

## Review Article

# Trophic Transfer and Accumulation of Microplastics in Freshwater Ecosystem: Risk to Food Security and Human Health

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Plastic pollution is not at all a novel matter to the scientific as well as the public community. However, the knowledge of the general public when it comes to microplastic pollution is still in its infancy. The major sources of these tiny plastic particles in the aquatic environment are laundry, abrasion of household plastics, cosmetics, personal care products, tyre wear, food wrappings, and so on. However, the public is not much aware that they are part of these major emission sources and how much they are contributing to it. Also, the vast majority of research conducted to date on plastic pollution in all size fractions has focused more on marine ecosystems than freshwater ecosystems. Hence, people are more associated with freshwater ecosystems than marine ecosystems; it should be given additional importance. Rather than the effect on aquatic organisms through ingestion and other ways, the ecological risks posed by micro and nanoplastics as vectors for chemical contaminants and their accumulation through trophic transfer are more serious and of utmost importance. Aquatic life or aquatic ecosystem is already affected by a multitude of environmental stressors, and now microplastics and nanoplastics may represent a significant additional risk to food security. Micro and nanoplastics have already invaded our diet in various ways. Even if it does not show any immediate effect on human health, long-term exposure may pose a serious threat to the human population. Hence, identifying the possible sources and reducing exposure to these sources is of utmost importance.

## 1. Introduction

The term “plastic” indicates a range of polymer materials that can be moulded into different sizes and shapes based on the requirements of the end product under different temperature and pressure conditions. Fossil resources such as coal, natural gas, and crude oil and organic products such as cellulose and so on are used for the production of these synthetic and semisynthetic polymers. Some of the major polymers include polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyamides (PA), and so on.

Microplastics (MPs) are those plastic particles with a size of not more than 5 mm and not less than 0.1 mm. Some researchers have suggested a few other terms and classifications according to size range, such as

macroplastics as particles larger than 5 mm, mesoplastics as particles in size between 5 and 1 mm, MPs as a size between 1 mm and 0.1  $\mu\text{m}$ , and NPs as particles in size less than 0.1  $\mu\text{m}$  [1]. Many such size ranges have been suggested by different researchers. However, generally, the size 5 mm is more accepted as the upper limit [2], as this size includes several small particles that can be readily consumed by organisms. The plastic particles in these size ranges are again classified according to their shape for research purposes and better understanding. Primarily, five main groups or categories are used for the classification of MPs based on their shape (Table 1); sometimes the nomenclature may differ among research groups.

Once plastics break down into smaller particles, also known as MPs, and disperse into the environment, their elimination from any part of the ecosystem is a strenuous

TABLE 1: Categories used for classifying MPs by shape [3].

Shape classification	Other terms used
Fragments	Irregularly shaped particles, crystals, fluff, powder, granules, shavings, flakes, and films
Fibers	Filaments, microfibers, strands, and threads
Beads	Grains, spherical microbeads, and microspheres
Foams	Polystyrene and expanded polystyrene
Pellets	Resin pellets, nurdles, preproduction pellets, and nibs

task. MPs are mostly introduced into aquatic habitats as a result of human activities, and their distribution is quite diverse. The rise in human population density and the abundance of MPs have been shown to have a positive association, which might contribute to an increase in plastic debris accumulating in aquatic habitats [4]. Among the plastic wastes accumulating in the marine environment, 70–80% of MPs are imported through rivers [5]. In a recent study done at the Saigon River Estuary system, Vietnam, it is estimated that anthropogenic fiber release from the river to sea was  $115\text{--}164 \times 10^{12}$  items  $\text{yr}^{-1}$  [6].

There is evidence showing the presence of plastic in different environments/ecosystems for many years [7] and even within pristine and remote locations [8] even in the Arctic [9]. These minute plastic particles are likely to be derived from different sources such as disposable articles, packaging items, particles from tyre and roads, wall paint, roadside litter, fibers from synthetic textiles, and so on [10]. The composition and physicochemical characteristics of MPs are quite diverse, and attention to their environmental occurrence and impacts has switched to our inland waterways in recent years. For addressing the raising environmental questions regarding MPs, a thorough characterisation including their size, shape, and other major characteristics are important and necessary. In the last two eras, the research regarding MPs pollution has increased exponentially but authenticated and standardized methods for sampling, quantification, and characterisation of MPs are still lacking. As a result, interlaboratory comparability has been hampered, resulting in worse quality assurance and under or overestimation of MPs [11].

Secondary MPs and NPs are formed by the degradation of macroplastics through different kinds of stresses that impact the structure and reactivity of the polymer, thereby inducing degradation. These stresses include hydrolysis, photodegradation due to UV exposure, mechanical abrasion by sand or wave action, and biodegradation [5]. Most of the MP and NP emissions to the environment are accidental and occur without the knowledge of the user because these releases occur during different processes which are part of our daily lives.

Different kinds of plastics are used in manufacturing a diversity of products. Individual monomers are polymerized, forming the backbone of the polymer for these products. During these processes, several solvents and other chemicals are used as initiators and catalysts. In addition, several additives such as flame retardants, stabilizers, pigments, and fillers are included in the production process to give plastic certain characteristics such as flexibility,

strength, and colour as per product requirements. These chemicals may get released into the environment at any stage of its life cycle, during production, use, or disposal of the product [12]. Based on the polymers used, additives, and by-products, the United Nations and European Union frameworks estimate that more than half of all plastics produced are dangerous to the environment [13]. These chemical additives may get leached into the surrounding environment. And these chemicals can act as vectors for the contaminants in the environment and organisms.

Several studies have been conducted regarding the threats posed by MPs to aquatic life and ecological processes. These studies suggest that MPs may affect food security mainly in lower trophic level organisms [14], human health and well-being [15], and the different ecological processes associated with the ecosystem. In this review, we assess the capacity of MPs and NPs as vectors of chemical contaminants and also their effect on food security and human health through trophic transfer.

## 2. Sources of MPs and NPs in the Aquatic Ecosystem

**2.1. Cosmetics and Personal Care Products.** The use of MP beads in personal care and cosmetic items is one of the most common sources and routes for persistent and potentially dangerous primary MP components to enter the aquatic environment [16]. Plastic particles are released directly into wastewater during and after daily use of personal care and cosmetic goods, as the majority of these products are washed off or flushed down the drain. A single scrape can release 4,500 to 94,500 PE microbeads, but a single 1.6 g of toothpaste can hold up to 4000 PE pieces [17]. A recent study in the UAE showed the presence of MPs in facial and body scrubs. Surprisingly, out of 37 products analysed, only 11 products had MPs particles in them [18].

