JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(2), 140–157
https://doi.org/10.12911/22998993/176802
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.10.07
Accepted: 2023.12.11
Published: 2024.01.01

A Review of Microplastic Pollution: Harmful Effect on Environment and Animals, Remediation Strategies

Hamza Jasim Albazoni[1,2*], Mohammed Jawad Salih Al-Haidarey[1], Afyaa Sabah Nasir[1]

[1] Ecology and Pollution Department, Faculty of Science, University of Kufa, Kufa, Iraq
[2] Ministry of Environment, Baghdad, Iraq
* Corresponding author's e-mail: hamza5279755@gmail.com

ABSTRACT

Microplastics are so widely dispersed and abundant throughout the globe that many scientists consider them to be important markers of the recent and current time, which is known as the Plasticene. The effects of microplastics are still not fully known, though. Because microplastics are multiple stressors with a variety of physical-chemical characteristics, understanding their impact is quite complicated. Toxic chemicals are transported by microplastics in ecosystems, acting as vectors of transport. Also, many dangerous chemicals are added during polymer production to enhance their properties as well as lengthen their life, and these chemicals must have detrimental effect. To date, many significant studies have been conducted, making a good progress to understand the effect of the key plastic additives on the environment. These additives are discharged into the environment and, hence become a source of many health issues, especially, when are coupled with micro-plastics. The current study thoroughly reviewed the most toxic and dangerous chemicals used in the plastic industry, elaborating the effects on organism health. Also, it provided information about the works that explored their abundance on microplastics.

Keywords: plastic pollution, microplastic, nanoplastic, human health.

INTRODUCTION

In general, "plastic" as a term refers to polymeric materials that are made from whether synthetic or natural materials and have high molecular weights. Industrially, plastics have been turned into many useful products since the 1950s. This is mainly due to their unique characteristics: affordability, high strength-to-weigh ratio, versatility and durability. Statistically, more than six billion tons of plastic products have been manufactured over the last sixty years. Of this quantity, about nine percent was recycled and re-used as secondary raw material, while about twelve percent was recycled using incineration technique (Alabi et al., 2019). One of the issues of plastic materials is the slow process of decomposition. For instance, 1 mm piece of plastic can take many years (perhaps hundreds) to break down into smaller parts. The decomposed plastic pieces that have size less than 5 mm are known as "microplastic"s or "MPs" (Chamas et al., 2020). In some studies, the term "nanoplastic" or "NPs" is used to describe tiny particles of plastic, especially the particles with size 100 nm and less. There are many methods to classify MP. One of the best methods is classifying plastics based on their origin. Accordingly, the micro-plastics can be classified into: primary and secondary MP. The primary is intentionally manufactured as microparticles for the consumers such as abrasive blasting agents, carriers for drug delivery, fertilizers, and plastic coating. The latter (i.e., Secondary MP) is a by-product of decomposition process of polymeric waste (Yee et al., 2021; Hirt and Body-Malapel, 2020).

Because MPs are small in size, they can be carried easily by air and water currents. Accordingly, MPs can be found everywhere (in rivers, lakes, in air we breathe, deep oceans and even in human bodies) (Fackelmann and Sommer, 2019). The MPs have a detrimental effect on living organisms. The effect of MPs, of course, depends on the type of the polymers that are made of and hence the physical and chemical properties of that polymer. Chemically, particles of thermoplastic polymers such polypropylene, polystyrene and polyethylene are well-known as dangerous MPs. Also, the additives used in the manufacturing of these polymers to improve certain properties are also harmful. These additives include fire retardants, colorants, UV stabilizers, plasticizers, antioxidants, molding agents. In terms of physical properties (i.e., shape, size, shear strength), MPs could be a highly poisonous agent. The large surface area per unit volume of tiny MPs makes them an excellent adsorbent media of pollutants and also the harmful micro-objects and hence they act as a poisonous agent once they enter the cells of living organisms, causing many health problems (Campanale et al., 2020; Wright et al., 2020).

ENVIRONMENTAL IMPACT OF MPS

Globally, about three – quarters of wastes found on Earth are plastic wastes and about ten percent of them are in the seas and oceans, Such huge quantity of wastes, as discussed, need hundreds of years to decompose into small parts (Gorbi and Regoli, 2017; Erni-Cassola et al., 2019). While it is difficult to quantify the marine load of plastic, a preliminary estimate indicates that at least five trillion plastic particles could be found in seas and oceans, making about 270 thousand tons (Eriksen et al., 2014). For instance, large quantities of plastic waste can be found in the center of north Pacific Ocean. Sometimes, it is named as "Pacific trash vortex". In some references, it is called "The Great Pacific Garbage Patch". According to Lebreton et al. (2018), this area is estimated to extend over of 1.6 million km^2 surface area. In terms of mass, the area includes not less than 80000 tons of plastics (i.e., about eight percent of the micro-plastics). To date, the accumulated plastic wastes have been determined in five important oceans. These are north and south of both Pacific and South Atlantic oceans and the South Indian Ocean) (Avio Gorbi and Regoli, 2017). Polyethylene is one of the most plastic wastes observed in the marine areas, forming about 23% of the plastics wastes. The co-polymer of polyesters-polyamides-acrylics is also observed accumulated in the marine areas, contributing to about 20%. Then, polypropylene and polystyrene are also prevalent forms of plastics of about 13 and 4%, respectively. Erni-Cassola et al. (2019) reported that plastic particle concentration is around 10^3–10^4 particles per each cubic meter in the tidal sediments, whereas it is about 0.1–1 particles per each cubic meter found close to water surfaces (mostly polyethylene). Further, in the deep-sea sediments, the concentration could be more than 10^5 particles/m^3 (mostly the other types of plastics, i.e., polyesters-polyamides-acrylics copolymer, polypropylene and polyester).

Effect of MPs on water

The main route that helps in transferring plastic wastes from the end users to far seas and oceans are rivers. They are responsible for transferring, about 1 to 2.5 million tons of plastic waste per year from the land to the deep-seas and oceans. Micro-plastic concentration range is shown in Table 1. As it can be seen, the highest concentration can be found in in Asian water bodies and then in North and South America and European rivers. This may be due to lack of regulations in Asia in relation to North and South America and European. Most the micro-plastic found in the area listed in Table 1 are as films, fibers and even shreds and foam of plastics (Sarijan et al., 2021). Although many efforts have been made in reducing MPs in tap water, plastic particles can be observed there. According to Kosuth, Mason and Wattenberg, (2018), samples were taken randomly from 159 sources (tap) around the world and the results showed that about 81% of them contain MPs with an average concentration of about 5.5 particles per each liter.

Moreover, MPs are not only in aquatic areas but also can be found in large quantities in soils. This includes greenhouses, gardens, large agricultural areas, floodplain, industrial areas and coastal (Hirt and Body-Malapel, 2020). In agricultural

Table 1. Range of microplastic concentration worldwide (Sarijan et al., 2021)

Location	MPs concentration (particles/m^3)
North and South America	0.16 to 3,438
European rivers	0.28 to 1,265
Asian water bodies	293 to 19,860

lands, MPs can come and accumulate as a result of precipitation or using polymeric fertilizers, irrigation runoff, mulch and pesticides (Kumar et al., 2020). Floodplain areas in Sweden, for example, can contain about 600 particles for each kilogram of soil (Scheurer and Bigalke, 2018). The plastics found in soils are usually not different than those observed in seas and oceans, such as polyethylene, polypropylene, polystyrene and polyvinyl chloride (Kumar et al., 2020).

It is also obvious that MPs particles are available in the atmosphere. Dris et al. (2016) reported that the daily average rates of MPs precipitation in urban and suburban Paris are 110 and 53 particles/m^2, respectively, while according to Cai et al. (2017) in Dongguan (China) and central London are 36 and 771 particles/m^2/day, respectively. To be more specific, the MPs in air mainly consist of acrylic fibers (5–75 µm thick and 250–2,500 µm long). Such MPs originally come from textiles. Non-fibrous particles of PE, PP, and PS with 50–350 µm in size can also be found in air. The source of most non-fibrous particles is the paint, industrial fumes, degradable packaging materials, as well as worn tires (Wright et al., 2020).

Sources of microplastic in drinking water

Microplastic contamination in drinking water has become a growing concern worldwide. These tiny plastic particles, measuring less than 5 millimeters in size, can originate from various sources and find their way into water systems. Understanding the sources of microplastic in drinking water is crucial in developing effective strategies to mitigate its presence and protect human health. In this section, the primary sources of microplastic contamination in drinking water were explored (Koelmans et al., 2019).

One significant source of microplastic in drinking water is urban runoff and stormwater. When it rains, water flows over roads, sidewalks, and other surfaces, picking up debris and pollutants along the way (Muller et al., 2020). This runoff carries microplastic particles from plastic litter, such as bottles, bags, and packaging materials, into storm drains and eventually into rivers, lakes, as well as reservoirs that serve as sources of drinking water. The fragmentation of larger plastic items due to weathering and mechanical forces further contributes to the release of microplastic particles into the water (Li et al., 2020).

