J Food Sci Technol (March 2024) 61(3):403–413
https://doi.org/10.1007/s13197-023-05720-4

REVIEW ARTICLE

How microplastics interact with food chain: a short overview of fate and impacts

Meysam Saeedi[1]

Revised: 1 March 2023 / Accepted: 6 March 2023 / Published online: 13 March 2023

Abstract Microplastics as one of the ubiquitous contaminants have recently attracted attentions. Microplastics have the potential to impact the social-ecological environment. Accordingly, negating adverse effects on the environment necessitates scrutinizing physical and chemical characteristics of microplastics, emission sources, effects on the ecological environment, contaminated food chains especially human food web, and the impacts on human health. Microplastics are defined as very small plastic particles with a size smaller than 5 mm, which come in heterogeneous colors depending on their emission source and are composed of thermoplastics and thermosets. These particles based on their emission source are classified into primary and secondary microplastics. These particles diminish the quality of terrestrial, aquatic and air environments, which directly impact the habitats and trigger disruptions in plants and wild life. The adverse effects of these particles are multiplied when adsorbing to toxic chemicals. Moreover, these particles have the potential to be transmitted in organisms and human food chain. Due to the fact that the retention time in the body of organisms is longer than the time elapsed from ingestion to excretion, microplastic bioaccumulation occurs in the food webs.

Keywords Microplastic pollution · Toxicity · Bioaccumulation · Food chain · Human health

✉ Meysam Saeedi
me.saeedi@ut.ac.ir

[1] Environment Department, College of Engineering, University of Tehran, Tehran, Iran

Abbreviations

MP	Microplastic
PP	Polypropylene
LDPE	Low density polyethylene
HDPE	High density polyethylene
PVC	Polyvinyl chloride
PUR	Polyurethane
PET	Polyethylene terephthalate, polyester
PS	Polystyrene
PA	Polyamide
PE	Polyethylene
PES	Polyether sulfone
PAA	Poly acrylic acid
UV	Ultraviolet
BPA	Bisphenol-A
DDT	Dichloro diphenyl trichloroethane
PAH	Polycyclic aromatic hydrocarbon
POP	Persistent organic pollutants
PCB	Polychlorinated biphenyl
SMT	Sulfamethazine
SMX	Sulfamethoxazole

Introduction

Concerns about the risks of environmental pollution with microplastics are increasing globally (Zhang et al. 2020). Millions of tons plastic wastes are produced every year. The production and consumption of plastics has made human life convenient in different aspects (Guo et al. 2020). Plastics have wide physico-chemical properties and their use is more economical than other materials such as metals, glass, and ceramics. Accordingly, they are widely utilized in various applications. Also, their simple processing has made it possible to produce different plastic products with different shapes (Kedzierski et al. 2020). Since 1950, more than 7800 million tons of plastic fibers and resins have been produced worldwide, more than half of which were from 2004 to 2017 (Schmaltz et al. 2020). Moreover, corona virus outbreak extraordinarily increased the amount of plastic wastes in the environment (Haque et al. 2021). Due to the continuous increase in the production of plastic materials and their stability. There is anticipated to be steady increase in the number of MPs in the environment, also their size will continuously de-escalate (Bai et al. 2021). While plastic materials are stable and recyclable materials, less than 5% of them are recycled and reused. Statistics on current production levels, consumption and disposal patterns, low recycling rates, and census data all point to the ever-increasing accumulation of plastic wastes. The contamination caused by MPs is pervasive and widespread, so that MP particles cover the entire globe from the equator to the North and South Poles (Guo et al. 2020).

MPs are ubiquitous in aquatic environments and constitute 80–85% of waste materials in water and 92%, i.e. 5.25 trillion, of plastic waste floating on oceans (Bai et al. 2021). The small size (< 5 mm) and low density make them well distributed and dispersed in water (Auta et al. 2017). Researches show that these particles are also present in soil ecosystems, so that 79% of plastic wastes worldwide are buried in landfills. This is why, the soil is a large burial site for MPs. The annual entry of MPs into the soil by farm lands is estimated at 63–430 thousand tons in Europe and 44–300 thousand tons in North America. These values are higher than the predicted annual release of MPs into ocean (Guo et al. 2020). MPs are also considered as one of the air contaminants. The atmosphere is one of the environments where suspended particles are easily moving regionally and globally. Due to the features such as light weight and stability, these particles have the potential to be transported to areas far away from their emission source through wind or snowfall (Zhang et al. 2020). This pollution also exists in polar regions with very high concentrations. For example, in the North Pole, the number of MP particles per cubic meter has been reported as 38–234. MPs have destructive effects on the soil and disrupt the soil functions. As in aquatic environments, soil contamination with MPs causes accidental ingestion of MPs by organisms such as earthworms. With the increase in the concentration of MPs in the soil, the probability of particles being swallowed by organisms increases (Guo et al. 2020). By conducting research on indoor and ambient air, it has been determined that dust particles have the potential to absorb MPs and endanger human health through breathing. In order to provide appropriate solutions to reduce the negative effects of plastic wastes, it is necessary to first investigate the emission sources, the mode of transmission, and their environmental fate (Angnunavuri et al. 2020). The purpose of this research was to investigate the characteristics, the sources identification, and the adverse effects of MPs on ecological environment and human health.

Physical and chemical characteristics of MPs

Size

Microplastics are usually plastic particles with a size of 100 nm–5 mm and according to the international standard (SI), are considered 1–5 µm (Zhang et al. 2020). According to a scientific classification based on the length, plastics longer than 100 mm are called megaplastics, 20–100 mm macroplastics, 20–5 mm mesoplastics, and with a length of < 5 mm MPs. Macroplastics are easily visible, while mesoplastics are intermediate between microplastics and macroplastics (Thushari and Senevirathna 2020). Size is the main factor determining the interaction between MPs and organisms, and their environmental fate. Also, size is one of the important parameters for analyzing atmospheric MPs. The size limits are determined by sampling methods. Atmospheric MPs are generally much smaller compared to aquatic MPs. Also, there is an inverse correlation between size and abundance of atmospheric MPs (Zhang et al. 2020).