**2.2. Textiles and Commercial Cleaning of Synthetic Fibers.** Recent field research identified fibers as a prominent type of MP in diverse habitats, including remote locales, even in polar glaciers [19]. Textile microfibers are one of the major MP fiber sources. These fibers get detached from the textile article during every step of its lifecycle, particularly during laundry [20]. Nonfiltered effluents from commercial laundries release into the drains, which become a point source of microfibers just like home laundries, in which a single garment can release approximately > 1900 fibers in just one wash [21]. Also, the different washing parameters such as the

usage of detergents, the period of washing, and the type of fabrics affect the amount of fiber released during laundry [22]. Synthetic fibers such as ester and nylon are often used in synthetic textiles [23]. Not only during washing but also during the normal usage of cloths, shredding of fibers will occur. A group of researchers studied this aspect in which they have done sampling lake sediment, snow, and ice purposefully wearing red overalls composed of cotton. And for all the detected fibers in the above-mentioned samples,  $25 \pm 1\%$ ,  $20 \pm 7\%$ , and  $8 \pm 6\%$  for snow, ice, and sediment, respectively, originated from sampling attire [11]. These findings show that the normal usage of cloths also leads to the shredding of fibers and also self-contamination plays a significant role when quantifying MP pollution. A recent addition to the release of microplastic fibers to the environment is the single-use surgical masks and gloves, whose usage has enormously increased among the public due to the surge in COVID-19 [24].

*2.3. From Household/Indoor.* There are many polymer-based products in our daily lives, both synthetic and natural, that we utilise both indoors and outdoors. The release of particles during their abrasion is of least concern because of their negligible size, and not a huge amount of material per day is produced. However, all of these plastic substances abrasion and weathering are expected to add home source materials of macro and MPs. The common things that we use in our households, such as plastic carpets, furniture, curtains, and so on, are shredding thousands of fibers daily. Even flakes and chips from ancient interior paint on the walls, polyurethane particles from mattresses, and plastic dust from electronics become microplastic sources [25]. Recent studies show that disposable plastic containers and disposable cups have traces of plastic particles, which may be unintentionally produced during manufacturing, becoming a primary source of MPs in the household [26]. Also, food packaging in plastic trays has shown traces of MPs in packed foods [27]. Toners in laser printers consist of a large amount of microscopic thermoplastic powder with a diameter of about 2–10 micrometers. Usually, this is a styrene-acrylate copolymer that is melted onto the paper when printing [28]. The spill out of these toner products adds to the number of MPs particles in the indoor environment.

*2.4. From Industrial or Commercial Usage.* Abrasive blasting media for cleaning metal surfaces, abrasive hand cleanser soaps, and various uses in the petroleum sector are just a few examples of commercial or industrial applications for primary MPs. In the process of abrasive blasting, sand or water is commonly used as the blasting media. Plastic beads, on the other hand, are favoured for blasting tougher surfaces when the blasting medium must not harm the surface. This will release a vast number of plastic particles into the surroundings during the process, which will be finally washed off into a drain. In geotechnical engineering, while drilling oil and natural gas wells, a drilling fluid is used. Drilling fluids based on plastic microbeads have been used for decades, and Teflon-enhanced particles have even been

trademarked and sold globally for drilling purposes [29]. Thermal cutting of polystyrene foam produces nanometer-sized polymer particles with a diameter of 22–220 nm [30]. During their life cycle, many polymers undergo similar thermal treatments. In a study, it is observed that nanometer-sized polymers are emitted during 3D printing in the range of ~11–116 nm [31], at a considerable rate. Furthermore, several polymer nanoparticles are simple to make and are employed in research and other uses, so they will end up in the environment.

*2.5. From Fisheries and Aquaculture.* In both fisheries and aquaculture, plastics are significant components. Many tools, such as nets, fishing gears, trawls, dredges, hooks and lines, fish hold insulation, fish crates, and packing materials, are used in both of these industries. With the advancement of industries, most of these tools are made from synthetic or semisynthetic plastic materials [3]. Synthetic fibers are considered to be more beneficial than natural fiber ropes as they offer more strength and durability and also reduce the overall weight of the tools to a great extent when compared with the old conventional tools. However, in addition to the benefits that synthetic types of equipment give, the flip side of the issue is that when these equipment age and get destroyed, the plastic components immediately enter the water [32], where they decompose to generate MPs and NPs.

*2.6. From Wastewater Treatment Plants.* Wastewater treatment plants could potentially be a major source of MPs in the aquatic environment [2, 33]. In all the above sources that we have discussed, the ultimate destination of those MPs will be wastewater, thereby entering a wastewater treatment plant [17]. Granulated PE, PP, and PS particles found in personal care products (PCPs), cleaning agents, and air-blasting media are small enough to bypass the treatment process in wastewater treatment plants [34]. Synthetic clothing, such as polyester and nylon, is also an issue since these materials may shed thousands of synthetic threads into drains during textile manufacturing and laundering. Wastewater treatment systems are not specifically designed to deal with plastic materials [35].

With the higher usage of pesticides in agriculture, approximately 80,000 tonnes annually [36], the soil ecosystems were damaged both physically and biologically. So, to improve the physical qualities of these soils, processed heat-dried sludge is marketed and used as a soil amendment/conditioner in some places. However, this may pose an additional threat to the soil ecosystem. A study conducted at a wastewater treatment plant in Spain found that the sludge from the plant used for soil improvement could spread up to  $10^{13}$  MP particles in agricultural soils per year [37].

*2.7. Spills during Production and Transport.* For the production of different plastic products, granulated forms of plastic are used as raw materials. Also, the used plastics in their recycling stage are converted into plastic granules. During the preproduction and recycling stages, there are

high chances for accidental discharge of these granules to the surrounding environment. Hence, the plastic manufacturing and conversion process is often considered a point source for MP discharge into the environment [38]. These pelleted or granulated plastics are transported through various means, such as rail, road, air, and water. During all these means particularly by rail, road, and water, these pellets can be spilled into the immediate surroundings.

*2.8. MPs and NPs as Vectors for Chemical Contaminants and Heavy Metals.* Compared to other usual pathways, the possible role of MPs and NPs as vectors for hydrophobic organic chemicals (HOCs) and heavy metals (HMs) is an issue of much concern. The sorption of HOCs and HMs to MPs is considered a significant environmental process because this will affect the mobility and bioavailability of these pollutants [39]. MPs interact with organic pollutants before, during, and after they are released into natural environments [40]. And adsorption kinetics are influenced by a variety of parameters, including polymer type, density, and crystallinity, as well as the surrounding environment and contaminants present [41].

Also, the photoaging of certain polymers is found to increase their absorption capacity for hydrophobic organic pollutants [42]. The buoyancy and transport mechanism of MPs primarily depends on their density, size, and shape [43]. In the freshwater environment, MPs are likely to co-occur with other emerging contaminants such as pharmaceuticals, personal care products, flame retardants, fluorinated and sulfonated organic compounds, household cleaning products, and other industrial chemicals, which enter the environment as a part of complex solid and liquid waste streams [44].