Wastewater treatment plants play a crucial role in removing contaminants from domestic and industrial wastewater before it is discharged into the environment or reused. However, these treatment plants are not designed to effectively remove microplastic particles (Rout et al., 2020). As a result, the microplastics present in wastewater can pass through the treatment process and enter rivers, lakes, and groundwater sources that serve as drinking water supplies. The primary sources of

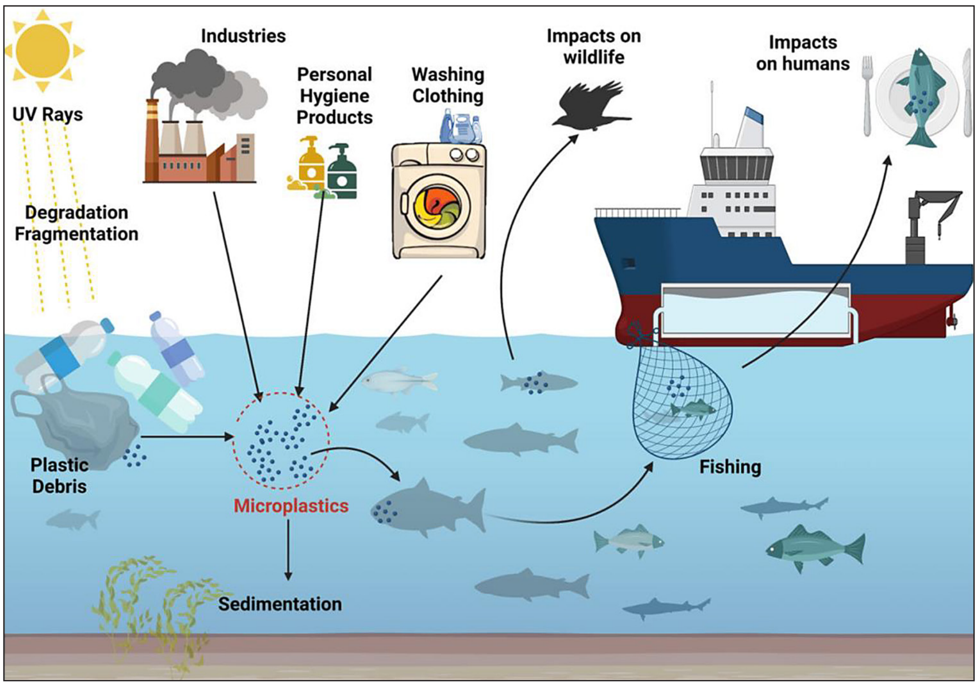

Figure 1. Effect of microplastic on water (Ziani et al., 2023)

microplastic in wastewater include personal care products, such as microbeads in exfoliating scrubs and toothpaste, as well as synthetic fibers shed from clothing during washing (Barchiesi et al., 2021).

Plastic items, such as bottles, bags, and packaging materials, can break down over time due to the exposure to sunlight, heat, and mechanical forces. This process, known as fragmentation, leads to the release of microplastic particles into the environment. These particles can then find their way into water bodies through various pathways, including wind transport, surface runoff, and direct deposition. Additionally, plastic degradation can occur in marine environments, where larger plastic debris is exposed to saltwater and wave action, resulting in the formation of microplastics that can be transported to freshwater sources (Zhang et al., 2021).

The impact of microplastic on land ecosystems

Microplastics can accumulate in soil through different mechanisms. One of the primary sources of microplastics in soil is the application of plastic-based mulches and films in agriculture. These materials, commonly used to control weeds and retain moisture, can degrade over time, releasing microplastic particles into the soil. Additionally, the breakdown of larger plastic debris, such as bottles and bags, can also contribute to microplastic contamination in soil. These plastic fragments can be transported by wind or water and eventually settle in terrestrial environments (Lwanga et al., 2022).

Once microplastics enter the soil environment, they can follow various pathways of accumulation. One pathway is through the application of microplastic-containing products, where the particles are directly introduced into the soil matrix. Another pathway is through the deposition of microplastics from the atmosphere, where they can be carried by wind or rainfall and settle onto the soil surface. Microplastics can also accumulate in soil through the decomposition of larger plastic items, as the particles break down and become incorporated into the soil (Piehl et al., 2018).

The transport of microplastics within soil is influenced by several factors. Soil texture plays a significant role, as microplastics tend to accumulate more in soils with higher clay and silt content, which have smaller pore sizes and greater potential for particle retention (Guo et al., 2022). The presence of organic matter in soil can also affect microplastic transport, as organic matter can bind to microplastics and facilitate their movement through the soil profile. Additionally, the presence of earthworms and other soil-dwelling organisms can contribute to the transport of microplastics, as they create burrows and channels that allow for particle movement (Xu et al., 2020)

Microplastics can alter the physical properties of soil, affecting its structure, porosity, and water-holding capacity. The presence of microplastics can lead to increased soil compaction, reducing the infiltration of water and air into the soil. This can result in poor root growth and decreased nutrient availability for plants. Additionally, microplastics can contribute to the formation of soil aggregates, which can further impact soil structure and stability (Wang et al., 2023).

Microplastics can also influence nutrient cycling in soil ecosystems. These particles can adsorb and accumulate nutrients, such as nitrogen and phosphorus, on their surfaces. This can lead to reduced nutrient availability for plants and microorganisms, affecting their growth and overall productivity. Furthermore, microplastics can alter the microbial communities in the soil, potentially disrupting important nutrient cycling processes, such as nitrogen fixation and organic matter decomposition (Kumar et al., 2023).

A fundamental step in managing microplastic pollution in land ecosystems is to establish comprehensive monitoring and assessment programs. These programs should aim to identify the sources, distribution, and abundance of microplastics in different land environments. By understanding the extent of contamination, policymakers and researchers can develop targeted strategies to mitigate the problem effectively. Monitoring programs can involve regular sampling and analysis of soil, sediment, and vegetation to track the presence and concentration of microplastics over time (Kershaw et al., 2019).

One of the primary sources of microplastics in land ecosystems is the improper disposal of plastic waste. To mitigate this issue, it is essential to improve the waste management practices and promote recycling. Governments and local authorities should implement strict regulations and policies to encourage proper waste disposal and recycling. This can include initiatives such as promoting the use of biodegradable or compostable materials, implementing extended producer responsibility programs, and establishing recycling facilities for plastic waste. By reducing the amount of plastic waste entering land ecosystems, the potential for

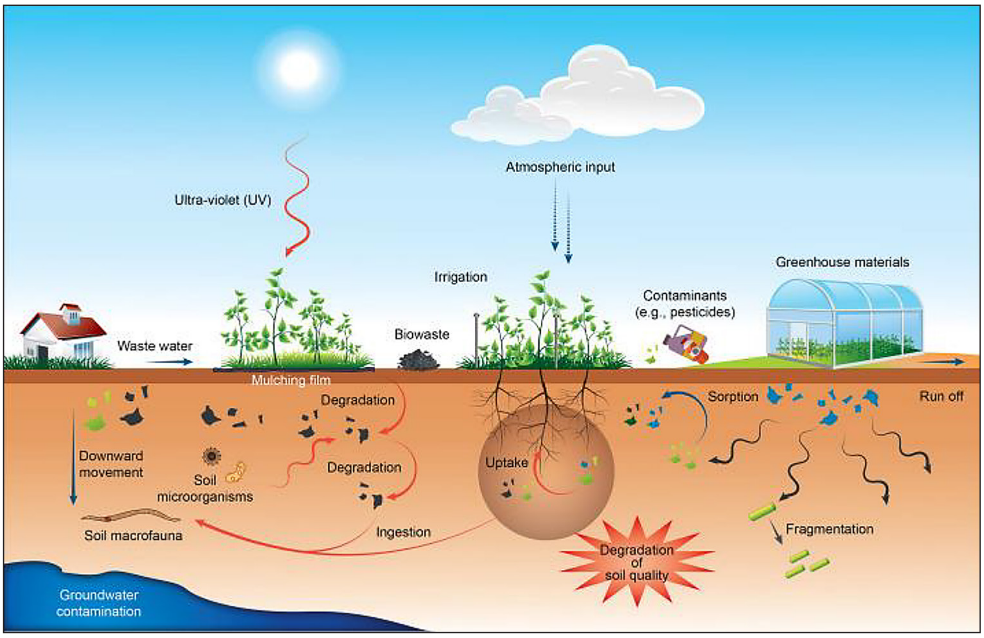

Figure 2. Effects of microplastics on the terrestrial environment (Dissanayake et al., 2022)

microplastic pollution can be significantly reduced (Kumar et al., 2021). Raising public awareness about the impacts of microplastics on land ecosystems is crucial for promoting behavioral changes and responsible consumption. Educational campaigns can be conducted to inform individuals about the sources and consequences of microplastic pollution. This can include educational programs in schools, community workshops, and public awareness campaigns through various media channels. By empowering individuals with knowledge, they can make informed choices and adopt sustainable practices that minimize the release of microplastics into the environment (Garcia-Vazquez and Garcia-Ael, 2021).

SOURCE OF MPS IN LIVING ORGANISMS

It is not surprising to find MPs in animals. This is due to using the plastics extensively and that leads, in turn, to a series pollution in all habitats by MPs and hence the animals. There are two sources for MPs to go inside animals anatomy: direct (from the media) or indirect (from prey, spread through the food chain) (Smith et al., 2018). It seems that MPs accumulate in the animal types that work as biofilters such as zooplankton sea squirts, and molluscs. For example, the MPs concentration in mussels and oysters (Pacific giant) are about 37 and 48 particles per 100 g of soft tissue of these creatures, respectively. Further, a mid-size fish can hold about 40 particles in their intestinal tract (Van Cauwenberghe and Janssen, 2014; Kwon et al., 2020).