Shape

MPs mostly are sphere, ball, bubble, bead, fiber, film, chip, and shell-shaped particles. The shape of MPs depends on different factors such as the shape of the initial MP, the processes of decomposition and erosion of the plastic surface, and the plastic durability. MPs with a sharp edge have less durability in the environment than others with a round shape. Atmospheric MPs are in the form of strings, films, bubbles, and chips. Also, the shape of MPs is applicable for their source determination; Due to the fact that one form is especially abundantly separated from one type of product. For example, in the city of Shanghai, the predominant form of MPs in the atmosphere has been reported as strings, which indicates the production of synthetic threads in the textile, carpet, sofa and chair manufacturing industries is prevalent; While chip-shaped MPs can be caused by exposure of plastics to factors such as stress, wear, and ultraviolet light. The microplastic texture (cracks, shells, grooves, and dimples) indicates that physical damage and chemical erosion are the most important factors in the decomposition of MPs. Fibrous MPs are 1–500 µm in width and thickness. Fibrous MPs may become difficult to distinguish from chip-shaped MPs if their length falls due to exposure to physical and chemical factors. For this reason, fibrous and chip-shaped MPs are both considered identical if they are small in size. The shape of MPs is effective in absorbing and transporting other pollutants; For instance, film-shaped MPs have more potential to absorb and transfer contaminants compared to chip-shaped MPs with the same mass. Special forms of MPs have more ability to cause physical damage to organisms; For example, MPs that have irregular surfaces have more ability to pass through organism membrane compared to MPs that have regular surfaces (Auta et al. 2017). What is more, researches have shown that fibrous MPs, due to their high surface-to-volume ratio, have a greater potential to be transferred from the soil environment to marine environments by the run-offs (Yang et al. 2022).

Color

MPs have been observed in red, orange, yellow, brown, bronze, cream, white, gray, blue, and green colors, among which the blue and red ones are more abundant, whereas dark and white have the lowest abundance compared to other colors. The MPs color can be used to determine their source, also to identify potential pollution in the environment. Although, it may be accompanied by difficulties, for example, the MPs color may deviate from their natural color during sampling process, as well as due to weather conditions; For this reason, spectroscopic and chemical analyzes are generally used to identify MPs. Crystal MPs are attributed to propylene, white to polyethylene, and opaque to LDPE.

Darker colored MPs in polar ice have more potential to absorb sunlight. Therefore, due to the fact that they accelerate the process of melting polar ice, they are considered as a threat in the context of intensifying the effects of climate change and global warming (Zhang et al. 2022). Also, most of the MPs observed in the digestive system of fishes were blue in color, which indicates that due to the fact that MPs color is similar to the blue color of sea water and food, the possibility of absorption of MPs by fish while eating is very high. Hence, MPs color plays crucial role in MPs biological risk assessment (Yang et al. 2022).

Composition

Chemical composition is a fundamental criterion in determining the pollution caused by plastics. MPs are composed of different types of polymers. A wide range of polymers are used for domestic and industrial purposes. The structure of plastic polymers determines the physical and chemical characteristics of plastic materials. Additionally, the physical characteristics of polymers such as size and density have an effect on the decomposition of macroplastics (Auta et al. 2017). In terms of structure, polymers are classified to two categories, namely thermoplastics and thermosets. Polymers such as PP, LDPE, HDPE, PVC, PUR, PET, and PS have more production and demand rates among all types of polymers (Zhang et al. 2020). In general, 80% of MPs are polyethylene (PE) (Fahrenfeld et al. 2019). Among the polymers found in seawater, PE is the most abundant; And PP and PS polymers are in the next ranks in terms of abundance. PP, PS, PE and PES polymers are also the most abundant among the polymers in the coastal areas. The abundance of polymer compounds in the atmosphere depends on the city and the region under investigation. For example, according to a study conducted in Shanghai, 54% of atmospheric particles are synthetic compounds, and among them 91% are PET, PS, PE, PAN, PS, PAA, and rayon MPs. The dominant composition of MPs in mountainous areas is PS polymer (chip-shaped) and then PE polymer. A diverse composition of MPs in the atmosphere has been reported in the arctic regions. Acrylic acid polymers, polyamides, and rubber have been the most abundant among the detected MPs in the atmosphere in the arctic regions. So far, no specific correlation and rule has been provided to justify the existence of diversity in microplastic compounds in the atmosphere. More studies are needed to determine whether there is a group of polymers that predominantly form atmospheric MPs or not, also to determine their composition depending on the investigated area and the distance they have traveled in the atmosphere (Zhang et al. 2020).

Source

MPs are classified into primary and secondary MPs. Primary MPs are produced in microscopic sizes in household and industrial applications and include plastic particles that are used in facial cleansers, toothpaste, resin beads, personal care products (such as sunscreen, hair dye, Beard paste, nail polish, etc.), artificial fibers of clothing, oil and gas drilling fluids, and sandblasting material are used. In the sandblasting process, acrylic, polyester, and melamine MP cleaners are used in machines, engines, and boat bodies to remove paint and remove rust. Sandblasting materials are used repeatedly and can be used as long as they have cutting and cleaning power and their size does not shrink from certain limits; accordingly, they are usually contaminated with heavy metals. In the field of their application in personal care products, the existence of polyethylene and polypropylene (< 5 mm), and polystyrene (< 2 mm) has been reported. In medicine they also are used as drug carriers (Auta et al. 2017). According to a research conducted in 2016, the amount of microfiber collected from ordinary household looms was 1471–2121 per garment produced. Also, according to the results of another study conducted in 2019, the amount of microfiber separated per square meter of fabric clothes was 30,000–465,000. These MPs are hardly removed by existing technologies for disposal and processing of industrial and household waste (Guo et al. 2020).