The general sorption mechanisms found in MPs are hydrophobic interactions, electrostatic interactions, pore filling, Van der Waals forces, hydrogen bonding, and  $\pi$ - $\pi$  interactions and the type of mechanism depends on the characteristics of the sorbent and sorbate [45]. Since common polymers such as PS, PP, PE, or PET are hydrophobic, among these sorption mechanisms, hydrophobic interaction is the most dominant one [46]. During hydrophobic interaction, an aggregate or cluster is formed by the attraction between two nonpolar substances. The electrostatic interactions occur due to the attraction between oppositely charged molecules or the repulsion of molecules of similar charge [46]. The pore-filling process depends on the polymer structure, particularly its pore diameter, and also on the molecular size of the pollutant/chemical. During the pore-filling process, the contaminants enter the polymer matrix and get trapped in the small pores of microplastics, and pollutants with lower molecular weight are found to move easily through the polymer matrix with larger pores [47, 48]. Laboratory and field studies show that MPs can adsorb chemicals ranging from 1 to 10,000 ng/g [49].

Due to the high surface area of NPs, they show higher sorption affinities for toxic compounds than MPs [50]. This sorption process may differ for different polymers and different chemicals based on the polymer structure and

hydrophobicity of the chemicals. The different additives used in the polymers can also change their structure and thereby affect the sorption process [51]. Polypropylene microfibrils are shown to adsorb toxic chemicals such as PCBs (polychlorinated biphenyls), DDE (dichlorodiphenyldichloroethylene), and nonylphenols, whereas polyethylene adsorbs four times more PCBs than polypropylene [52]. After the adsorption of the chemicals to the polymer surface, their transport through the polymer matrix depends on different factors of the polymer, such as the free volume within the polymer, the distance between the polymer chains, and the ability of a polymer to transform into different physical conformations, which is the segmental mobility of the polymer. With the increase in the distance between polymer chains, the sorptive capacity also increases. The immediate environment (water, sediment) of the polymer and the chemical also affects the sorption capacity [53].

These chemical contaminants and HMs can be transferred from MPs to organisms in an aquatic environment either through the liquid media or by direct interaction exposure of MPs to the organism's skin or exoskeleton. If an organism ingests MPs containing these sorbed contaminants, these contaminants can be moved to the organism's tissue via extracellular/interstitial fluids or direct contact between the MPs and the organism's interior walls. While uptake occurs through water or intraorganismal fluids, desorption of HOCs from the sorbent is required to form freely dissolved molecules. This desorption of adsorbed molecules depends on many factors, and it mainly decreases with an increase in partition ratios and increasing binding strength [39]. Mayer [54] in one of his studies found out that HOCs sorbed to MPs are likely to be transferred more rapidly through intraorganismal fluids than water to biota. The uptake through direct contact with the external or internal parts of the organism might be an important but still overlooked route of exposure.

Also, the increased surface area of MPs provides a favourable environment for the establishment of microbial communities on the MPs' surface and thereby alters the natural composition and structure of microbial communities in the natural environment [55]. Such bacterial biofilms formed on MPs have been shown to include bacteria with antibiotic-resistant genes [56], which might originate from human and animal populations treated with antibiotics and transfer downstream through wastewater into aquatic ecosystems [57]. These antibiotics have shown higher adsorption to MPs in freshwater ecosystems than in marine ecosystems. The spread of these antibiotic-resistant bacteria (ARB) and/or antibiotic-resistant genes (ARG) makes water bodies natural sinks of antibiotic resistance and paves the way for another major societal and economic concern.

*2.9. Accumulation of Micro and Nano Plastics through Trophic Transfer.* Concerns about the incorporation of MPs and NPs into food webs have grown as the number of MPs and NPs in the aquatic system has increased. The effect of polymers or plastics starts from the lowest level of the food

web itself in the aquatic environment. MPs are the same size as plankton and grains of other organic food materials, allowing them to be consumed by a variety of organisms with various feeding strategies [58]. Also, the difference in densities and shapes of these polymers affects their behavior [59] and distribution into different compartments (surface, water column, and sediment) of the aquatic environment and influences their availability to organisms at different trophic levels [60]. The ingestion of MPs causes several physical and biological impacts on the organisms. It disrupts feeding in algae and filter-feeding organisms [61], thereby reducing the weight of the organisms and thus leading to mortality and a decrease in fertility [62]. As discussed in the earlier section, apart from the physical impacts of ingested MPs alone on organisms, adverse health effects also occur from additives, sorbed contaminants, and so on, which are carcinogenic and even capable of endocrine disruption in organisms [63]. The effects of different types of polymers on some freshwater organisms are listed in Table 2.

The ingestion could be due to a failure to distinguish MPs from the prey, or it could be due to the intake of lifeforms from lower trophic levels that contain these particles [76]. MPs may also adhere directly to organisms [77]. In terms of food safety, MPs and NPs are also an emerging threat, as these particles can eventually end up in the human food chain through fish and other kinds of aquatic foods and also through other aquatic-based products [78].

Biofouling may play a key role in the faulty identification of plastic as a food source by organisms [79]. Studies suggest that the formation of biofilms increases the likelihood of MP ingestion by altering the vertical distribution of the particle, and they attract organisms by a diethyl sulphide odour which is associated with organic matter that is produced during the breakdown of biofilms on the plastic surface [80]. Sea turtles were also found to ingest plastics for the same reason, with visual cues also playing an important role [81]. The ingestion of fouled plastic particles is not limited to higher trophic organisms. Copepods exposed to both clean and fouled PS particles ingested a higher frequency of aged particles with a biofilm [82].

The nutrient cycling or nutrient availability in an aquatic ecosystem is highly dependent on Zooplanktons. The primary producers and higher trophic organisms are linked by them. They consume the primary producers and convert the organic matter into fecal pellets of high density and sinking velocity [83] so that it becomes available to sedimentary organisms and also adds to the carbon sink in the aquatic ecosystem [84]. Along with the food intake, MPs also get ingested and also get egested with fecal pellets. These plastic particles present in the fecal pellet could be trophically transferred to other coprophagous animals [85]. All the plastic particles which are ingested by the zooplankton may not get egested through feces. Thus, the residual plastics in the gut of zooplanktons directly get transferred to the higher trophic levels by preying on them.

NPs, either primary or degraded from MPs, enter the food chain through algae, bacteria, and/or filter-feeding organisms [58]. Algae and phytoplankton, which are the major primary producers and credited for half of the total photosynthesis on

Earth and the conversion of solar energy into biomass, are facing a threat from these tiny plastic particles. Bhattacharya published the first evidence of the physical influence of NP beads on two algae species, *Chlorella sp.* and *Scenedesmus sp* [86]. In that study, the adsorption of NPs occurred due to the electrostatic attraction between the positively charged algal cellulose and negatively charged NP beads. This tendency of adsorption depends on the cell morphology and motility of the algae and it leads to the generation of an induced reactive oxygen species in the algae. In another study, a significant reduction of photosynthesis was seen in algae *Dunaliella tertiolecta*, *Thalassiosira pseudonana*, and *Chlorella vulgaris* upon 72 h exposure to micropolystyrene particles, but no changes in algal growth rate were found [87].