MPs can also be found inside the animals organs that live on land (terrestrial food chain). Many studies detected MPs in chicken stomach (5.1 particles/g) and manure (105 particles/g) (Huerta Lwanga et al., 2017) and sheep manure (1,000 particles/g) (Beriot et al., 2021). It should be expected that human can also be exposed to different levels of MPs concentration. This can occur during having food and water, and also inhaling MPs through spreading in the air. Further, MPs are observed in many types of essential food, as shown in Table 2 (Cox et al., 2019; Yee et al., 2021).

A study done by Danopoulos et al. (2020) showed that high concentrations of MPs can be found in Seafood. The results were up to 27,825, 17,716 and 8,323 MPs particles in shellfish, crustaceans, and fish, respectively, per year. Thus, the total amount of MPs in seafood can reach 53,864 MPs per person each year. Another study conducted by Kwon et al. (2020) shows that half the polymer type found in food as plastics are polyethylene, polypropylene, polyethylene terephthalate (PET), as well as polystyrene. The form of MPs are usually filaments and fibres. It is believed that fibers have more detrimental effect than than spherical particles, even at lower doses (Kwon et al., 2020). Additionally, according to Cox et al.

Table 2. Microplastic concentration in different essential food (Sarijan et al., 2021)

Food types	MPs concentration
Sugar	0.44 particles/g
Salt	0.11 particles/g
Alcohol	33 particles/L
Water bottle	95 particles/L
Hoeny	0.10 particles/g

(2019), the average human consumption of food and beverages corresponds to 39,000 to 52,000 MPs particles per year. Adding the respirable plastic particles in the air, about 74,000–121,000 MPs per year can enter a person (Yee et al., 2021). It is important to note here, however, that these statistics are rough and may need further investigation. Further, human feces can contain 20 MPs per 50-500 mm (Schwabl et al., 2019), while human placenta contains single MPs (Ragusa et al., 2021).

EFFECTS OF MICROPLASTIC ON ANIMALS

Invertebrates

The effect of MPs on many aquatic species has been discussed in detail. Haegerbaeumer et al. (2019) reviewed critically the effects of MPs on freshwater invertebrates and benthic marine. This comprises sea urchins, annelids, arthropods, rotifers and bivalves. In general, about twenty-eight studies explore the effect of MPs on mortality. While these studies are useful, only three of them reported pronounced changes. The main outcomes of Haegerbaeumer et al. (2019) reviews are summarized in Table 3.

The effect of MPs on invertebrates may cause many compilations such decreased foraging activity and fertility. Further, MPs slow larval growth and development and can increase the consumption of O_2 and production of reactive forms. Despite a wide range of parameters is considered in the studies (i.e., different types, sizes, and concentrations of MPs and using different animal strains), a comparative study showing clearly the effects of MPs is of lesser interest.

Mammals

Mammals can also be exposed to microplastics through trophic transfer, where microplastics move up the food chain. This occurs when microplastics are ingested by prey organisms and subsequently consumed by predators. For example, a predator mammal that feeds on the fish contaminated with microplastics, can be indirectly exposed to these particles (Egbeocha et al*.,* 2018). Trophic transfer of microplastics can result in the bioaccumulation of these particles in mammalian tissues. As predators consume multiple prey items over time, the concentration of microplastics can increase, posing a greater risk to their health. This route of exposure highlights the interconnectedness of ecosystems and the potential for microplastic pollution to impact multiple trophic levels (Alava, 2020).

In conclusion, mammals can be exposed to microplastics through various routes, including ingestion, inhalation, dermal contact, transplacental transfer, and trophic transfer. Each exposure route presents unique risks and potential impacts on mammalian health. Understanding these exposure routes is crucial for developing effective mitigation strategies and protecting the well-being of mammals in ecosystems (Rahman et al., 2020). Mammals can be exposed to microplastics through various routes, including ingestion, inhalation, and dermal contact. Ingestion is considered the primary route of exposure for many mammalian species (Meaza et al., 2021). Microplastics

Table 3. Outcomes of the recent studies reviewed by Haegerbaeumer et al. (2019)

Creatures name	MPs type and size	MPs concentration
Perinereis aibuhitensis (Polychaetas)	Polystyrene (8–12 mm)	100–1,000 MPs/mL
T*igriopus japonicas* (Copepods)	Polystyrene (0.05 mm)	1.25 mg/L
Shrimps Palaemonetes pugio	Polyethylene, polystyrene and polypropylene (30–165 mm)	50,000 MPs/L

can be mistaken for food items, leading to their ingestion by mammals. For example, filter-feeding mammals, such as whales and dolphins, may inadvertently consume microplastics while feeding on plankton or small fish (Ryan, 2019).

Once ingested, microplastics can accumulate in the gastrointestinal tract of mammals, leading to potential health issues. The accumulation of microplastics can cause physical blockages, leading to reduced nutrient absorption and digestive problems. Additionally, the presence of microplastics in the gut can disrupt the gut microbiota, which plays a crucial role in maintaining overall health and immune function in mammals (Deng et al., 2020).

Microplastics can also pose a chemical toxicity risk to mammals. Many plastic polymers contain additives such as plasticizers, flame retardants, and dyes, which can leach out into the surrounding environment (Campanale et al., 2020). When ingested by mammals, these chemicals can be absorbed into their tissues and organs, potentially causing adverse health effects (Pandey and Madhuri, 2014). Some of these chemicals have been linked to endocrine disruption, reproductive abnormalities, and developmental issues in mammals. For example, certain plasticizers, such as phthalates, have been found to interfere with hormone signaling pathways in mammals, leading to reproductive disorders and impaired fertility. The accumulation of these chemicals in mammalian tissues over time can have long-term consequences for individual health and population dynamics (Mathieu-Denoncourt et al., 2015).

Microplastic exposure can also have physiological and immunological effects on mammals. Studies have shown that microplastics can induce oxidative stress and inflammation in mammalian tissues, leading to cellular damage and impaired organ function. This can compromise the overall health and well-being of affected individuals (Yong et al., 2020).

Furthermore, microplastics can trigger immune responses in mammals, leading to chronic inflammation and immune system dysregulation. This can make mammals more susceptible to infections and diseases, ultimately impacting their survival and reproductive success. The immune system plays a vital role in maintaining the health and resilience of mammalian populations, and any disruption caused by microplastic exposure can have cascading effects throughout the ecosystem (Hirt and Body-Malapel, 2020).

Fish

Many studies have been done about the impact of MPs on fishes. The results showed that MPs are present in about half the studied fishes in the northeast Atlantic (Scomber colias, Trachurus trachurus and Dicentrachus labrax). Interestingly, it was found that about 35% of the tested samples containing MPs in their intestinal tract and about 36 and 32% in the back muscles and gills of the examined fishes, respectively. MPs are essentially composed of 151–1500 μm of fibers as well as 100–1500 μm of polyethylene and polyester chips. In terms of health complications, the fishes exposed to MPs suffer from increasing lipid peroxidation in the spinal muscles, gills, and brain. MPs also make acetylcholinesterase more active in the brain of the examined fishes (Barboza et al., 2019).

Recently, Yong, Valiyaveetill, and Tang (2020) carried out an analysis. They showed that a significant toxic or a pathological effect caused by the presence of MPs in fishes tissues. During the experiments, MPs were added with roe to fish tank at concentrations of 1 to 1,000 mg per liter (typically 20 mg per liter). The experiments showed that the detrimental reactions are generally caused by the particles that have diameter ≤ 5 μm, while larger (greater than 100 μm) ones had no series effects. In general, the exposure time to MPs is variable and ranged from hours to months (typically is 7 days). However, it is shown that the effective amount of MPs can change the feeding behavior in general and makes musculoskeletal system less effective at any age, and also can affect the breeding activity adversely. The development of fish offspring exposed to MPs has observed in many studies (Pitt et al., 2018a). There is evidence that exposure to MPs affects the development of fish in their early age (Wang et al., 2019). Also, as the dose of MP increases, they accumulate in tissues more and hence the histological and biochemical changes become worse (Lu et al., 2016; Wang et al., 2019; Pannetier et al., 2020). As a protocol, most studies done on the effect of MPs on fishes are made in zebrafish using usually polystyrene and sometimes polyethylene (but rare). It is found that the small particles of polystyrene (25–70 nm) can affect the deeper organs and tissues, such as yolk sac, caviar membrane and the intestinal tract. Even in the early developmental stage of fish (embryos), micro/nanoplastics are found in the liver, gut, pancreas, heart and brain. The transportation of micro/nanoplastics (polystyrene) from fish mother to embryos has been proven experimentally.

Further, the nanoparticles of plastic could also cause juvenile fish to move fast (hyperactivity) or slow their movement (weakness). Metabolically, the nanoparticles of plastic can rise cortisol levels and heart rate as well as lower blood sugar levels. Inflammatory response and hepatic lipolysis also can occur. Same complications can happen to adult fishes. The nanoparticles of plastic can inhibit acetylcholinesterase activity, affecting the synaptic transmission (Lu et al., 2016; Chen et al., 2017; Pitt et al., 2018a; Pitt et al., 2018b; Brun et al., 2019).

