Review Article

MICROPLASTICS: Current status, Environmental challenges, and Future Research Directions.

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Abstract

Microplastics are polymer particles smaller than 5 mm in size, which have become ubiquitous environmental contaminants with high potential ecological and human health risks due to their abundance in marine and freshwater environments, as well as their improper disposal into terrestrial environments. Microplastics originate from a variety of primary and secondary sources. Due to their persistence in the environment, small size, and large surface area, microplastics can accumulate and transfer pollutants and pathogens into the food chain, where they can affect organisms at different levels by causing oxidative stress, inflammation, toxicity, and impairing reproduction and ecosystems. Although there is evidence of the impact of microplastics, the long-term effects on human health are still unclear. This review aims to provide an in-depth understanding of current knowledge on microplastic sources, classification, and environmental occurrence; analytical methodologies for their identification, characterisation, and quantification; ecological and human health impacts; and mitigation and remediation measures. In addition, this review discusses regulatory aspects, research gaps, and future directions for microplastic pollution management. Microplastics require integrated research and appropriate policies to control them and mitigate their environmental and health effects.

KEYWORDS: Microplastics; plastic pollution; Environmental contamination; Ecotoxicology; Human health; Analytical techniques; Remediation; sustainable waste management.

Introduction

Microplastics are tiny plastic particles that come from two main types of sources: primary and secondary microplastics. Primary microplastics are manufactured at a microscopic level for specific use, whereas secondary microplastics come from the fragmentation of larger plastics. For example, plastics such as bags, bottles, packaging materials, and fishing gear subjected to various physical forces can break down to form secondary microplastics.

These tiny plastic particles are pervasive and can be found in water, soil, air, sediments, food, and even inside organisms. Their small size and ability to persist in the environment make them prone to transportation and consumption by organisms. In addition, microplastics can accumulate and transfer harmful pollutants and pathogens in the food chain, where they may have adverse effects on the organisms and negatively impact ecosystems [12-14]. A major concern with microplastics is their potential to cause adverse effects, which has prompted extensive research into their sources, as well as their environmental pathways, impacts on wildlife, and exposure risks to humans. The main approaches to this issue have focused on reducing plastic production, improving waste management, promoting alternative materials, and enhancing environmental monitoring [15-17]. Microplastics pose various opportunities for exposure to humans, animals, and plants. For instance, aquatic organisms such as fish can ingest them from their habitats and consequently transfer them to other organisms in the food chain. Microplastics can also be adhered to other particles in the environment and, therefore, become part of organisms' interactions. However, characterising microplastics from different sources can be challenging, especially when using conventional techniques. The differences in microplastic size, polymer type, and shape, among other factors, can influence the choice of an appropriate analytical method. For example, microscopy can be used to examine the shape of microplastics, whereas FTIR and Raman spectroscopy can help identify polymers. In addition, thermal analyses can complement spectroscopic analyses in determining the nature and amount of plastic polymers [8,9].



Global plastic waste management and microplastics

At the policy level, there is a need for extended producer responsibility, prohibiting the production of selected plastic products, promoting recycling strategies, promoting research, and standardising monitoring methods for microplastics. However, international collaboration is needed in managing the global plastics waste problem because microplastics can originate from and affect different countries through water, air, and oceans. Future directions for managing plastics waste and managing microplastics include environmental monitoring, extended producer responsibility, and engaging stakeholders such as the public [23].

In general, the problem of controlling microplastic pollution requires removing them from the environment, which involves managing waste after they reach various ecosystems. However, eliminating plastic waste before it reaches the environment is a more effective strategy in microplastic management since it minimises the need for costly downstream waste management approaches. Shifting from a plastics waste management system to a circular economy will ensure that plastics are used in a way that limits long-term environmental damage [23].

Environmental concern:

Microplastics are a serious environmental problem due to their prevalence and persistence in the environment, as well as the impact they have on biological organisms. Microplastics originate from anthropogenic activity, as well as the degradation process of larger plastics [18,19].

Microplastics in the aquatic environment: Microplastics are ubiquitous pollutants and are present in various environmental media, including marine and freshwater environments. Microplastics originate from both anthropogenic activities and the degradation of larger plastics.



SOURCES OF MICROPLASTICS:

According to the International Union for Conservation of Nature (IUCN, there are six primary sources of marine microplastics. They include textile fibres, rubber from tyres, road marking paints, personal care and cosmetics, industrial plastic pellets, marine paints and coatings, and urban dust. These sources are well documented with regard to their contribution to marine microplastics, and therefore, there is a vast body of information on their role in the creation of microplastics. However, these sources should not be considered as an exclusive list of potential sources of microplastics because the problem encompasses a wide range of human activities and economic sectors. There is a need to identify and characterise other sources of microplastics contamination and determine their contribution to the overall burden of microplastics in the environment.

In terms of textile pollution, it is crucial to note that fibres come from both synthetic and natural materials. However, only synthetic fibres are considered to be microplastics, since they are typically made of plastic polymers [2].

Other sources of microplastics:

Microplastic pollution can originate from various human activities, including those taking place in industrial, residential, agricultural, and transportation settings. In accordance with the mechanism by which they are introduced into the environment, microplastics can be divided into primary and secondary types.