The effects of food chain transfer have been experimented within a study in which an algal species exposed to nanopolystyrene particles and affected by a reduction in chlorophyll were further exposed to the zooplankton *Daphnia sp.*, which resulted in several alterations in reproduction and reduced body size [88]. It was the first study to show the effects of NPs exposure in algae and *Daphnia* populations through food chain transfer. A study on the next level of the food chain was conducted in which *Daphnia magna* exposed to PS nanoparticles was further given to fish (*Crucian carp*), and the results were more than expected, that is, not only did the direct uptake of PS NPs from *Daphnia magna* to fish (*Crucian carp*) occurred but also the PS NPs entered the brain of the fish, which resulted in behavioral disorders and decreased survival rate of the fish [89].

Benthic and pelagic food webs also get affected by MP and NP accumulation and transfer. There is evidence of the trophic transfer of MPs from blue mussels to crabs. The blue mussel (*Mytilus edulis*) previously exposed to PS-MPs was further fed to crabs (*Carcinus maenas*). After 24 hours of exposure, 0.027% of the concentration of MPs fed to the mussels was reported in the crab hemolymph [90]. It is suggested that the feeding type or feeding habits may also affect the percentage of uptake of MPs in organisms. A study reveals that omnivorous fish species have registered higher MP content than carnivores and herbivores organisms. They concluded that the broader diet source of omnivorous organisms is the reason for higher MP content in them [91]. All these results indicate the possible accumulation of micro and nanoplastic particles through the food chain either via direct or indirect uptake. Direct uptake occurs when the organisms could not distinguish between natural prey and synthetic items, while indirect uptake occurs through feeding on previously exposed prey [92]. If the basic level of a food web gets harmed, its effects will be forwarded through the food chain to the entire food web, maybe not very rapidly but in an unpredictable or less recognized manner.

In the case of human consumption of fish or other aquatic organisms, mostly only the edible fleshy parts are consumed, and the visceral organs are excluded, where the ingested MPs are more likely to accumulate but in the case of some small pelagic fish species that are consumed as such, it poses a risk to human food security. As discussed earlier, rather than the effects of plastics, the additives and chemical contaminants in them pose a greater threat to ecosystem health.

TABLE 2: Effects of different polymers in different freshwater organisms.

Polymer	Organism	Effect	Reference
PVC, PP	Chlorella (C.) pyrenoidosa and Microcystis (M.) flos-aquae	Inhibited photosynthesis activity	[64]
PS	Chlorella pyrenoidosa	Physical damage, oxidative stress, reduction in growth	[65]
PA, PE, PP, PVC	Danio rerio	Intestinal damage, oxidative stress	[66]
PVC, PE	Dicentrarchus labrax	Immune system dysfunction, histopathological effects	[67]
PA, PE, PP, PVC	Caenorhabditis elegans	Inhibited survival rate, body length, and reproduction	[66]
PE	Hydra attenuate	Changes in feeding and morphology	[68]
PET	Gammarus pulex	Affect survival and metabolism	[69]
Polymer microspheres	Dicentrarchus labrax	Negative effect on swimming performance	[70]
PS, PA (polyethylene acrylate), EVA (ethylene vinyl acetate)	Carassius auratus	Histopathological effects, damages in jaw	[71]
LDPE	Clarias gariepinus	Histopathological effects	[72]
PVC	Dicentrarchus labrax	Histological changes and alterations in intestinal tissues	[73]
PS	Danio rerio	Inflammation and lipid accumulation in fish liver-oxidative stress was induced. Alterations of metabolic profiles in fish liver	[74]
PE, PP	Hyalella azteca	Decreased growth and reproduction	[75]

### 2.10. Microplastic to Humans through the Aquatic Food Chain.

Several studies have been reported on the exposure and transfer of different types of MPs to humans [93] and to different parts of the human body. Recently, scientists confirmed the presence of microplastics even in human blood [94] and in human lung tissue [95], which indicates the level of microplastic pollution and its impact on humans. The available literature regarding the trophic transfer of MPs from aquatic food chains, particularly freshwater ecosystems, to humans is found to be scarce.

The two significant exposure pathways of MPs to humans are inhalation and ingestion, and the latter mostly happens through aquatic food consumption. In the freshwater ecosystem, the transfer of MPs to humans happens through the consumption of aquatic organisms. There is evidence of MPs in many freshwater organisms consumed by humans, such as fish [1], bivalves [96], shrimps, and crabs [97]. The greater risk is when, in the case of some species of fish, consumption as a whole or incomplete removal of the viscera can increase the MPs load entering the human body [98]. Also, studies show the presence of microplastics in the edible flesh part of fish, which increases the risk of exposure to MPs [99].

In a study conducted by Senathirajah et al. [100], they made a preliminary estimate of the potential amount of microplastics that may be ingested by humans from aquatic, atmospheric, and other consumables. The results indicate that globally, on average, humans could potentially be ingesting 0.1–5 g of microplastics per week. So far, there is no accurate data on the mass of MPs ingested by humans through the aquatic food chain alone. However, in a recent study, it is estimated that the per capita microplastic intake through the consumption of shellfish can be approximately  $13 \pm 58$  microplastic particles per year, in which they studied two species of shrimp, one crab species and one species of squid. An average of  $3.2 \pm 10$  microplastic particles  $\text{kg}^{-1}$  have been reported in the edible tissue of one species of crab, *Portunus pelagicus* [98].

The impact of MPs on aquatic organisms is a well-discussed area, but the impacts on humans are yet to be studied or are still in their infancy. There is stronger evidence for the ingestion of microplastics by humans since studies show the presence of MPs even in human feces [101]. Deng [102] in his study on mice found that the MPs may accumulate in the liver, kidney, and gut and have adverse effects on the liver, such as troubles in lipid and energy metabolism, oxidative stress, and neurotoxic responses. This raises concerns about the same toxicity in human liver cells too [103]. A study conducted on the toxicity of PS-MPs in the human lung epithelial BEAS-2B cells revealed that it can cause cytotoxic and inflammatory effects in BEAS-2B cells by inducing reactive oxygen species formation, thereby posing a risk to human respiratory health [104].

### 3. Conclusion

Biomagnification is not often reported in the case of MPs in organisms and the higher risk is posed or more reported to lower trophic level organisms. However, many studies have

revealed the presence of MPs in species of marine organisms particularly fishes consumed by humans which may occur by the direct exposure of the species to MPs. Currently, there is no clear evidence whether MPs and NPs have a serious effect on humans as it does on aquatic organisms, as the level of these plastics ingested is not at sufficient concentrations to cause the same issues as they do in aquatic animals. When we consider that many aquatic organisms are relevant to the fish industry and that they can ingest these tiny plastics, it is logical to hypothesize potential risks to human health and food security. Chemically speaking, the plastics themselves are generally inert and do not have much effect on human health. However, the substances with greater concern are the chemical additives used in plastics during manufacturing, toxic chemicals absorbed, and harmful pathogens attached to plastics from the contaminated ecosystem that have potentially negative effects on organisms and ecosystem health. Since these plastic particles have an impact on all environmental matrices, thorough studies on their impact on the terrestrial ecosystem, plant growth performance and yield, atmospheric interactions, and so on also should be conducted.