Although larger polystyrene particles (5 mm) may not easily penetrate into fish organs, they can be found in the liver, intestine and gills of both embryos and adult fishes. Such particles can lead to steatosis in hepatocytes and changes in the mentioned organs (i.e liver and intestine). Also, they can change the lipid metabolism and the expression of genes that are responsible for antioxidant protection associated with oxidative stress (Lu et al., 2016; Qiao et al., 2019; Wan et al., 2019).

Birds

When birds mistakenly consume micro-plastics, these tiny particles can have detrimental effects on their physiology (Chatterjee and Sharma, 2019). One of the primary concerns is the physical obstruction caused by the accumulation of microplastics in the digestive system. These particles can block the passage of food, leading to reduced nutrient absorption and weight loss. In severe cases, the blockage can result in starvation and even death (Ziani et al., 2023). Furthermore, the chemical composition of microplastics poses additional risks to avian health. Many plastics contain additives such as plasticizers, flame retardants, and dyes, which can leach into the birds' digestive system. These chemicals may disrupt hormonal balance, impair reproductive functions, as well as weaken the immune system, making birds more susceptible to diseases and infections (Huang et al., 2021).

Studies have also shown that microplastics can cause inflammation and damage to the gastrointestinal tract of birds. The abrasive nature of these particles can lead to ulceration and tissue necrosis, further compromising the birds' overall health and well-being. Additionally, the accumulation of microplastics in the liver and other organs can impair their normal functioning, potentially leading to organ failure (de Souza et al., 2022). Microplastic ingestion can also have profound behavioral impacts on birds. Research has indicated that the birds exposed to microplastics may exhibit altered feeding behaviors. The presence of microplastics in their environment can lead to reduced foraging efficiency, as birds mistakenly consume these particles instead of their natural prey. This can result in decreased energy intake and nutritional deficiencies, affecting their growth, reproduction, and overall fitness (Courtene-Jones et al., 2022).

Furthermore, the ingestion of microplastics can disrupt the birds' feeding hierarchy and social interactions. In some cases, birds may compete for the food contaminated with microplastics, leading to increased aggression and territorial disputes. This disruption in social dynamics can have cascading effects on population dynamics and ecosystem stability (Critchell and Hoogenboom, 2018). Another behavioral impact of microplastic ingestion is the potential for altered migration patterns. Birds rely on precise navigation and orientation during their long-distance migrations. However, the presence of microplastics in their system may interfere with their ability to navigate accurately, leading to disorientation and the inability to reach their intended destinations. This disruption in migration patterns can have severe consequences for population dynamics and the overall functioning of ecosystems (Sau and Shiuly, 2023).

EFFECTS OF MICROPLASTIC ON MICROORGANISMS

Microplastics can interact with microbial communities in various ways. Firstly, microorganisms can colonize the surface of microplastics, forming biofilms. These biofilms consist of a complex matrix of microorganisms embedded in a slimy substance, known as extracellular polymeric substances (EPS). Biofilm formation on microplastics can alter their physical and chemical properties, potentially affecting their fate and transport in the environment (Stabnikova et al., 2021). Furthermore, microplastics can serve as a substrate for microbial growth and activity. The presence of microplastics can provide a surface for microbial attachment and biofilm formation, creating microhabitats for microbial communities. This colonization of microplastics by microorganisms can lead to the degradation of the plastic through enzymatic activity, potentially influencing the persistence and breakdown of microplastics in the environment (Ukil et al., 2022). The presence of microplastics can have significant effects on microbial diversity and function. Studies have shown that microplastics can alter the composition and structure of microbial communities. The colonization of microplastics by specific microbial taxa can lead to shifts in community composition, potentially favoring certain microbial species over others. These changes in microbial diversity can have cascading effects on ecosystem functioning and nutrient cycling (Li et al., 2020).

Microplastics can also influence microbial activity and function. Some studies have suggested that microplastics can stimulate microbial growth and activity, potentially leading to increased nutrient cycling rates. However, other studies have shown that microplastics can have negative effects on microbial function, such as reducing microbial respiration rates and impairing enzymatic activity. These conflicting findings highlight the complexity of microplastic-microbe interactions and the need for further research to fully understand their implications (Lin et al., 2020). The disruption of microbial communities and functions by microplastics can have significant implications for biogeochemical cycles. Microbes play a vital role in the cycling of carbon, nitrogen, and other essential elements in ecosystems. Changes in microbial diversity and function can disrupt these cycles, leading to imbalances and potential long-term consequences (Wang et al., 2020). For example, the breakdown of organic matter by microorganisms releases carbon dioxide (CO_2) into the atmosphere. However, when microplastics inhibit microbial activity, the decomposition process slows down, resulting in the accumulation of organic matter and reduced CO_2 release. This can contribute to carbon sequestration and potentially impact global climate patterns (Raza et al., 2023).

Similarly, microplastics can affect the cycling of nitrogen, a critical nutrient for plant growth. Microbes are responsible for converting nitrogen in the environment into the forms that plants can utilize. However, the disruption of microbial communities and functions by microplastics can impair this process, leading to reduced nitrogen availability for plants and potential nutrient limitations in ecosystems (Zhang et al., 2023).

EFFECTS OF MICROPLASTIC ON HUMAN HEALTH

All research done by World Health Organization (WHO) confirmed that microplastics are present in the atmosphere and water. WHO also warned in many reports that MPs have a detrimental effect on human health when they are present at a certain level (Lehner et al., 2019; Revel and Mouneyrac, 2018; Rist et al., 2018; Bradney et al., 2019).

The food contaminated by polymeric waste is considered one of the main sources of MPs. MPs can enter into human body through skin (by absorption) or mouth (by ingestion) (Waring et al., 2018; Toussaint et al., 2019). According to Table 2, MPs can be found in human essential food. Fruits and vegetables are also a source of human MPs. A person can have about eighty grams of MPs per day from plants only. Transferring MPs to plants usually occurs through a diffusion process from contaminated soil (Ebere et al., 2019). Another source of MPs is eating seafood (e.g., fish and crustaceans) and animals. This is reported in many papers (Smith et al., 2018).

The absorption process of MPs from food to human body is quite clear. It was proven that the polymeric particles can penetrate through body skin, reaching human internal organs (intestine, liver, bladder). Nano-size plastic particles are able to pass across cellular membranes. Further, such tiny particles can circulate through the blood steam reaching brain barrier and even placenta (Barboza et al., 2018). While dose amounts can be detected, the information on nano/microplastics in the ambient is still lacking. This is, perhaps, due to the difficulties in identifying, characterizing and quantifying such tiny particles.

After the plastics particles enter human body when having food, the tiny ones (i.e., those smaller than 2.5 μm) penetrate easily to the intestinal tract. This happens through endocytosis by Peyer's lymph node. Microfold cells helps the transport of MPs, leading them to the mucosa-associated lymphoid tissues from lumen. This can happen also through intercellular shunt pathway (i.e., between cells). Osmosis is the mechanical transport of solid particles into the circulatory system through the epithelial monolayer at the tip of the villi in the gastrointestinal tract (the desquamative zone). As the microplastics infiltrate into human body, an inflammation can be noticed as a result of toxicity

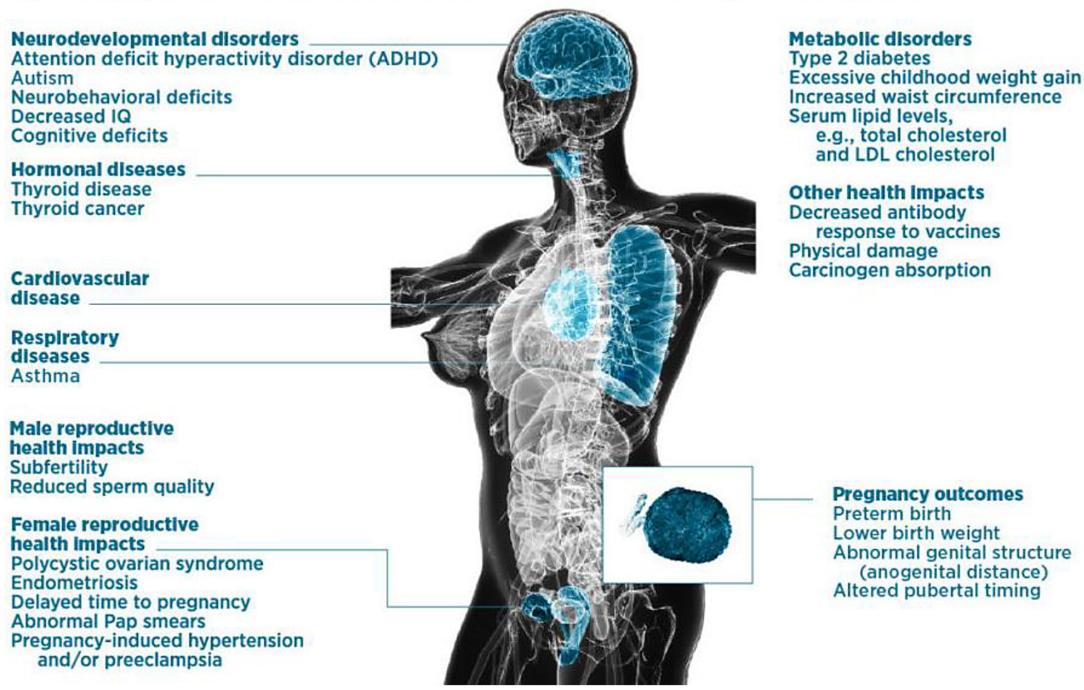

Figure 3. Effect of microplastic on human health

effect of MPs (Wright and Kelly, 2017). In addition to above, MPs are observed in human feces. Statistically, twenty plastic particles are appromitaly can be found in human feces. Two types of MPs are typically found in feces: polyethylene and polypropylene and PP with a wide range of size (from 50 to 500 mm) (Schwabl et al., 2019). In general, most of MPs (about 90%) can be removed through human excretory systems (Smith et al., 2018).