Secondary MPs are created due to the breakdown of macroplastics. The integrity of macroplastic structure falters over time during physical, chemical, and biological processes (Auta et al. 2017) and they are broken down into smaller particles by environmental factors such as wind, waves, temperature, and ultraviolet light, thus producing secondary MPs (Guo et al. 2020). For example, the exposure of macroplastics to the sunlight ultraviolet ray leads to the optical decomposition of plastics, in such a way that the ultraviolet ray of sunlight oxidizes the structure of the polymer and then their bonds are split. This process in coastal environments is more effective than other environments due to UV radiation, physical erosion by waves, abundance of oxygen, and turbulence (Auta et al. 2017). In addition, frequent use of plastic artifacts also causes them to decompose and create secondary MPs. As an instance, one of the main sources of creating MPs in the environment related to vehicle transportation includes wear and tear of tires, vehicle brakes, and road markings. Artificial grass also plays a significant role in creating secondary MPs in the environment by creating 760–4500 tons annually (Guo et al. 2020). Figure 1 depicts primary and secondary MPs sources. MPs resulting from plastic production processes in manufacturing industries and waste management industries have endangered human health by entering the environment and food chain (Zhang et al. 2020). The production of low-quality plastic material as well as the inefficient disposal of plastic waste in countries that have relatively poor waste management has a significant effect on creating pollution caused by MPs (Schmaltz et al. 2020). Due to the fact that the sludge in industrial and domestic sewage contains a large amount of MPs (their latent MPs are more than that of runoffs), these materials are also considered as sources of MPs (Auta et al. 2017).

Ecological effects

Effects on soil, water, and air environments

The presence of MPs in the physicochemical environment greatly reduces soil, air, and water quality. MPs change soil properties such as structure, performance, and microbial diversity (Guo et al. 2020) by imposing impacts on soil characteristics e.g. organic matter in the soil, stability and size of soil particles, water holding capacity in soil, density, and soil acidity (Yang et al. 2022).

Some MPs contain carbon elements with long-term stability, which increase the amount of organic carbon in the soil. Subsequently, carbon cycle is affected by means of an increase in the emission of carbon dioxide in the soil, the impact on soil microbial processes, plant growth, and the decomposition of waste materials in the soil. With polyethylene MPs adding to the soil, the amount of total phosphorus, total nitrogen, and potassium in the soil fall significantly. Also, the amount of soil organic matter correlates with the amount of polyethylene, polypropylene and polystyrene MP particles.

The stability of soil particles is considered the most important factor in evaluating soil quality. Particles such as HDPE and PLA, by sticking to soil particles, provide the basis for the formation of larger particles and disturb the water stability of soil particles. The presence of MP particles

Fig. 1 Primary and secondary MP sources

in the soil facilitates the water movement by providing channels in the soil, so much so that the water and moisture evaporation rate in the soil and the drying process of the soil will intensify remarkably. What is more, the role of MP particles in materializing these adverse effects is more crucial than that of the larger plastic particles. However, polyester particles could enhance the soil holding water capability. Additionally, polyester, polyacrylic, and polyethylene particles reduce soil bulk density. On the other hand, HDPE particles, being exposed to light and heat, have the potential to reduce the acidity of soil PH (Yang et al. 2022).

MPs impose direct or indirect effect on the biodiversity of microorganisms. MP particles also are able to falter the microorganisms' metabolic function (Yu et al. 2021), and could disrupt the eco-physiological functions pertaining to the biodiversity in organism (Guo et al. 2020). The MPs surface could also be a suitable place for the accumulation of microorganisms (Wright et al. 2020), thus MPs trigger changes in organisms' population structure, their biogeographic transfer to remote areas, and finally their biodiversity in the environment directly (Wright et al. 2013). Another example for changing microorganisms' population and biodiversity is pertaining to the PE particles decomposition by the microorganism *Actinobacteria* through the microbial synthesis reaction, consequently, the microorganism *Proteobacteria* emerges as the dominant group of microorganisms thus changing microbial diversity directly (Ma et al. 2020; Shi et al. 2020). Further to that, nanoplastics accelerate the production of viruses such as *Singapore grouper iridovirus* and *red-spotted grouper nervous necrosis virus* (Wang et al. 2021). Hence in the mentioned cases, MPs directly affect biodiversity, composition, and population structure of microorganisms. Phosphorus is one of the elements that play pivotal role in providing bacteria needed by the soil; Polystyrene and polyvinyl chloride reduce the total amount of phosphorus in the soil and indirectly affect the biodiversity of soil microorganisms. Also, earthworms provide the organic maters needed by the bacteria in the deep soil. MPs endanger the life of earthworms and indirectly affect the biodiversity of microorganisms in the soil (Yu et al. 2021). Changing soil characteristics has negative consequences for plants and animals, the safety and food quality, and ultimately causes a threat to human health. Soil polluting sources include landfills, soil-improving materials, sewage sludge, irrigation by wastewater, compost and organic fertilizers (Guo et al. 2020), and protective plastic litter (He et al. 2018), rubber tear and wear, atmospheric deposition, etc.

MPs polluting the soil, in addition to the possibility of moving inside the soil, can also be transferred to other environments such as air and water through natural and human factors such as wind, dust, erosion, and water flows. Water polluting sources are mainly land sources (with 80% share), coastal tourism, recreational activities, and commercial fishing (with 18% share), industries (such as aquaculture and oil rigs) and sea crossings (Guo et al. 2020). Moreover, 66% of the MPs that enter the oceans are originated from the surface waters. Wastewater treatment systems are next with 25%, and wind with 5% (Nanthini devi et al. 2022). MPs utilized in personal care products such as toothpaste, cleaners, sandblasting materials, and clothing, could enter the water environment through municipal and industrial wastewater disposal systems. Also, the synthetic fibers derived from clothes could generate MP particles in wastewater processing systems; The runoff from these systems will have the possibility of contaminating water environments (Auta et al. 2017).