From the above-mentioned sources of MP and NP emissions to the environment, it is well understood that the major pathways of MP emissions are by the common people through laundry, cosmetics and personal care products, abrasion of household plastics, and so on. However, the public is not much aware of their contribution to this type of pollution. Hence, awareness should be given to the general public about these harmful emissions and they should be encouraged to use plastic-free personal care products, fewer plastics in households, and so on, thereby trimming down the emissions. More efforts should be given to better plastic waste management and monitoring so that it will not enter the environment in a harmful way.

For a better understanding of the current stage of plastic pollution in the aquatic ecosystem, the field databases about plastics in all size fractions should be increased particularly in freshwater environments. Since plastics find their way to oceans mainly through rivers, the estimation of river plastic emissions to the oceans is important. Also, more research studies are needed to identify the role of plastics as vectors for biological and chemical contaminants in the biota. There is a lack of studies on the effect of MPs and NPs on humans through the food chain which is a very serious threat to human food security. Therefore, in-depth studies should be carried out and immediate remedial measures should be taken before the MPs and NPs invade our daily diet.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## References

- [1] L. B. Merga, P. E. Redondo-Hasselerharm, P. J. Van den Brink, and A. A. Koelmans, "Distribution of microplastic and small macroplastic particles across four fish species and sediment in an African lake," *Science of the Total Environment*, vol. 741, Article ID 140527, 2020.
- [2] T. Gomes, A. Bour, C. Coutris et al., "Ecotoxicological impacts of micro-and nanoplastics in terrestrial and aquatic environments," *Microplastic in the Environment: Pattern and Process*, p. 199, Springer, Berlin, Germany, 2021.
- [3] A. Lusher, P. Hollman, and J. Mendoza-Hill, *Microplastics in Fisheries and Aquaculture: Status of Knowledge on Their Occurrence and Implications for Aquatic Organisms and Food Safety*, FAO, Rome, Italy, 2017.
- [4] C. M. Rochman, M. A. Browne, B. S. Halpern et al., "Classify plastic waste as hazardous," *Nature*, vol. 494, no. 7436, pp. 169–171, 2013.
- [5] O. S. Alimi, J. Farner Budarz, L. M. Hernandez, and N. Tufenkji, "Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport," *Environmental Science and Technology*, vol. 52, no. 4, pp. 1704–1724, 2018.
- [6] E. Strady, T. C. Kieu-Le, J. Gasperi, and B. Tassin, "Temporal dynamic of anthropogenic fibers in a tropical river-estuarine system," *Environmental Pollution*, vol. 259, Article ID 113897, 2020.
- [7] A. T. Williams and S. L. Simmons, "The degradation of plastic litter in rivers: implications for beaches," *Journal of Coastal Conservation*, vol. 2, no. 1, pp. 63–72, 1996.
- [8] C. M. Free, O. P. Jensen, S. A. Mason, M. Eriksen, N. J. Williamson, and B. Boldgiv, "High-levels of microplastic pollution in a large, remote, mountain lake," *Marine Pollution Bulletin*, vol. 85, no. 1, pp. 156–163, 2014.
- [9] A. L. Lusher, V. Tirelli, I. O'Connor, and R. Officer, "Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples," *Scientific Reports*, vol. 5, no. 1, pp. 14947–14949, 2015.
- [10] W. Wang, J. Ge, X. Yu, and H. Li, "Environmental fate and impacts of microplastics in soil ecosystems: progress and perspective," *Science of the Total Environment*, vol. 708, Article ID 134841, 2020.
- [11] C. Scopetani, M. Esterhuizen-Londt, D. Chelazzi, A. Cincinelli, H. Setälä, and S. Pflugmacher, "Self-contamination from clothing in microplastics research," *Ecotoxicology and Environmental Safety*, vol. 189, Article ID 110036, 2020.
- [12] B. Papaleo, L. Caporossi, F. Bernardini et al., "Exposure to styrene in fiberglass-reinforced plastic manufacture: still a problem," *Journal of Occupational and Environmental Medicine*, vol. 53, no. 11, pp. 1273–1278, 2011.
- [13] K. J. Groh, T. Backhaus, B. Carney-Almroth et al., "Overview of known plastic packaging-associated chemicals and their hazards," *Science of the Total Environment*, vol. 651, pp. 3253–3268, 2019.
- [14] C. Walkinshaw, P. K. Lindeque, R. Thompson, T. Tolhurst, and M. Cole, "Microplastics and seafood: lower trophic organisms at highest risk of contamination," *Ecotoxicology and Environmental Safety*, vol. 190, Article ID 110066, 2020.
- [15] N. J. Beaumont, M. Aanesen, M. C. Austen et al., "Global ecological, social and economic impacts of marine plastic," *Marine Pollution Bulletin*, vol. 142, pp. 189–195, 2019.
- [16] A. Bellasi, G. Binda, A. Pozzi, S. Galafassi, P. Volta, and R. Bettinetti, "Microplastic contamination in freshwater environments: a review, focusing on interactions with sediments and benthic organisms," *Environments*, vol. 7, no. 4, p. 30, 2020.
- [17] S. Raju, M. Carbery, A. Kuttykattil et al., "Transport and fate of microplastics in wastewater treatment plants: implications to environmental health," *Reviews in Environmental Science and Biotechnology*, vol. 17, no. 4, pp. 637–653, 2018.
- [18] R. Z. Habib, M. M. Salim Abdoon, R. M. Al Meqbaali et al., "Analysis of microbeads in cosmetic products in the United Arab Emirates," *Environmental Pollution*, vol. 258, Article ID 113831, 2020.
- [19] F. Salvador Cesa, A. Turra, and J. Baruque-Ramos, "Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings," *Science of the Total Environment*, vol. 598, pp. 1116–1129, 2017.
- [20] B. Henry, K. Laitala, and I. G. Klepp, "Microfibres from apparel and home textiles: prospects for including microplastics in environmental sustainability assessment," *Science of the Total Environment*, vol. 652, pp. 483–494, 2019.
- [21] F. De Falco, M. P. Gullo, G. Gentile et al., "Evaluation of microplastic release caused by textile washing processes of synthetic fabrics," *Environmental Pollution*, vol. 236, pp. 916–925, 2018.
- [22] F. S. Cesa, A. Turra, H. H. Checon, B. Leonardi, and J. Baruque-Ramos, "Laundering and textile parameters influence fibers release in household washings," *Environmental Pollution*, vol. 257, Article ID 113553, 2020.
- [23] J. Gong and P. Xie, "Research progress in sources, analytical methods, eco-environmental effects, and control measures of microplastics," *Chemosphere*, vol. 254, Article ID 126790, 2020.
- [24] T. Haritha and P. Siddhuraju, "Is the covid-19 pandemic increasing the microplastic load in our environment?" *Pollution Research*, vol. 40, no. 3, pp. 817–822, 2021.
- [25] J. Gago, O. Carretero, A. V. Filgueiras, and L. Viñas, "Synthetic microfibers in the marine environment: a review on their occurrence in seawater and sediments," *Marine Pollution Bulletin*, vol. 127, pp. 365–376, 2018.
- [26] O. O. Fadare, B. Wan, L. H. Guo, and L. Zhao, "Microplastics from consumer plastic food containers: are we consuming it?" *Chemosphere*, vol. 253, Article ID 126787, 2020.
- [27] M. Kedzierski, B. Lechat, O. Sire, G. Le Maguer, V. Le Tilly, and S. Bruzard, "Microplastic contamination of packaged meat: occurrence and associated risks," *Food Packaging and Shelf Life*, vol. 24, Article ID 100489, 2020.
- [28] D. E. Tsatsis, K. A. Valta, A. G. Vlyssides, and D. G. Economides, "Assessment of the impact of toner composition, printing processes and pulping conditions on the deinking of office waste paper," *Journal of Environmental Chemical Engineering*, vol. 7, no. 4, Article ID 103258, 2019.
- [29] P. Sundt, P. E. Schulze, and F. Syversen, "Sources of microplastic-pollution to the marine environment Project report," 2014, [https://d3n8a8spro7vhmx.cloudfront.net/boomerangalliance/pages/507/attachments/original/1481155578/Norway\\_Sources\\_of\\_Microplastic\\_Pollution.pdf?1481155578](https://d3n8a8spro7vhmx.cloudfront.net/boomerangalliance/pages/507/attachments/original/1481155578/Norway_Sources_of_Microplastic_Pollution.pdf?1481155578).
- [30] H. Zhang, Y. Y. Kuo, A. C. Gerecke, and J. Wang, "Co-release of hexabromocyclododecane (HBCD) and nano-and

