the issue when they were informed that MPs may affect human health. In addition, the research assessed the factors influencing the public's willingness to reduce MP emissions based on the results from the conducted survey and socioeconomic characteristics of the respondents. Knowledge of plastics, knowledge of MPs (effects on environment and human health), concern level of MPs, gender, occupation and family members had significant influence on the willingness to reduce MP emissions. The most significant factors were knowledge of plastics and knowledge of MPs, that is, the higher the respondents' knowledge of MPs was, the stronger was their willingness to reduce emission. It was clear that MPs may still be an unknown concept for the general public even though the topic has been widely discussed in academia. Further it became clear that people may not know how to effectively reduce MP pollution.

Conclusion

Apparently, MPs are found almost everywhere in the environment. In spite of efforts, such as the ban of various single-use plastic items in the European Union (2019), the increase of global production and consumption of plastics seems unstoppable, and MP contamination in the environment – oceans, freshwater, soils, sediments, and air – is expected to rise further. Even though MPs enjoy huge research attention recently, their distribution behaviors and mechanisms are still unclear. Therefore, further investigations are needed for better predicting and monitoring of MP occurrences in environmental systems. Via ingestion, inhalation, and dermal contact, and under conditions of high concentration or high individual susceptibility, MPs may affect human health by inducing inflammation, immune disorders, or cancers. However, knowledge on the human health effects of environmental exposure to MPs is limited, leading to necessity of further investigations.

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