REMOVAL AND REMEDIATION TECHNIQUES FOR MICROPLASTIC

Physical removal methods

Microplastics have become a significant environmental concern due to their widespread presence in various ecosystems. To address this issue, several physical removal methods have been developed to help mitigate the impact of microplastics on the environment. These methods aim to remove microplastics from different sources, such as water bodies, soil, and even the atmosphere. In this section, some of the physical removal methods that have shown promise in tackling the microplastic pollution problem (Padervand et al., 2020) were explored.

Filtration systems

Filtration systems are commonly used to remove microplastics from water bodies. These systems work by passing water through a series of filters with different pore sizes, effectively trapping microplastic particles. The filters can be made of various materials, such as mesh screens, membranes, or even activated carbon. The choice of filter material depends on the size and type of microplastics being targeted (Cai et al., 2020). One example of a filtration system is the use of mesh screens in wastewater treatment plants. These screens are designed to capture larger microplastic particles, preventing them from entering rivers and oceans. Additionally, advanced filtration techniques, such as ultrafiltration and nanofiltration, can be employed to remove smaller microplastics that may pass through conventional filters (Ziajahromi et al., 2017).

Sedimentation and settling tanks

Sedimentation and settling tanks are commonly used in water treatment facilities to remove suspended particles, including microplastics. These tanks work on the principle of gravity, allowing the microplastic particles to settle at the bottom of the tank while the clean water is collected from the top (Bilgin et al., 2020). In these tanks, the water is allowed to flow slowly, giving enough time for the microplastics to settle. The settled microplastics can then be removed and properly disposed of, preventing them from re-entering the environment. Sedimentation and settling tanks are particularly effective in removing larger microplastics and can be used in combination with other physical removal methods for enhanced efficiency (Bilgin et al., 2020).

Skimming and surface collection

Skimming and surface collection methods are primarily used to remove microplastics from water bodies, such as rivers, lakes, and oceans. These methods involve the use of specialized equipment, such as skimmers or floating booms, to skim the surface of the water and collect floating microplastic particles (Nikiema et al., 2020). Skimmers are designed to create a thin layer of water flow, allowing the microplastics to be efficiently collected. The collected microplastics can then be separated from the water and properly disposed of. Surface collection methods are particularly effective in the areas with high concentrations of microplastics, such as near wastewater discharge points or coastal regions (Tang and Hadibarata, 2021).

Chemical remediation techniques

Chemical remediation techniques are an important aspect of addressing the issue of microplastics in the environment. These techniques involve the use of various chemicals to break down or remove microplastics from different sources, such as water bodies, soil, and even the atmosphere. In this section, some of the commonly used chemical remediation techniques and their effectiveness in tackling the problem of microplastics were explored (Bhatt et al., 2021).

Oxidation

Oxidation is a chemical process that involves the use of strong oxidizing agents to break down microplastics into smaller fragments or even completely degrade them. One commonly used oxidizing agent is hydrogen peroxide (H_2O_2). When applied to microplastics, hydrogen peroxide reacts with the polymer chains, causing them to break down. This process can be accelerated by the addition of catalysts, such as iron or titanium dioxide (Kim et al., 2022). Another effective oxidizing agent is ozone (O_3). Ozone treatment involves exposing microplastics to ozone gas, which reacts with the polymer chains, leading to their degradation. Ozone treatment has been found to be particularly effective in removing microplastics from water bodies, as it not only breaks down the plastic particles but also helps in removing any associated organic contaminants (Cai et al., 2023).

Photocatalysis

Photocatalysis is a chemical process that utilizes light energy and a catalyst to degrade microplastics. Titanium dioxide (TiO_2) is one of the most commonly used photocatalysts. When exposed to ultraviolet (UV) light, titanium dioxide generates reactive oxygen species (ROS) that can break down the polymer chains of microplastics. This process is known as photocatalytic degradation (Ge et al., 2022). Photocatalysis has shown promising results in the removal of microplastics from water bodies. It not only breaks down the plastic particles but also helps in the removal of organic contaminants. However, the efficiency of photocatalysis can be influenced by various factors, such as the concentration of the photocatalyst, the intensity of UV light, and the presence of other substances in the water (Xu et al., 2021).

Advanced oxidation processes

Advanced oxidation processes (AOPs) are a combination of various chemical processes that involve the generation of highly reactive species to degrade microplastics. One commonly used AOP is the Fenton process, which involves the use of hydrogen peroxide and iron catalysts. The Fenton process generates hydroxyl radicals (OH•), which are highly reactive and can break down the polymer chains of microplastics (Kim et al., 2022). Another AOP is the photo-Fenton process, which combines the Fenton process with UV light. The UV light activates the catalysts, leading to the generation of additional hydroxyl radicals. This process enhances the degradation efficiency of microplastics (Brillas, 2020). AOPs have shown promising results in the removal of microplastics from water bodies and wastewater treatment plants. However, the implementation of AOPs on a larger scale can be challenging due to the high cost of the required chemicals and the need for specialized equipment (Dos Santos et al., 2023).

Solvent extraction

Solvent extraction is a chemical remediation technique that involves the use of solvents to dissolve microplastics. This technique is particularly effective for removing microplastics from soil and sediment. Organic solvents, such as chloroform, acetone, and methanol, are commonly used for this purpose (Goli et al., 2022). The solvent extraction process involves mixing the contaminated soil or sediment with the solvent, which dissolves the microplastics. The mixture is then filtered to separate the dissolved microplastics from the soil or sediment. The solvent can be evaporated to recover the microplastics (Raguso et al., 2021). Solvent extraction is a relatively simple and cost-effective technique for removing microplastics from soil and sediment. However, it is important to ensure that the solvents used are properly handled and disposed of to prevent any environmental contamination (Sajid et al., 2018).

Biological remediation strategies

Biological remediation strategies offer promising solutions for the removal and degradation of microplastics in the environment. These strategies utilize the natural abilities of various organisms to break down and remove microplastics, providing a sustainable and eco-friendly approach to tackle this global issue. In this section, some of the most effective biological remediation strategies that have been developed and their potential applications were explored (Bhatt et al., 2021).

Microorganisms

Microorganisms, such as bacteria and fungi, play a crucial role in the degradation of organic matter in the environment. Recent research has shown that certain microorganisms have the ability to break down microplastics as well. These microorganisms produce enzymes, known as plastic-degrading enzymes, which can break down the chemical bonds of microplastics, leading to their degradation (Othman et al., 2021. One example of a microorganism with plastic-degrading capabilities is *Ideonella sakaiensis*. This bacterium was discovered in 2016 and has the ability to degrade polyethylene terephthalate (PET), a common type of plastic used in bottles and packaging. The enzymes produced by *Ideonella sakaiensis* can break down PET into its basic building blocks, which can then be utilized by the bacterium as a carbon source (Taniguchi et al., 2019).

Another group of microorganisms that have shown potential in microplastic degradation are marine bacteria. These bacteria have been found to colonize microplastic particles in marine environments and produce the enzymes that can degrade various types of plastics. By harnessing the power of these microorganisms, it may be possible to develop the biological remediation strategies that can effectively remove microplastics from marine ecosystems (Roager and Sonnenschein, 2019).

Enzymes

Enzymes are biological catalysts that can accelerate chemical reactions. In recent years, researchers have been exploring the use of enzymes for the degradation of microplastics. By identifying and isolating the enzymes that have the ability to break down specific types of plastics, it is possible to develop enzymatic treatments for the removal of microplastics (Othman et al., 2021). One enzyme that has shown promise in microplastic degradation is called PETase. PETase is an enzyme produced by *Ideonella sakaiensis* and is capable of breaking down PET into its constituent parts. Researchers have been studying the structure and function of PETase to better understand its mechanism of action and to potentially optimize its activity for industrial applications (Cui et al., 2021). In addition to PETase, other enzymes – such as esterases and lipases – have also been found to have plastic-degrading capabilities. These enzymes can break down the ester bonds present in many types of plastics, including polyethylene and polypropylene. By harnessing the power of these enzymes, it may be possible to develop enzymatic treatments that can effectively degrade a wide range of microplastics (Khairul Anuar et al., 2022).

Biodegradable polymers

Biodegradable polymers offer an alternative to conventional plastics that are designed to degrade more rapidly in the environment. These polymers are typically made from natural materials, such as starch or cellulose, and can be broken down by microorganisms through natural processes (Luckachan and Pillai, 2011) One example of a biodegradable polymer is polylactic acid (PLA).