MPs have the ability to combine with pollutants such as phthalates, which are present as aerosols in the atmosphere, as well as mercury and PAHs, hence they are considered as one of the air contaminants (Zhang et al. 2020).

Physical and chemical effects on animals

The impact of MPs on ecosystems depends on different factors such as the affected area, the type of plastic waste, the level of ecosystem vulnerability, and the available organisms in the ecosystem. The factors that determine the toxicity of MPs are particle size, concentration, type of polymer, particle shape, gender of the affected species, growth stage of the affected species, environmental conditions, species present in the investigated environment, and exposure time (Kögel et al. 2020). For instance, the size of MPs has negative correlation with their abundance in marine environments, potential in leaching, absorption and excretion in the digestive system of organisms, the variety of organisms that have the ability to swallow particles, the vulnerability of organisms to MPs, and the effect of MPs on the organism's life time (Auta et al. 2017).

It is estimated that 245 tons of MPs enter aquatic environments every year and swallowed by organisms in aquatic environments and accumulate in their bodies and tissues (Auta et al. 2017). Turtles, mammals, and birds such as green turtles, pigs, seagulls, and sea lions are the most vulnerable marine organisms to the negative effects of MPs in aquatic environments (Thushari and Senevirathna 2020). In addition to underlying interruptions in growth levels, bioaccumulation of MPs disrupts the performance of digestive system, damages organs, diminishes organisms' population by stimulating organisms' infertility, undermines biodiversity, triggers changes in the population composition and structure of organisms, and degrades habitats (Guo et al. 2020).

Growth levels

MPs are likely to enter the animal body through the digestive system (Yang et al. 2022). Some MPs may be stored throughout the digestive tracts after ingestion (Mahamud et al. 2022). This makes the organisms feel falsely full and causes less amount of carbon mass to enter the digestive system of the organisms thus resulting in a fall in the amount of received energy; this effect is associated with growth levels in organisms and eventually may cause their death (Guo et al. 2020). Polystyrene MPs could induce lipid metabolism disturbance, lipid accumulation, and metabolic alterations in the zebra fish liver. Lipid metabolic substances such as triglycerides and fatty acids can significantly change after MPs exposure. It also interrupts the synthesis and transportation of phospholipid and hampers lipid metabolism through choline, phosphorylcholine, and cholesterol level alterations. MPs exposure in *zebrafish* also reduces branched-chain amino acids, which play a vital role in fatty acid metabolism and fatty acid accumulation prevention (Mahamud et al. 2022).

Digestive system and organs

MPs trigger the blockage of entire digestive system and damaging organs (Mahamud et al. 2022). For example, MPs ingestion significantly damages the small intestine, alters villi height-width, epithelial cell height and functional patterns of villi, epithelial, goblet and cryptic glandular cells, leucocytic infiltration in *Oreochromis urolepis* larvae (Mbugani et al. 2022). The absorption of polystyrene particles by mice leads to intestinal obstruction, metabolic disorders related to the gallbladder, and dysfunction in intestinal microorganisms (Jin et al. 2019).

Passing through the membrane wall, nanoplastic particles also have the potential to enter different body organs. Iron-contaminated MPs could accumulate in the brain and pose damages to brain by disrupting the balance of iron in the brain, which ultimately causes the destruction of brain cells whose life depend on iron. By interacting with the body's defense system, these particles have the potential to cause oxidative stress and changes in DNA. Absorption of BPA causes oxidative and inflammatory damage, which ultimately leads to the occurrence of cardiovascular diseases through the destruction of vessel wall cells and changes in the amount of lipids in the blood serum, in addition to the occurrence of type 2 diabetes which originate from the dysfunction in pancreas beta type cells. Furthermore, the malfunction of the body's defense system in filtering MP particles causes chronic inflammation and increases the possibility of neoplasia. Fish gills could be an entry route for MPs. Gill filaments trapped MPs could cause respiratory issues, including hypoxia, and may cause gill infection through rupturing gill filaments (Mahamud et al. 2022).

Reproduction system

There is also the possibility of MP particles entering the blood and then the placenta, passing through the membrane wall, thus affecting the reproductive system and the population of organisms (Mahamud et al. 2022; Mbugani et al. 2022). MP particles originated from the face masks have disrupted the function of spermatogenic tissue in the earthworms' reproductive system (Kwak and An 2021). PS particles with a diameter of 10 μm are capable of disrupting the function of the reproductive endocrine glands. Phenanthin compounds adsorbed to LDPE particles or even alone are able to change the information of genes pertaining to the reproduction. Polystyrene particles have dwindled sperm speed and egg diameter in oyster. Also, polyethylene particles with a wavelength of 5.64–38.26 μm have the potential to reduce the survival rate and fertilization of larvae, as well as to change parameters related to the shape and size of larvae in *zebrafish* (Sangkham et al. 2022; Malafaia et al. 2019; Grafmueller et al. 2015).

Biodiversity and habitats

The accumulation of MPs containing pollutants and additives in the organisms' tissues leads to disturbances in the eco-physiological functions related to biodiversity, such as the immune system performance, mortality, and interrupting oxidative stress. Animals that have been exposed to nonylphenol and phenanthrene MPs have been more susceptible to pathogens, oxidative stress interruptions, and mortality. For example, by absorbing MPs containing nonylphenol, the ability of coelomycytes fluid against pathogenic agents in lugworms has been diminished by at least 60%; Moreover, with the absorption of sediment containing PVC, their ability to control oxidative stress has de-escalated by at least 30% (Browne et al. 2013). On the other hand, lamprey species, which are still in the larval stage, not only are considered as suitable source of nutrients in the freshwater food chain, but also by providing benefits such as oxygenating sediments, facilitating nutrient cycles, improving microbial composition and habitat variability, they play a significant role in aquatic environments; thus provide favorable habitats for other aquatic species. The exposure of lampreys to MPs triggers alterations in lampreys' reduced ability to migrate, thus impacts species' population structure and composition, and degrade aquatic habitats (Rendell-Bhatti et al. 2023).