- microparticles from thermal cutting of polystyrene foams," *Environmental Science and Technology*, vol. 46, no. 20, pp. 10990–10996, 2012.
- [31] B. Stephens, P. Azimi, Z. El Orch, and T. Ramos, "Ultrafine particle emissions from desktop 3D printers," *Atmospheric Environment*, vol. 79, pp. 334–339, 2013.
- [32] H. Y. Lee, "Plastics at sea (microplastics): a potential risk for hong kong," Postgraduate Thesis, HKU, Hong Kong, China, 2013.
- [33] P. Silambarasan and S. A. Merline, "Microplastics distribution in freshwater lake and drinking water treatment plant: a case study," *Indian Journal of Ecology*, vol. 47, no. 4, pp. 930–933, 2020.
- [34] J. C. Prata, "Airborne microplastics: consequences to human health?" *Environmental Pollution*, vol. 234, pp. 115–126, 2018.
- [35] J. Talvitie, A. Mikola, A. Koistinen, and O. Setälä, "Solutions to microplastic pollution—removal of microplastics from wastewater effluent with advanced wastewater treatment technologies," *Water Research*, vol. 123, pp. 401–407, 2017.
- [36] S. Tripathi, P. Srivastava, R. S. Devi, and R. Bhadouria, "Influence of synthetic fertilizers and pesticides on soil health and soil microbiology," in *Agrochemicals Detection, Treatment and Remediation*, pp. 25–54, Butterworth-Heinemann, Oxford, UK, 2020.
- [37] C. Edo, M. González-Pleiter, F. Leganés, F. Fernández-Piñas, and R. Rosal, "Fate of microplastics in wastewater treatment plants and their environmental dispersion with effluent and sludge," *Environmental Pollution*, vol. 259, Article ID 113837, 2020.
- [38] A. Verschoor, L. De Poorter, E. Roex, and B. Bellert, "Quick scan and prioritization of microplastic sources and emissions," *RIVM Letter report*, vol. 156, pp. 1–41, 2014.
- [39] C. Campanale, G. Dierkes, C. Massarelli, G. Bagnuolo, and V. F. Uricchio, "A relevant screening of organic contaminants present on freshwater and pre-production microplastics," *Toxics*, vol. 8, no. 4, p. 100, 2020.
- [40] N. B. Hartmann, S. Rist, J. Bodin et al., "Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota," *Integrated Environmental Assessment and Management*, vol. 13, no. 3, pp. 488–493, 2017.
- [41] M. Wagner, S. Lambert, M. W. Lambert, and F. Microplastics, *Freshwater Microplastics*, Springer International Publishing, Cham, Switzerland, 2018.
- [42] G. Liu, Z. Zhu, Y. Yang, Y. Sun, F. Yu, and J. Ma, "Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater," *Environmental Pollution*, vol. 246, pp. 26–33, 2019.
- [43] P. Vermeiren, C. C. Muñoz, and K. Ikejima, "Sources and sinks of plastic debris in estuaries: a conceptual model integrating biological, physical and chemical distribution mechanisms," *Marine Pollution Bulletin*, vol. 113, no. 1–2, pp. 7–16, 2016.
- [44] O. H. Fred-Ahmadu, G. Bhagwat, I. Oluyoye, N. U. Benson, O. O. Ayejuyo, and T. Palanisami, "Interaction of chemical contaminants with microplastics: principles and perspectives," *Science of the Total Environment*, vol. 706, Article ID 135978, 2020.
- [45] F. G. Torres, D. C. Dioses-Salinas, C. I. Pizarro-Ortega, and G. E. De-la-Torre, "Sorption of chemical contaminants on degradable and non-degradable microplastics: recent progress and research trends," *Science of the Total Environment*, vol. 757, Article ID 143875, 2021.
- [46] P. S. Tourinho, V. Kočí, S. Loureiro, and C. A. van Gestel, "Partitioning of chemical contaminants to microplastics: sorption mechanisms, environmental distribution and effects on toxicity and bioaccumulation," *Environmental Pollution*, vol. 252, pp. 1246–1256, 2019.
- [47] S. Maity, C. Biswas, S. Banerjee et al., "Interaction of plastic particles with heavy metals and the resulting toxicological impacts: a review," *Environmental Science and Pollution Research*, vol. 28, no. 43, pp. 60291–60307, 2021.
- [48] F. Wang, M. Zhang, W. Sha et al., "Sorption behavior and mechanisms of organic contaminants to nano and microplastics," *Molecules*, vol. 25, no. 8, p. 1827, 2020.
- [49] A. A. Koelmans, E. Besseling, A. Wegner, and E. M. Foekema, "Plastic as a carrier of POPs to aquatic organisms: a model analysis," *Environmental Science and Technology*, vol. 47, no. 14, pp. 7812–7820, 2013.
- [50] I. Velzeboer, C. J. A. F. Kwadijk, and A. A. Koelmans, "Strong sorption of PCBs to nanoplastics, microplastics, carbon nanotubes, and fullerenes," *Environmental Science and Technology*, vol. 48, no. 9, pp. 4869–4876, 2014.
- [51] S. Endo, M. Yuyama, and H. Takada, "Desorption kinetics of hydrophobic organic contaminants from marine plastic pellets," *Marine Pollution Bulletin*, vol. 74, no. 1, pp. 125–131, 2013.
- [52] A. W. Verla, C. E. Enyoh, E. N. Verla, and K. O. Nwarorh, "Microplastic-toxic chemical interaction: a review study on quantified levels, mechanism and implication," *SN Applied Sciences*, vol. 1, no. 11, pp. 1400–1430, 2019.
- [53] A. Bakir, S. J. Rowland, and R. C. Thompson, "Transport of persistent organic pollutants by microplastics in estuarine conditions," *Estuarine, Coastal and Shelf Science*, vol. 140, pp. 14–21, 2014.
- [54] P. Mayer, M. M. Fernqvist, P. S. Christensen, U. Karlson, and S. Trapp, "Enhanced diffusion of polycyclic aromatic hydrocarbons in artificial and natural aqueous solutions," *Environmental Science and Technology*, vol. 41, no. 17, pp. 6148–6155, 2007.
- [55] M. Arias-Andres, U. Klümper, K. Rojas-Jimenez, and H. P. Grossart, "Microplastic pollution increases gene exchange in aquatic ecosystems," *Environmental Pollution*, vol. 237, pp. 253–261, 2018.
- [56] X. P. Guo, X. L. Sun, Y. R. Chen, L. Hou, M. Liu, and Y. Yang, "Antibiotic resistance genes in biofilms on plastic wastes in an estuarine environment," *Science of the Total Environment*, vol. 745, Article ID 140916, 2020.
- [57] S. Berkner, S. Konradi, and J. Schönfeld, "Antibiotic resistance and the environment—there and back again: science & society series on science and drugs," *EMBO Reports*, vol. 15, no. 7, pp. 740–744, 2014.
- [58] M. Carbery, W. O'Connor, and T. Palanisami, "Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health," *Environment International*, vol. 115, pp. 400–409, 2018.
- [59] L. Nizzetto, G. Bussi, M. N. Futter, D. Butterfield, and P. G. Whitehead, "A theoretical assessment of microplastic transport in river catchments and their retention by soils and river sediments," *Environmental Sciences: Processes & Impacts*, vol. 18, no. 8, pp. 1050–1059, 2016.
- [60] M. Cole, P. Lindeque, C. Halsband, and T. S. Galloway, "Microplastics as contaminants in the marine environment: a review," *Marine Pollution Bulletin*, vol. 62, no. 12, pp. 2588–2597, 2011.
- [61] R. Sussarellu, M. Suquet, Y. Thomas et al., "Oyster reproduction is affected by exposure to polystyrene