PLA is derived from renewable resources, such as corn or sugarcane, and can be used as a substitute for conventional plastics in various applications. PLA has been shown to degrade more rapidly than traditional plastics, and when it does break down, it produces non-toxic byproducts (Taib et al., 2023). By promoting the use of biodegradable polymers and encouraging the development of new biodegradable materials, the accumulation of microplastics in the environment can be reduced. However, it is important to ensure that these biodegradable materials are properly managed and disposed of, to prevent them from becoming a source of pollution themselves (Qin et al., 2021).

Biofilms and biofouling

Biofilms are complex communities of microorganisms that adhere to surfaces and form a protective matrix. These biofilms can play a role in the degradation of microplastics by providing a suitable environment for microorganisms to colonize and break down the plastics (Percival et al., 2011). Biofouling, on the other hand, refers to the accumulation of microorganisms, algae, and other organic matter on the surface of microplastics. This process can enhance the degradation of microplastics by promoting the growth of the microorganisms that have plastic-degrading capabilities (Debroy et al., 2022). By understanding the mechanisms behind biofilm formation and biofouling, it may be possible to develop the strategies to enhance the degradation of microplastics in various environments. For example, the use of biofilm-forming microorganisms in wastewater treatment plants or the development of biofouling-resistant materials could help to improve the removal of microplastics from water sources (Rummel et al., 2017).

CONCLUSIONS

Huge quantities of plastic waste are generated each year, reaching millions of tons. Unfortunately, less than 25% of this quantity can be recycled and/or handed in a proper way. One of the challenges is that plastic waste could decompose, producing tiny particles that pollute the environment and spread easily with wind and water. Moreover, these tiny particles (microplastics) penetrate through living organism bodies, including humans, causing a serious health issues. The experimental studies reviewed here confirm the effect of these particles on fish, mice, invertebrates. Further, the studies suggest that MPs are a threat to human health as well. However, the magnitude of this threat is not fully known or even clear. There are some essential parameters that are uncertain and must be studied thoroughly, such as the adsorption capacity and degradation level of pathogens. Accordingly, one can infer that further works are definitely needed to better understand the impact of MPs on the environment.

REFERENCES

1. Alabi, O.A., Ologbonjaye, K.I., Awosolu, O., and Alalade, O.E. (2019). Public and environmental health effects of plastic wastes disposal: a review. J Toxicol Risk Assess, 5(021), 1-13.
2. Alava, J.J. (2020). Modeling the bioaccumulation and biomagnification potential of microplastics in a cetacean foodweb of the northeastern pacific: a prospective tool to assess the risk exposure to plastic particles. Frontiers in Marine Science, 7, 566101.
3. Avio, C.G., Gorbi, S., and Regoli, F. (2017). Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. Marine environmental research, 128, 2-11.
4. Barboza, L.G.A., Lopes, C., Oliveira, P., Bessa, F., Otero, V., Henriques, B., ... and Guilhermino, L. (2020). Microplastics in wild fish from North East Atlantic Ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. Science of the total environment, 717, 134625.
5. Barboza, L.G.A., Vethaak, A.D., Lavorante, B.R., Lundebye, A.K., and Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. Marine pollution bulletin, 133, 336-348.
6. Barchiesi, M., Chiavola, A., Di Marcantonio, C., and Boni, M.R. (2021). Presence and fate of microplastics in the water sources: focus on the role of wastewater and drinking water treatment plants. Journal of Water Process Engineering, 40, 101787.
7. Beriot, N., Peek, J., Zornoza, R., Geissen, V., and Lwanga, E.H. (2021). Low density-microplastics detected in sheep faeces and soil: A case study from the intensive vegetable farming in Southeast Spain. Science of the Total Environment, 755, 142653.
8. Bhatt, P., Pathak, V.M., Bagheri, A.R., and Bilal, M. (2021). Microplastic contaminants in the aqueous environment, fate, toxicity consequences, and remediation strategies. Environmental Research, 200, 111762.
9. Bilgin, M., Yurtsever, M., and Karadagli, F. (2020).

Microplastic removal by aerated grit chambers versus settling tanks of a municipal wastewater treatment plant. Journal of Water Process Engineering, 38, 101604.

10. Bradney, L., Wijesekara, H., Palansooriya, K.N., Obadamudalige, N., Bolan, N.S., Ok, Y.S., ... and Kirkham, M. B. (2019). Particulate plastics as a vector for toxic trace-element uptake by aquatic and terrestrial organisms and human health risk. Environment international, 131, 104937.
11. Brillas, E. (2020). A review on the photoelectro-Fenton process as efficient electrochemical advanced oxidation for wastewater remediation. Treatment with UV light, sunlight, and coupling with conventional and other photo-assisted advanced technologies. Chemosphere, 250, 126198.
12. Brun, N.R., Van Hage, P., Hunting, E.R., Haramis, A.P.G., Vink, S.C., Vijver, M.G., ... and Tudorache, C. (2019). Polystyrene nanoplastics disrupt glucose metabolism and cortisol levels with a possible link to behavioural changes in larval zebrafish. Communications Biology, 2(1), 382.
13. Cai, H., Chen, M., Chen, Q., Du, F., Liu, J., and Shi, H. (2020). Microplastic quantification affected by structure and pore size of filters. Chemosphere, 257, 127198.
14. Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., and Chen, Q. (2017). Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. Environmental Science and Pollution Research, 24, 24928-24935.
15. Cai, Y., Zhao, Y., Yadav, A.K., Ji, B., Kang, P., and Wei, T. (2023). Ozone based inactivation and disinfection in the pandemic time and beyond: Taking forward what has been learned and best practice. Science of The Total Environment, 862, 160711.
16. Campanale, C., Massarelli, C., Savino, I., Locaputo, V., and Uricchio, V.F. (2020). A detailed review study on potential effects of microplastics and additives of concern on human health. International journal of environmental research and public health, 17(4), 1212.
17. Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., ... and Suh, S. (2020). Degradation rates of plastics in the environment. ACS Sustainable Chemistry and Engineering, 8(9), 3494-3511.
18. Chatterjee, S., and Sharma, S. (2019). Microplastics in our oceans and marine health. Field Actions Science Reports. The Journal of Field Actions, (Special Issue 19), 54-61.
19. Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D., and Hollert, H. (2017). Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. Science of the total environment, 584, 1022-1031.
20. Courtene-Jones, W., Clark, N.J., Fischer, A.C., Smith, N.S., and Thompson, R.C. (2022). Ingestion of microplastics by marine animals. Plastics and the Ocean: Origin, Characterization, Fate, and Impacts, 349-366.
21. Cox, K.D., Covernton, G.A., Davies, H.L., Dower, J.F., Juanes, F., and Dudas, S.E. (2019). Human consumption of microplastics. Environmental science and technology, 53(12), 7068-7074.
22. Critchell, K., and Hoogenboom, M.O. (2018). Effects of microplastic exposure on the body condition and behaviour of planktivorous reef fish (Acanthochromis polyacanthus). PloS one, 13(3), e0193308.
23. Cui, Y., Chen, Y., Liu, X., Dong, S., Tian, Y.E., Qiao, Y., ... and Wu, B. (2021). Computational redesign of a PETase for plastic biodegradation under ambient condition by the GRAPE strategy. Acs Catalysis, 11(3), 1340-1350.
24. Danopoulos, E., Jenner, L.C., Twiddy, M., and Rotchell, J.M. (2020). Microplastic contamination of seafood intended for human consumption: a systematic review and meta-analysis. Environmental Health Perspectives, 128(12), 126002.
25. de Souza, S.S., Freitas, Í.N., de Oliveira Gonçalves, S., da Luz, T.M., da Costa Araújo, A.P., Rajagopal, R., ... and Malafaia, G. (2022). Toxicity induced via ingestion of naturally-aged polystyrene microplastics by a small-sized terrestrial bird and its potential role as vectors for the dispersion of these pollutants. Journal of Hazardous Materials, 434, 128814.
26. Debroy, A., George, N., and Mukherjee, G. (2022). Role of biofilms in the degradation of microplastics in aquatic environments. Journal of Chemical Technology and Biotechnology, 97(12), 3271-3282.
27. Deng, Y., Yan, Z., Zhu, Q., and Zhang, Y. (2020). Tissue accumulation of microplastics and toxic effects: widespread health risks of microplastics exposure. Microplastics in Terrestrial Environments: Emerging Contaminants and Major Challenges, 321-341.
28. Dissanayake, P.D., Kim, S., Sarkar, B., Oleszczuk, P., Sang, M.K., Haque, M.N., ... and Ok, Y.S. (2022). Effects of microplastics on the terrestrial environment: a critical review. Environmental Research, 209, 112734.
29. Dos Santos, N.D.O., Busquets, R., and Campos, L.C. (2023). Insights into the removal of microplastics and microfibres by Advanced Oxidation Processes. Science of the Total Environment, 861, 160665.
30. Dris, R., Gasperi, J., Saad, M., Mirande, C., and Tassin, B. (2016). Synthetic fibers in atmospheric fallout: a source of microplastics in the environment?. Marine pollution bulletin, 104(1-2), 290-293.
31. Ebere, E.C., Wirnkor, V.A., and Ngozi, V.E. (2019). Uptake of microplastics by plant: a reason to worry or to be happy?. World Scientific News, (131), 256-267.
32. Egbeocha, C.O., Malek, S., Emenike, C.U., and Milow, P. (2018). Feasting on microplastics:

ingestion by and effects on marine organisms. Aquatic Biology, 27, 93-106.