Physical and chemical effects on plants

Due to the fact that MPs are similar in size and density to minerals, plants grown with the aid of industrial composts are likely to transfer these particles from the roots to their tissue (Smith 2018). PS nanoparticles are able to penetrate the plant through the available openings on the plants' leaves (Eichert et al. 2008). Due to the relatively high molecular weight, MPs penetration into the cell through the plant cell wall is practically not possible (Ng et al. 2018). MP particles are likely to block the seed coating layer, which in turn preventing water absorption and seed germination (Bosker et al. 2019). Accumulated MPs in plants cause disruption in cell function, thus underlying a negative impact on the absorption and transfer of nutrients in plants (Guo et al. 2020). Polyamide, HDPE, polyester, polyethylene terephthalate, polypropylene, and polystyrene MPs significantly increase the root length of spring onion (*Allium fistulosum*) and some of these particles cause changes in root tissue density and average root diameter of this plant (Machado et al. 2019).

Transfer of MPs in the food chain

MPs can be absorbed and ingested by a variety of organisms, including species that are widely present in the human diet (Zhang et al. 2020). The proof of the hypothesis that MPs transfer in the food chain is done by collecting the required data, conducting controlled experiments, and simulating the transfer of MPs through the fictitious food chain. In the first study, in order to prove the transfer of MPs in the food chain, the transfer of polystyrene nanoparticles (24 nm) within a freshwater food chain from a moss to zooplankton and then to a type of fish has been investigated. In this study, the transfer of polystyrene particles to fish has left significant effects; Zooplankton consumption time by fish has been doubled and metabolic effects such as lose in fish weight, altered triglyceride-to-cholesterol ratio, and altered liver and muscle cholesterol distribution have been reported. Simulation of the food chain has also confirmed the hypothesis of MPs transfer from the prey element to the predator in a food web (Guo et al. 2020).

Aquatic animals such as *shrimp*, *paropa*, *polychaetes*, and *ciliates* are capable of ingesting polystyrene MPs with a size of 10 µm, among which polychaetes and pinworms are able to transfer absorbed MP particles to shrimp at higher levels of the food chain (Carbery et al. 2018). Small plastic particles discovered in *otoliths* (scallop bones that help fish in orientation and balance), *lantern fish* and *sea lion* feces all point to the transfer of MPs in the food chain. In fact, due to the fact that the retention time of MPs in the organs of the predator element in a food chain is longer than the time from ingestion to excretion, the possibility of consuming MPs by the predator elements in the food chain is higher. This issue shows the pervasiveness of MPs transfer in the food chain. Therefore, MPs biomagnification occurs in marine ecosystems.

There is limited information regarding the transfer of MPs in the soil food chain. There are two hypotheses about the MP existence in the gravel and feces of *chickens* whose diet was free of any MP. The first hypothesis is that larger plastics may have turned into MPs during digestion, and the second hypothesis is that the source of MPs may be the consumption of *earthworms* by chickens. If the second hypothesis is true, the transfer of MPs in the soil food chain is possible. Also, the result of a toxicology test that examined the presence of MPs in mice shows that the accumulation of MPs occurs in tissues such as the liver, kidney, and intestine, which means that the mice internalize the MPs in tissues of the body and stores them in tissues. These tissues are consumed as food by other animals at higher levels of the food chain (Guo et al. 2020).

Currently, 5 trillion plastic wastes are found in the world's aquatic environments, of which more than 250,000 tons are floating on the waters. Due to the fact that most of the MPs in aquatic environments float on the surface of the water, it is possible for the particles to be swallowed by small marine organisms such as *plankton* that live on the surface of the water and presented at different levels of the food chain (Bai et al. 2021). Aquaculture plays a significant role in providing food security in many developing countries. However the organisms' life in the cultivated environments is endangered by the contamination of the food chain with MPs (Wu et al. 2022).

Transfer of MPs containing toxic pollutants in the food chain

In some of the studies conducted in the field of MPs transmission in the food chain, only the effects of pure MPs transmission have been investigated and to some extent the real conditions, i.e. the presence of other adsorbed pollutants in the food chain, have been neglected, which causes the results obtained from the studies are not sufficiently accurate (Carbery et al. 2018). MPs have the potential to absorb and transfer chemicals, additives used in plastic production processes, pathogens, and parasites to the human food chain (Schmaltz et al. 2020). In addition to the problems caused by the direct ingestion of MPs and their toxic nature in organisms (Guo et al. 2020),due to the hydrophobicity and lipophilicity of MPs, also their high surface-to-volume ratio, these particles can trigger adsorption of toxic pollutants including toxic organic chemicals such as BPA, monomers, and refractory chemicals (Thushari and Senevirathna 2020), heavy metals, antibiotics, oligomers; Consequently the transfer of pollutants to the tissues in organism's body such as fish, molluscs, and mammals at different levels of the food chain, thus multiplying the risks and problems for organisms and humans (Guo et al. 2020). MPs are capable of carrying toxic elements such as DDT and hexachlorobenzene. Ingestion of MPs containing chemicals such as mercury and PAHs, whose origin can be composite plastic chemicals, causes genetic toxicity in organisms, and these particles are considered a threat to plants and animals in their habitats (Zhang et al. 2020). POPs including DDT such as organochlorine pesticides, various industrial wastes such as dioxins, and industrial chemicals such as PCBs are resistant to biodegradation and are adsorbed to the MPs surface.