- microplastics," *Proceedings of the National Academy of Sciences*, vol. 113, no. 9, pp. 2430–2435, 2016.
- [62] P. M. Canniff and T. C. Hoang, "Microplastic ingestion by *Daphnia magna* and its enhancement on algal growth," *Science of the Total Environment*, vol. 633, pp. 500–507, 2018.
- [63] C. E. Talsness, A. J. M. Andrade, S. N. Kuriyama, J. A. Taylor, and F. S. Vom Saal, "Components of plastic: experimental studies in animals and relevance for human health," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1526, pp. 2079–2096, 2009.
- [64] Y. Wu, P. Guo, X. Zhang, Y. Zhang, S. Xie, and J. Deng, "Effect of microplastics exposure on the photosynthesis system of freshwater algae," *Journal of Hazardous Materials*, vol. 374, pp. 219–227, 2019.
- [65] Y. Mao, H. Ai, Y. Chen et al., "Phytoplankton response to polystyrene microplastics: perspective from an entire growth period," *Chemosphere*, vol. 208, pp. 59–68, 2018.
- [66] L. Lei, S. Wu, S. Lu et al., "Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*," *Science of the Total Environment*, vol. 619–620, pp. 1–8, 2018.
- [67] C. Espinosa, M. Á. Esteban, and A. Cuesta, "Dietary administration of PVC and PE microplastics produces histological damage, oxidative stress and immunoregulation in European sea bass (*Dicentrarchus labrax* L.)," *Fish & Shellfish Immunology*, vol. 95, pp. 574–583, 2019.
- [68] F. Murphy and B. Quinn, "The effects of microplastic on freshwater *Hydra attenuata* feeding, morphology & reproduction," *Environmental Pollution*, vol. 234, pp. 487–494, 2018.
- [69] A. Weber, C. Scherer, N. Brennholt, G. Reifferscheid, and M. Wagner, "PET microplastics do not negatively affect the survival, development, metabolism and feeding activity of the freshwater invertebrate *Gammarus pulex*," *Environmental Pollution*, vol. 234, pp. 181–189, 2018.
- [70] L. G. A. Barboza, L. R. Vieira, and L. Guilhermino, "Single and combined effects of microplastics and mercury on juveniles of the European seabass (*Dicentrarchus labrax*): changes in behavioural responses and reduction of swimming velocity and resistance time," *Environmental Pollution*, vol. 236, pp. 1014–1019, 2018.
- [71] K. Jabeen, B. Li, Q. Chen et al., "Effects of virgin microplastics on goldfish (*Carassius auratus*)," *Chemosphere*, vol. 213, pp. 323–332, 2018.
- [72] A. Karami, N. Romano, T. Galloway, and H. Hamzah, "Virgin microplastics cause toxicity and modulate the impacts of phenanthrene on biomarker responses in African catfish (*Clarias gariepinus*)," *Environmental Research*, vol. 151, pp. 58–70, 2016.
- [73] C. Peda, L. Caccamo, M. C. Fossi et al., "Intestinal alterations in European sea bass *Dicentrarchus labrax* (Linnaeus, 1758) exposed to microplastics: preliminary results," *Environmental Pollution*, vol. 212, pp. 251–256, 2016.
- [74] Y. Lu, Y. Zhang, Y. Deng et al., "Uptake and accumulation of polystyrene microplastics in zebrafish (*Danio rerio*) and toxic effects in liver," *Environmental Science and Technology*, vol. 50, no. 7, pp. 4054–4060, 2016.
- [75] S. Y. Au, T. F. Bruce, W. C. Bridges, and S. J. Klaine, "Responses of *hyalella azteca* to acute and chronic microplastic exposures," *Environmental Toxicology and Chemistry*, vol. 34, no. 11, pp. 2564–2572, 2015.
- [76] J. A. Ivar do Sul and M. F. Costa, "The present and future of microplastic pollution in the marine environment," *Environmental Pollution*, vol. 185, pp. 352–364, 2014.
- [77] M. Cole, P. Lindeque, E. Fileman et al., "Microplastic ingestion by zooplankton," *Environmental Science and Technology*, vol. 47, no. 12, pp. 6646–6655, 2013.
- [78] M. Correia and K. Loeschner, "Detection of nanoplastics in food by asymmetric flow field-flow fractionation coupled to multi-angle light scattering: possibilities, challenges and analytical limitations," *Analytical and Bioanalytical Chemistry*, vol. 410, no. 22, pp. 5603–5615, 2018.
- [79] M. Kooi, E. H. V. Nes, M. Scheffer, and A. A. Koelmans, "Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics," *Environmental Science and Technology*, vol. 51, no. 14, pp. 7963–7971, 2017.
- [80] M. S. Savoca, M. E. Wohlfeil, S. E. Ebeler, and G. A. Nevitt, "Marine plastic debris emits a keystone infochemical for olfactory foraging seabirds," *Science Advances*, vol. 2, no. 11, Article ID e1600395, 2016.
- [81] S. E. Nelms, E. M. Duncan, A. C. Broderick et al., "Plastic and marine turtles: a review and call for research," *ICES Journal of Marine Science: Journal du Conseil*, vol. 73, no. 2, pp. 165–181, 2016.
- [82] R. Vroom, C. Halsband, E. Besseling, and A. A. Koelmans, "Effects of microplastics on zooplankton: microplastic ingestion: the role of taste," in *ICES/PICES 6th Zooplankton Production Symposium: New Challenges in a Changing Ocean*, Staff Publications, Washington, DC, USA, 2016.
- [83] J. T. Turner, "Zooplankton fecal pellets, marine snow, phytodetritus and the ocean's biological pump," *Progress in Oceanography*, vol. 130, pp. 205–248, 2015.
- [84] S. L. C. Giering, R. Sanders, R. S. Lampitt et al., "Reconciliation of the carbon budget in the ocean's twilight zone," *Nature*, vol. 507, no. 7493, pp. 480–483, 2014.
- [85] M. Cole, P. K. Lindeque, E. Fileman et al., "Microplastics alter the properties and sinking rates of zooplankton faecal pellets," *Environmental Science and Technology*, vol. 50, no. 6, pp. 3239–3246, 2016.
- [86] P. Bhattacharya, S. Lin, J. P. Turner, and P. C. Ke, "Physical adsorption of charged plastic nanoparticles affects algal photosynthesis," *Journal of Physical Chemistry C*, vol. 114, no. 39, pp. 16556–16561, 2010.
- [87] S. B. Sjollema, P. Redondo-Hasselerharm, H. A. Leslie, M. H. Kraak, and A. D. Vethaak, "Do plastic particles affect microalgal photosynthesis and growth?" *Aquatic Toxicology*, vol. 170, pp. 259–261, 2016.
- [88] E. Besseling, A. Wegner, E. M. Foekema, M. J. Van Den Heuvel-Greve, and A. A. Koelmans, "Effects of microplastic on fitness and PCB bioaccumulation by the lugworm *arenicola marina* (L.)," *Environmental Science and Technology*, vol. 47, no. 1, pp. 593–600, 2013.
- [89] K. Mattsson, E. V. Johnson, A. Malmendal, S. Linse, L. A. Hansson, and T. Cedervall, "Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain," *Scientific Reports*, vol. 7, no. 1, pp. 11452–11457, 2017.
- [90] P. Farrell and K. Nelson, "Trophic level transfer of microplastic: *Mytilus edulis* (L.) to *Carcinus maenas* (L.)," *Environmental Pollution*, vol. 177, pp. 1–3, 2013.
- [91] R. Mizraji, C. Ahrendt, D. Perez-Venegas et al., "Is the feeding type related with the content of microplastics in intertidal fish gut?" *Marine Pollution Bulletin*, vol. 116, no. 1–2, pp. 498–500, 2017.
- [92] A. Lusher, "Microplastics in the marine environment: distribution, interactions and effects," in *Marine Anthropogenic Litter*, pp. 245–307, Springer, Berlin, Germany, 2015.