33. Eriksen, M., Lebreton, L.C., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., ... and Reisser, J. (2014). Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PloS one, 9(12), e111913.
34. Erni-Cassola, G., Zadjelovic, V., Gibson, M.I., and Christie-Oleza, J.A. (2019). Distribution of plastic polymer types in the marine environment; A meta-analysis. Journal of hazardous materials, 369, 691-698.
35. Fackelmann, G., and Sommer, S. (2019). Microplastics and the gut microbiome: how chronically exposed species may suffer from gut dysbiosis. Marine Pollution Bulletin, 143, 193-203.
36. Garcia-Vazquez, E., and Garcia-Ael, C. (2021). The invisible enemy. Public knowledge of microplastics is needed to face the current microplastics crisis. Sustainable Production and Consumption, 28, 1076-1089.
37. Ge, J., Zhang, Z., Ouyang, Z., Shang, M., Liu, P., Li, H., and Guo, X. (2022). Photocatalytic degradation of (micro) plastics using TiO2-based and other catalysts: Properties, influencing factor, and mechanism. Environmental Research, 209, 112729.
38. Goli, V.S.N.S., Paleologos, E.K., Farid, A., Mohamed, A.M.O., O'Kelly, B.C., El Gamal, M.M., ... and Singh, D.N. (2022). Extraction, characterisation and remediation of microplastics from organic solid matrices. Environmental Geotechnics, 40(XXXX), 1-34.
39. Guo, Z., Li, P., Yang, X., Wang, Z., Lu, B., Chen, W., ... and Xue, S. (2022). Soil texture is an important factor determining how microplastics affect soil hydraulic characteristics. Environment International, 165, 107293.
40. Haegerbaeumer, A., Mueller, M.T., Fueser, H., and Traunspurger, W. (2019). Impacts of micro-and nano-sized plastic particles on benthic invertebrates: a literature review and gap analysis. Frontiers in Environmental Science, 7, 17.
41. Harvey, F., and Watts, J. (2018). Microplastics found in human stools for the first time. The Guardian, 22.
42. Hirt, N., and Body-Malapel, M. (2020). Immunotoxicity and intestinal effects of nano-and microplastics: a review of the literature. Particle and fibre toxicology, 17, 1-22.
43. Huang, W., Song, B., Liang, J., Niu, Q., Zeng, G., Shen, M., ... and Zhang, Y. (2021). Microplastics and associated contaminants in the aquatic environment: A review on their ecotoxicological effects, trophic transfer, and potential impacts to human health. Journal of Hazardous Materials, 405, 124187.
44. Huerta Lwanga, E., Mendoza Vega, J., Ku Quej, V., Chi, J.D.L.A., Sanchez del Cid, L., Chi, C., ... and Geissen, V. (2017). Field evidence for transfer of plastic debris along a terrestrial food chain. Scientific reports, 7(1), 14071.
45. Kershaw, P.J., Turra, A., and Galgani, F. (2019). Guidelines for the monitoring and assessment of plastic litter and microplastics in the ocean.
46. Khairul Anuar, N.F.S., Huyop, F., Ur-Rehman, G., Abdullah, F., Normi, Y.M., Sabullah, M.K., and Abdul Wahab, R. (2022). An overview into polyethylene terephthalate (PET) hydrolases and efforts in tailoring enzymes for improved plastic degradation. International Journal of Molecular Sciences, 23(20), 12644.
47. Kim, S., Sin, A., Nam, H., Park, Y., Lee, H., and Han, C. (2022). Advanced oxidation processes for microplastics degradation: A recent trend. Chemical Engineering Journal Advances, 9, 100213.
48. Koelmans, A.A., Nor, N.H.M., Hermsen, E., Kooi, M., Mintenig, S.M., and De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water research, 155, 410-422.
49. Kosuth, M., Mason, S.A., and Wattenberg, E.V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. PloS one, 13(4), e0194970.
50. Kumar, A., Mishra, S., Pandey, R., Yu, Z.G., Kumar, M., Khoo, K.S., ... and Show, P.L. (2023). Microplastics in terrestrial ecosystems: Un-ignorable impacts on soil characterises, nutrient storage and its cycling. TrAC Trends in Analytical Chemistry, 158, 116869.
51. Kumar, M., Xiong, X., He, M., Tsang, D.C., Gupta, J., Khan, E., ... and Bolan, N.S. (2020). Microplastics as pollutants in agricultural soils. Environmental Pollution, 265, 114980.
52. Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P.K., ... and Vara Prasad, P.V. (2021). Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustainability, 13(17), 9963.
53. Kwon, J.H., Kim, J. W., Pham, T.D., Tarafdar, A., Hong, S., Chun, S.H., ... and Jung, J. (2020). Microplastics in food: a review on analytical methods and challenges. International Journal of Environmental Research and Public Health, 17(18), 6710.
54. Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., ... and Reisser, J. (2018). Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Scientific reports, 8(1), 1-15.
55. Lehner, R., Weder, C., Petri-Fink, A., and Rothen-Rutishauser, B. (2019). Emergence of nanoplastic in the environment and possible impact on human health. Environmental science and technology, 53(4), 1748-1765.
56. Li, J., Huang, W., Jiang, R., Han, X., Zhang, D., and Zhang, C. (2020). Are bacterial communities associated with microplastics influenced by marine habitats?. Science of The Total Environment, 733, 139400.

57. Li, Y., Li, W., Jarvis, P., Zhou, W., Zhang, J., Chen, J., ... and Tian, Y. (2020). Occurrence, removal and potential threats associated with microplastics in drinking water sources. Journal of Environmental Chemical Engineering, 8(6), 104527.
58. Lin, D., Yang, G., Dou, P., Qian, S., Zhao, L., Yang, Y., and Fanin, N. (2020). Microplastics negatively affect soil fauna but stimulate microbial activity: insights from a field-based microplastic addition experiment. Proceedings of the Royal Society B, 287(1934), 20201268.
59. Lu, Y., Zhang, Y., Deng, Y., Jiang, W., Zhao, Y., Geng, J., ... and Ren, H. (2016). Uptake and accumulation of polystyrene microplastics in zebrafish (Danio rerio) and toxic effects in liver. Environmental science and technology, 50(7), 4054-4060.
60. Luckachan, G.E., and Pillai, C.K.S. (2011). Biodegradable polymers-a review on recent trends and emerging perspectives. Journal of Polymers and the Environment, 19, 637-676.
61. Lwanga, E.H., Beriot, N., Corradini, F., Silva, V., Yang, X., Baartman, J., ... and Geissen, V. (2022). Review of microplastic sources, transport pathways and correlations with other soil stressors: a journey from agricultural sites into the environment. Chemical and Biological Technologies in Agriculture, 9(1), 1-20.
62. Mathieu-Denoncourt, J., Wallace, S.J., de Solla, S.R., and Langlois, V.S. (2015). Plasticizer endocrine disruption: Highlighting developmental and reproductive effects in mammals and non-mammalian aquatic species. General and comparative endocrinology, 219, 74-88.
63. Meaza, I., Toyoda, J.H., and Wise Sr, J.P. (2021). Microplastics in sea turtles, marine mammals and humans: a one environmental health perspective. Frontiers in environmental science, 298.
64. Microplastics in Drinking-Water. World Health Organization; Geneva, Switzerland: 2019. [(accessed on 28 November 2019)]. Available online: https://apps.who.int/iris/bitstream/handle/10665/326499/9789241516198-eng.pdf?ua=1
65. Müller, A., Österlund, H., Marsalek, J., and Viklander, M. (2020). The pollution conveyed by urban runoff: A review of sources. Science of the Total Environment, 709, 136125.
66. Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H., Hamann, M., ... and Godley, B. J. (2016). Plastic and marine turtles: a review and call for research. ICES Journal of Marine Science, 73(2), 165-181.
67. Nikiema, J., Asiedu, Z., Mateo-Sagasta, J., Saad, D., and Lamizana, B. (2020). Catalogue of technologies to address the risks of contamination of water bodies with plastics and microplastics.
68. Othman, A.R., Hasan, H.A., Muhamad, M.H., Ismail, N.I., and Abdullah, S.R.S. (2021). Microbial degradation of microplastics by enzymatic processes: a review. Environmental Chemistry Letters, 19, 3057-3073.
69. Padervand, M., Lichtfouse, E., Robert, D., and Wang, C. (2020). Removal of microplastics from the environment. A review. Environmental Chemistry Letters, 18, 807-828.
70. Pandey, G., and Madhuri, S. (2014). Heavy metals causing toxicity in animals and fishes. Research Journal of Animal, Veterinary and Fishery Sciences, 2(2), 17-23.
71. Pannetier, P., Morin, B., Le Bihanic, F., Dubreil, L., Clérandeau, C., Chouvellon, F., ... and Cachot, J. (2020). Environmental samples of microplastics induce significant toxic effects in fish larvae. Environment international, 134, 105047.
72. Percival, S.L., Malic, S., Cruz, H., and Williams, D.W. (2011). Introduction to biofilms. Biofilms and veterinary medicine, 41-68.
73. Piehl, S., Leibner, A., Löder, M.G., Dris, R., Bogner, C., and Laforsch, C. (2018). Identification and quantification of macro-and microplastics on an agricultural farmland. Scientific reports, 8(1), 17950.
74. Pitt, J.A., Kozal, J.S., Jayasundara, N., Massarsky, A., Trevisan, R., Geitner, N., ... and Di Giulio, R. T. (2018a). Uptake, tissue distribution, and toxicity of polystyrene nanoparticles in developing zebrafish (Danio rerio). Aquatic Toxicology, 194, 185-194.
75. Qiao, R., Sheng, C., Lu, Y., Zhang, Y., Ren, H., and Lemos, B. (2019). Microplastics induce intestinal inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish. Science of the Total Environment, 662, 246-253.
76. Qin, M., Chen, C., Song, B., Shen, M., Cao, W., Yang, H., ... and Gong, J. (2021). A review of biodegradable plastics to biodegradable microplastics: another ecological threat to soil environments?. Journal of Cleaner Production, 312, 127816.
77. Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., ... and Giorgini, E. (2021). Plasticenta: First evidence of microplastics in human placenta. Environment international, 146, 106274.
78. Rahman, A., Sarkar, A., Yadav, O. P., Achari, G., and Slobodnik, J. (2021). Potential human health risks due to environmental exposure to nano-and microplastics and knowledge gaps: a scoping review. Science of the Total Environment, 757, 143872.
79. Raza, T., Qadir, M.F., Khan, K.S., Eash, N.S., Yousuf, M., Chatterjee, S., ... and Oetting, J. N. (2023). Unrevealing the potential of microbes in decomposition of organic matter and release of carbon in the ecosystem. Journal of Environmental Management, 344, 118529.
80. Revel, M., Châtel, A., and Mouneyrac, C. (2018). Micro (nano) plastics: a threat to human