MPs have the ability to accumulate in the body of organisms through the food chain. Phthalates and BPA have negative effects on reproduction, mutation of chromosomes, and organisms' growth. What is more, antibiotics such as SMX and SMT are adsorbed to MPs such as PE, PP, PA, PET, PS, and PVC cause a change in the population of bacteria, and then it has dangerous effects on the organisms and humans health (Thushari and Senevirathna 2020). Also, due to the possibility of release of additives used in the production process of plastics in water, MPs can have negative effects on the endocrine function of marine organisms (Bai et al. 2021).

Effects on human health

MPs can enter the human body through various ways such as breathing dust particles, consuming food, or drinking contaminated water (Guo et al. 2020). Plastic particles present in aquatic and terrestrial environments are absorbed by humans through consumption of seafood, non-sea food, and drinking water. The results of medical studies on humans and rats indicate the transfer of PS and PVC particles smaller than 150 µm from the intestine to the circulatory system through the consumption of seafood. The transport of MPs and pollutants within the marine food chain has significant negative effects on seafood as a source of protein for human, especially if the amount of these particles is significant at the lower levels of the food chain. Furthermore, aquatic animals whose whole bodies are consumed have more potential to cause problems for human health compared to aquatic animals whose digestive system is separated and then consumed. MPs are biologically resistant and have the ability to pass through the epithelial tissue in the digestive system. Very small MP particles have the ability to pass through the cell membrane which leads to adverse effects such as damage to cells, disruption in energy allocation, oxidative stress, and swelling for humans (Zhang et al. 2020). In order to assess human risks and detect unhealthy seafood, it is necessary to conduct more research on the factors affecting the

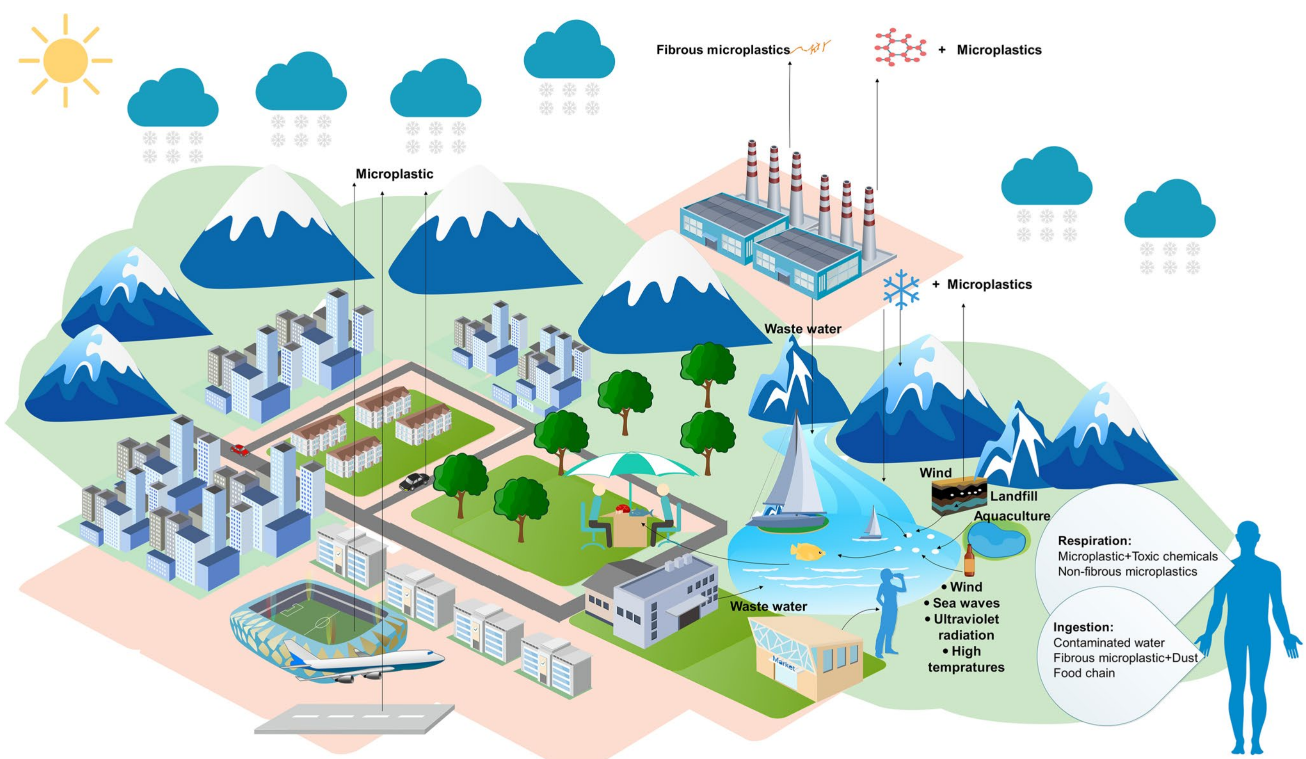

Fig. 2 Transmission of MPs to the human body through respiration and ingestion

ingestion of MPs by aquatic organisms, the bioaccumulation factors, and the interaction of organisms in the food chain (Carbery et al. 2018).

Recent findings about atmospheric MPs reveal the transfer of MPs from one place to another and their impacts on humans. Epidemiological studies show that atmospheric air pollution with MPs can induce respiratory and cardiovascular disruptions. The size of visible fibrous MPs is so large that it is practically impossible to enter the body by breathing. Nevertheless, it is possible for MPs to ride on dust particles in the air and enter the body through ingestion. Previous studies indicate the possibility of plastic and cellulose fibers entering the lungs and causing people to get cancer. Also, MPs pose disruptions for the respiratory system and health condition of workers (cough, shortness of breath, and asthma) in plastic processing factories. MPs including the additives used in the plastic production cause negative effects such as infertility, cancer, and genetic mutation for humans. According to the conducted studies, MPs containing phthalates cause disruption of endocrine glands, shortening of pregnancy time, and low birth weight of babies. Phthalate is also available as an aerosol in the atmospheric environment and its concentration reaches a significant amount of 174,000 pg/m^3 (Zhang et al. 2020). Figure 2 demonstrates the ways MPs are transferred from their sources to the human body.