- [93] S. Usman, A. F. Abdull Razis, K. Shaari et al., "Microplastics pollution as an invisible potential threat to food safety and security, policy challenges and the way forward," *International Journal of Environmental Research and Public Health*, vol. 17, no. 24, p. 9591, 2020.
- [94] H. A. Leslie, M. J. Van Velzen, S. H. Brandsma, D. Vethaak, J. J. Garcia-Vallejo, and M. H. Lamoree, "Discovery and quantification of plastic particle pollution in human blood," *Environment International*, vol. 163, Article ID 107199, 2022.
- [95] L. F. Amato-Lourenço, R. Carvalho-Oliveira, G. R. Júnior, L. dos Santos Galvão, R. A. Ando, and T. Mauad, "Presence of airborne microplastics in human lung tissue," *Journal of Hazardous Materials*, vol. 416, Article ID 126124, 2021.
- [96] Y. Cho, W. J. Shim, M. Jang, G. M. Han, and S. H. Hong, "Abundance and characteristics of microplastics in market bivalves from South Korea," *Environmental Pollution*, vol. 245, pp. 1107–1116, 2019.
- [97] B. Nan, L. Su, C. Kellar, N. J. Craig, M. J. Keough, and V. Pettigrove, "Identification of microplastics in surface water and Australian freshwater shrimp *Paratya australiensis* in Victoria, Australia," *Environmental Pollution*, vol. 259, Article ID 113865, 2020.
- [98] D. B. Daniel, P. M. Ashraf, S. N. Thomas, and K. T. Thomson, "Microplastics in the edible tissues of shellfishes sold for human consumption," *Chemosphere*, vol. 264, Article ID 128554, 2021.
- [99] A. G. Garcia, D. C. Suárez, J. Li, and J. M. Rotchell, "A comparison of microplastic contamination in freshwater fish from natural and farmed sources," *Environmental Science and Pollution Research*, vol. 28, no. 12, pp. 14488–14497, 2021.
- [100] K. Senathirajah, S. Attwood, G. Bhagwat, M. Carbery, S. Wilson, and T. Palanisami, "Estimation of the mass of microplastics ingested—A pivotal first step towards human health risk assessment," *Journal of Hazardous Materials*, vol. 404, Article ID 124004, 2021.
- [101] P. Schwabl, S. Köppel, P. Königshofer et al., "Detection of various microplastics in human stool: a prospective case series," *Annals of Internal Medicine*, vol. 171, no. 7, pp. 453–457, 2019.
- [102] Y. Deng, Y. Zhang, B. Lemos, and H. Ren, "Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure," *Scientific Reports*, vol. 7, no. 1, pp. 46687–46710, 2017.
- [103] W. Wang, H. Gao, S. Jin, R. Li, and G. Na, "The ecotoxicological effects of microplastics on aquatic food web, from primary producer to human: a review," *Ecotoxicology and Environmental Safety*, vol. 173, pp. 110–117, 2019.
- [104] C. D. Dong, C. W. Chen, Y. C. Chen, H. H. Chen, J. S. Lee, and C. H. Lin, "Polystyrene microplastic particles: *in vitro* pulmonary toxicity assessment," *Journal of Hazardous Materials*, vol. 385, Article ID 121575, 2020.