health?. Current Opinion in Environmental Science and Health, 1, 17-23.

81. Rist, S., Almroth, B.C., Hartmann, N.B., and Karlsson, T.M. (2018). A critical perspective on early communications concerning human health aspects of microplastics. Science of the Total Environment, 626, 720-726.
82. Roager, L., and Sonnenschein, E.C. (2019). Bacterial candidates for colonization and degradation of marine plastic debris. Environmental science and technology, 53(20), 11636-11643.
83. Rout, P.R., Zhang, T.C., Bhunia, P., and Surampalli, R.Y. (2021). Treatment technologies for emerging contaminants in wastewater treatment plants: A review. Science of the Total Environment, 753, 141990.
84. Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., and Schmitt-Jansen, M. (2017). Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environmental science and technology letters, 4(7), 258-267.
85. Ryan, P.G. (2019). Ingestion of plastics by marine organisms. Hazardous chemicals associated with plastics in the marine environment, 235-266.
86. Sajid, M., Nazal, M.K., Baig, N., and Osman, A.M. (2018). Removal of heavy metals and organic pollutants from water using dendritic polymers based adsorbents: a critical review. Separation and Purification Technology, 191, 400-423.
87. Sarijan, S., Azman, S., Said, M. I. M., and Jamal, M.H. (2021). Microplastics in freshwater ecosystems: a recent review of occurrence, analysis, potential impacts, and research needs. Environmental Science and Pollution Research, 28, 1341-1356.
88. Sau, D., Hazra, T., and Shiuly, A. (2023). Microplastics in lentic environments: implications for Indian ecosystems. Environmental Science and Pollution Research, 1-23.
89. Scheurer, M., and Bigalke, M. (2018). Microplastics in Swiss floodplain soils. Environmental science and technology, 52(6), 3591-3598.
90. Schwabl, P., Köppel, S., Königshofer, P., Bucsics, T., Trauner, M., Reiberger, T., and Liebmann, B. (2019). Detection of various microplastics in human stool: a prospective case series. Annals of internal medicine, 171(7), 453-457.
91. Sharma, S., and Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environmental Science and Pollution Research, 24, 21530-21547.
92. Silva-Cavalcanti, J. S., Silva, J. D. B., de França, E. J., de Araújo, M. C. B., and Gusmao, F. (2017). Microplastics ingestion by a common tropical freshwater fishing resource. Environmental pollution, 221, 218-226.
93. Smith, M., Love, D.C., Rochman, C.M., and Neff, R.A. (2018). Microplastics in seafood and the implications for human health. Current environmental health reports, 5, 375-386.
94. Stabnikova, O., Stabnikov, V., Marinin, A., Klavins, M., Klavins, L., and Vaseashta, A. (2021). Microbial life on the surface of microplastics in natural waters. Applied Sciences, 11(24), 11692.
95. Taib, N.A.A.B., Rahman, M.R., Huda, D., Kuok, K.K., Hamdan, S., Bakri, M.K.B., ... and Khan, A. (2023). A review on poly lactic acid (PLA) as a biodegradable polymer. Polymer Bulletin, 80(2), 1179-1213.
96. Tang, K.H.D., and Hadibarata, T. (2021). Microplastics removal through water treatment plants: Its feasibility, efficiency, future prospects and enhancement by proper waste management. Environmental Challenges, 5, 100264.
97. Taniguchi, I., Yoshida, S., Hiraga, K., Miyamoto, K., Kimura, Y., and Oda, K. (2019). Biodegradation of PET: current status and application aspects. Acs Catalysis, 9(5), 4089-4105.
98. Toussaint, B., Raffael, B., Angers-Loustau, A., Gilliland, D., Kestens, V., Petrillo, M., ... and Van den Eede, G. (2019). Review of micro-and nanoplastic contamination in the food chain. Food Additives and Contaminants: Part A, 36(5), 639-673.
99. Ukil, M., Roy, S., Choudhury, A.R., and Ganesh, P.S. (2022). Role of Microplastics as Attachment Media for the Growth of Microorganisms. Microplastics Pollution in Aquatic Media: Occurrence, Detection, and Removal, 313-325.
100. Van Cauwenberghe, L., and Janssen, C.R. (2014). Microplastics in bivalves cultured for human consumption. Environmental pollution, 193, 65-70.
101. Wan, Z., Wang, C., Zhou, J., Shen, M., Wang, X., Fu, Z., and Jin, Y. (2019). Effects of polystyrene microplastics on the composition of the microbiome and metabolism in larval zebrafish. Chemosphere, 217, 646-658.
102. Wang, J., Li, Y., Lu, L., Zheng, M., Zhang, X., Tian, H., ... and Ru, S. (2019). Polystyrene microplastics cause tissue damages, sex-specific reproductive disruption and transgenerational effects in marine medaka (Oryzias melastigma). Environmental Pollution, 254, 113024.
103. Wang, J., Peng, C., Li, H., Zhang, P., and Liu, X. (2021). The impact of microplastic-microbe interactions on animal health and biogeochemical cycles: a mini-review. Science of the Total Environment, 773, 145697.
104. Wang, Z., Li, W., Li, W., Yang, W., and Jing, S. (2023). Effects of microplastics on the water characteristic curve of soils with different textures. Chemosphere, 317, 137762.
105. Waring, R.H., Harris, R.M., and Mitchell, S.C. (2018). Plastic contamination of the food chain:

A threat to human health?. Maturitas, 115, 64-68.
106. Wright, S.L., and Kelly, F.J. (2017). Plastic and human health: a micro issue?. Environmental science and technology, 51(12), 6634-6647.
107. Wright, S.L., Ulke, J., Font, A., Chan, K.L.A., and Kelly, F.J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environment international, 136, 105411.
108. Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., ... and Xu, J. (2020). Microplastics in the soil environment: occurrence, risks, interactions and fate–a review. Critical Reviews in Environmental Science and Technology, 50(21), 2175-2222.
109. Xu, Q., Huang, Q.S., Luo, T.Y., Wu, R.L., Wei, W., and Ni, B.J. (2021). Coagulation removal and photocatalytic degradation of microplastics in urban waters. Chemical Engineering Journal, 416, 129123.
110. Yee, M. S. L., Hii, L. W., Looi, C.K., Lim, W.M., Wong, S.F., Kok, Y.Y., ... and Leong, C. O. (2021). Impact of microplastics and nanoplastics on human health. Nanomaterials, 11(2), 496.
111. Yong, C.Q.Y., Valiyaveettil, S., and Tang, B. L. (2020). Toxicity of microplastics and nanoplastics in mammalian systems. International Journal of Environmental Research and Public Health, 17(05), 1509.
112. Zhang, K., Hamidian, A.H., Tubić, A., Zhang, Y., Fang, J.K., Wu, C., and Lam, P.K. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. Environmental Pollution, 274, 116554.
113. Zhang, S., Pei, L., Zhao, Y., Shan, J., Zheng, X., Xu, G., ... and Wang, F. (2023). Effects of microplastics and nitrogen deposition on soil multifunctionality, particularly C and N cycling. Journal of Hazardous Materials, 451, 131152.
114. Ziajahromi, S., Neale, P.A., Rintoul, L., and Leusch, F.D. (2017). Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water research, 112, 93-99.
115. Ziani, K., Ioniță-Mîndrican, C.B., Mititelu, M., Neacșu, S.M., Negrei, C., Moroșan, E., ... and Preda, O.T. (2023). Microplastics: a real global threat for environment and food safety: A state of the art review. Nutrients, 15(3), 617.