Conclusion

MPs have various negative physical–chemical effects on ecological and social environments. Factors such as the possibility of being transferred in the food chain and the potential of absorbing and transporting toxic substances have caused these particles to be considered as serious threat to marine and terrestrial ecosystems and human health. In this review, to investigate MPs side-effects, first the physico-chemical characteristics of MPs were investigated. The shape of MPs depends on factors such as the initial shape of the MP, the processes of degradation and erosion of the plastic surface, the source of the MPs, and their durability in the environment. The MPs shape plays pivotal role in absorbing and transporting other pollutants as well as triggering damage to organisms. The size of MPs determines MP interactions and is applicable for analyzing them. The MPs color can be used to determine source and identify potential environmental contamination. To investigate the source of MPs, the common classification of MPs was used. MPs are classified into primary and secondary categories. Primary MPs are produced for the household and industrial applications in microscopic sizes, while secondary MPs are generated due to the destruction of macro-plastics structure by environmental factors such as wind, waves, temperature, and ultraviolet light over time. The intake of MPs by organisms interferes with the eco-physiological function, health status, and movement of organisms. These particles are absorbed by a variety of microorganisms and species that are widely present in the human diet diffuse in the human food chain. The presence of MPs in the physicochemical environment greatly reduces soil, air, and water quality. Bioaccumulation of MPs triggers detrimental impacts on habitats, species composition and organisms' diversity, disrupts growth, poses malfunctions in organs, and deescalate organisms' population while ascending organism infertility. MPs are likely to absorb and transfer chemicals, additives used in plastic production processes, pathogens, and parasites to the human food chain, thus coupling MPs toxicity. Plastic particles present in aquatic and terrestrial environments are absorbed by humans through respiration, consumption of seafood, non-sea food, and drinking water which in turn inducing damages to human body. Hence, it is of the ut-most importance to designate appropriate solutions for tackling against the detrimental impacts of the MP particles on the human food web.

Funding Not applicable.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Angnunavuri PN, Attiogbe F, Mensah B (2020) Consideration of emerging environmental contaminants in Africa: review of occurrence, formation, fate, and toxicity of plastic particles. Sci Afr 9:e00546. https://doi.org/10.1016/j.sciaf.2020.e00546

Auta HS, Emenike CU, Fauziah SH (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. Environ Int 102:165–176. https://doi.org/10.1016/j.envint.2017.02.013

Bai Z, Wang N, Wang M (2021) Effects of microplastics on marine copepods. Ecotoxicol Environ Saf 217:112243. https://doi.org/10.1016/j.ecoenv.2021.112243

Bosker T, Bouwman LJ, Brun NR, Behrens P, Vijver MG (2019) Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *Lepidium* *sativum*. Chemosphere 226:774–781. https://doi.org/10.1016/j.chemosphere.2019.03.163

Browne MA, Niven SJ, Galloway TS, Rowland SJ, Thompson RC (2013) Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr Biol 23(23):2388–2392. https://doi.org/10.1016/j.cub.2013.10.012

Carbery M, O'Connor W, Palanisami T (2018) Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ Int 115:400–409. https://doi.org/10.1016/j.envint.2018.03.007

Eichert T, Kurtz A, Steiner U, Goldbach H (2008) Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles. Physiol Plant 134:151–160. https://doi.org/10.1111/j.1399-3054.2008.01135.x

Fahrenfeld NL, Arbuckle-Keil G, Beni NN, Bartelt-Hunt SL (2019) Source tracking microplastics in the freshwater environment. TrAC Trends Anal Chem 112:248–254. https://doi.org/10.1016/j.trac.2018.11.030

Grafmueller S, Manser P, Diener L, Diener P-A, Maeder-Althaus X, Maurizi L, Jochum W et al (2015) Bidirectional transfer study of polystyrene nanoparticles across the placental barrier in an ex vivo human placental perfusion model. Environ Health Perspect 123(12):1280–1286. https://doi.org/10.1289/ehp.1409271

Guo J-J, Huang X-P, Xiang L, Wang Y-Z, Li Y-W, Li H, Cai Q-Y, Mo C-H, Wong M-H (2020) Source, migration and toxicology of microplastics in soil. Environ Int 137:105263. https://doi.org/10.1016/j.envint.2019.105263

Haque MS, Uddin S, Sayem SM, Mohib KM (2021) Coronavirus disease 2019 (COVID-19) induced waste scenario: a short overview. J Environ Chem Eng 9(1):104660. https://doi.org/10.1016/j.jece.2020.104660

He D, Luo Y, Lu S, Liu M, Song Y, Lei L (2018) Microplastics in soils: analytical methods, pollution characteristics and ecological risks. TrAC Trends Anal Chem 109:163–172. https://doi.org/10.1016/j.trac.2018.10.006

Jin Y, Lu L, Tu W, Luo T, Fu Z (2019) Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. Sci Total Environ 649:308–317. https://doi.org/10.1016/j.scitotenv.2018.08.353

Kedzierski M, Frère D, Le Maguer G, Bruzaud S (2020) Why is there plastic packaging in the natural environment? Understanding the roots of our individual plastic waste management behaviours. Sci Total Environ 740:139985. https://doi.org/10.1016/j.scitotenv.2020.139985

Kögel T, Bjorøy Ø, Toto B, Bienfait AM, Sanden M (2020) Micro- and nanoplastic toxicity on aquatic life: determining factors. Sci Total Environ 709:136050. https://doi.org/10.1016/j.scitotenv.2019.136050

Kwak JI, An Y-J (2021) Post COVID-19 pandemic: biofragmentation and soil ecotoxicological effects of microplastics derived from face masks. J Hazard Mater 416:126169. https://doi.org/10.1016/j.jhazmat.2021.126169

Ma J, Sheng G, O'Connor P (2020) Microplastics combined with tetracycline in soils facilitate the formation of antibiotic resistance in the *Enchytraeus crypticus* microbiome. Environ Pollut 264:114689. https://doi.org/10.1016/j.envpol.2020.114689

Machado A, Lau C, Kloas W, Bergmann J, Bachelier J, Faltin E, Becker R, Görlich A, Rillig M (2019) Microplastics can change soil properties and affect plant performance. Environ Sci Technol 53:6044–6052. https://doi.org/10.1021/acs.est.9b01339

Mahamud AGM, Uddin S, Anu MS, Baroi A, Datta A, Khan MSU, Rahman M, Tabassum T, Tanwi JT, Rahman T (2022) Microplastics in fishmeal: a threatening issue for sustainable aquaculture and human health. Aquacult Rep 25:101205. https://doi.org/10.1016/j.aqrep.2022.101205

Malafaia G, de Souza AM, Pereira AC, da Silva Matos S, Araújo A, Robeiro R, Rocha TL (2019) Developmental toxicity in zebrafish exposed to polyethylene microplastics under static and semi-static aquatic systems. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2019.134867

Mbugani JJ, Machiwa JF, Shilla DA, Kimaro W, Joseph D, Khan FR (2022) Histomorphological damage in the small intestine of Wami Tilapia (*Oreochromis urolepis*) (Norman, 1922) exposed to microplastics remain long after depuration. Microplastics 1(2):240–253. https://doi.org/10.3390/microplastics1020017

Nanthini devi K, Raju P, Santhanam P, Perumal P (2022) Impacts of microplastics on marine organisms: present perspectives and the way forward. Egypt J Aquat Res 48(3):205–209. https://doi.org/10.1016/j.ejar.2022.03.001

Ng EL, Huerta E, Eldridge S, Johnston P, Hu H, Geissen V, Chen D (2018) An overview of microplastic and nanoplastic pollution in agroecosystems. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2018.01.341

Rendell-Bhatti F, Bull C, Cross R, Cox R, Adediran GA, Lahive E (2023) From the environment into the biomass: microplastic uptake in a protected *Lamprey* species. Environ Pollut 323:121267. https://doi.org/10.1016/j.envpol.2023.121267

Sangkham S, Faikhaw O, Munkong N, Sakunkoo P, Arunlertaree C, Chavali M, Mousazadeh M, Tiwari A (2022) A review on microplastics and nanoplastics in the environment: their occurrence, exposure routes, toxic studies, and potential effects on human health. Mar Pollut Bull 181:113832. https://doi.org/10.1016/j.marpolbul.2022.113832

Schmaltz E, Melvin EC, Diana Z, Gunady EF, Rittschof D, Somarelli JA, Virdin J, Dunphy-Daly MM (2020) Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution. Environ Int 144:106067. https://doi.org/10.1016/j.envint.2020.106067

Shi J, Wu D, Su Y, Xie B (2020) Selective enrichment of antibiotic resistance genes and pathogens on polystyrene microplastics in landfill leachate. Sci Total Environ 765:142775. https://doi.org/10.1016/j.scitotenv.2020.142775

Smith M (2018) Microplastic residuals in municipal compost bioaccumulate in plant tissue. Royal Roads University, Victoria. https://doi.org/10.25316/IR-402

Thushari GGN, Senevirathna JDM (2020) Plastic pollution in the marine environment. Heliyon 6(8):e04709. https://doi.org/10.1016/j.heliyon.2020.e04709

Wang Q, Duan X, Huang F, Cheng H, Zhang C, Li L, Ruan X et al (2021) Polystyrene nanoplastics alter virus replication in orange-spotted grouper (*Epinephelus coioides*) spleen and brain tissues and spleen cells. J Hazard Mater 416:125918. https://doi.org/10.1016/j.jhazmat.2021.125918

Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. Environ Pollut 178:483–492. https://doi.org/10.1016/j.envpol.2013.02.031

Wright R, Erni-Cassola G, Zadjelovic V, Latva M, Christie-Oleza J (2020) Marine plastic debris: a new surface for microbial colonization. Environ Sci Technol 54:11657–11672. https://doi.org/10.1021/acs.est.0c02305

Wu C, Xiong X, Hamidian AH, Zhang Y, Xu X (2022) A review on source, occurrence, and impacts of microplastics in freshwater aquaculture systems in China. Water Biol Secur 1(3):100040. https://doi.org/10.1016/j.watbs.2022.100040

Yang H, Yumeng Y, Yu Y, Yinglin H, Fu B, Wang J (2022) Distribution, sources, migration, influence and analytical methods of microplastics in soil ecosystems. Ecotoxicol Environ Saf 243:114009. https://doi.org/10.1016/j.ecoenv.2022.114009

Yu H, Qi W, Cao X, Hu J, Li Y, Peng J, Hu C, Qu J (2021) Microplastic residues in wetland ecosystems: Do they truly threaten the plant-microbe–soil system? Environ Int 156:106708. https://doi.org/10.1016/j.envint.2021.106708

Zhang Y, Kang S, Allen S, Allen D, Gao T, Sillanpää M (2020) Atmospheric microplastics: a review on current status and perspectives. Earth Sci Rev 203:103118. https://doi.org/10.1016/j.earscirev.2020.103118

Zhang Y, Gao T, Kang S, Shi H, Mai L, Allen D, Allen S (2022) Current status and future perspectives of microplastic pollution in typical cryospheric regions. Earth-Sci Rev 226:103924. https://doi.org/10.1016/j.earscirev.2022.103924