1. Primary sources

Primary sources of microplastics include polymer particles that are produced or introduced into the environment deliberately at a relatively small scale. Primary microplastic sources comprise:

Synthetic textiles: Textile fibres such as polyester, nylon, and acrylic can enter the environment through washing and wearing synthetic clothes. In particular, this type of microplastic can enter aquatic environments via wastewater treatment facilities [2].

Personal-care products and cosmetics: Previously, the personal-care and cosmetics industry has been using tiny plastic particles as an abrasive component in a variety of cosmetics products. Following the use of such products, the microplastic particles enter the environment through wastewater treatment works.

Industrial plastic pellets: Tiny plastic granules used in the production process can enter the environment at several points during their manufacture, packing, and transport. These sources contribute to microplastic contamination of soils and aquatic environments.

Industrial applications: The abrasive blasting process can involve plastic particles, which are subsequently discharged into the environment if they are inadequately handled or disposed of. In addition, this procedure can lead to the release of microplastic particles into the atmosphere.

Paints and coatings: Similar to other plastics, paints and coatings can enter the environment in the form of particulate matter and subsequently affect various ecosystems [15-17].

2. Secondary sources

Secondary sources comprise plastics that have been introduced into the environment through human activity and degraded to form microplastics. Degradation processes such as UV exposure, oxidation, thermal stresses, physical abrasion, and mechanical forces can all contribute to the degradation of plastics into smaller pieces.

Plastic packaging and other consumer items: Numerous consumer goods such as bags, plastic bottles, packaging materials, food packaging, and other items are often discarded, subsequently being subjected to environmental degradation processes.

Fishing and aquaculture activities: Fishing nets, ropes, cages, and other plastic accessories degrade in marine and freshwater environments, eventually contributing to the formation of microplastics [15-17].

Agricultural plastics: Plastic materials used in agriculture and exposed to environmental conditions gradually break down, generating microplastic particles [12-14].

Poor waste management: Improper disposal, treatment, and recycling of plastic waste can enhance its distribution in the environment. In addition, plastics can undergo degradation processes due to exposure to solar radiation and temperature variations, which may also contribute to the formation of microplastics [15-17].

1. Wastewater treatment plants

Are not confined to freshwater environments. In fact, airborne microplastics can originate from a variety of sources, including synthetic textiles, tyre and road wear, degradation processes, and industrial activities, and can be transported over long distances before settling on various surfaces. Household wastewater can contain a

considerable amount of microplastics, mainly in the form of fibres and fragments. Wastewater treatment works play a critical role in removing microplastics from wastewater by retaining them in sludge, whereas some are discharged in effluent into surface waters [3,4].

2. Urban runoff

Urban areas can be a significant source of microplastics due to the high concentration of human activity and the potential for various microplastic particles to be transported by urban runoff directly into freshwater systems. Tyre and road wear particles, fragments, and fibres, as well as litter, can originate from a variety of anthropogenic activities, including vehicle traffic, industrial activity, and domestic and commercial waste [5,6].

3. Agricultural activities

Agricultural soils can be contaminated by microplastics from a variety of sources, including plastic mulch, greenhouse films, and irrigation systems, as well as fertilisers, compost, and manure. Synthetic polymers can also be present in irrigation water or sewage sludge [3,4].

4. Landfills and waste-management facilities.

Plastic waste disposed of in landfills can undergo photodegradation and chemical and mechanical degradation processes.

5. Marine and fishing activities

Larger plastics break down into smaller particles due to physical forces and can enter the water through landfill leachate.

6. Tire and road- wear particles

Road traffic can contribute significantly to microplastic pollution by generating particulate matter from tyre wear, which can then be transferred into the environment by both wind and water [5,6].

7. Textile industry

The textile industry can be a major source of microplastic pollution through the release of synthetic fibres at various stages of the textile production process, including fibre production, fabric manufacturing, garment sales, washing, and disposal [7].

8. Paints and coatings

It is crucial to recognise that paint particles can be a considerable source of plastic pollution, as a wide range of human activities can generate microplastic-like particulate matter from weathering, peeling, sanding, and other activities.

Environmental distribution of microplastics

Microplastics are now ubiquitous in the environment, particularly in aquatic, terrestrial, and atmospheric habitats. The relative abundance of these pollutants depends on the sources, as well as environmental conditions and processes that promote their transport or transformation [12-14].

1. Aquatic environments

Marine and freshwater environments can be contaminated with microplastics from urban and industrial wastes, which are often transported by rivers to freshwater systems and eventually to the oceans. Due to their size and density, microplastics may remain suspended in aquatic solutions or settle to the bottom of water bodies [18,19]

2. Soil and terrestrial environments:

Soils can be a major sink for microplastics due to the significant amounts of plastic waste that have been disposed of there. Sources of microplastics in agricultural and urban soils include plastic mulch, sewage sludge, compost, and fertiliser, among others. The presence of microplastics in the soil can affect its physical properties and, consequently, its ability to function. This phenomenon occurs when the plastic particle's size, density, shape, and other properties combine with the soil's structure and water content [3,4]

3. Sediments

Microplastics are commonly found in river, lake, estuarine, and ocean sediments. Dense polymer particles and polymer particles coated with biofilm or minerals can sink and be permanently incorporated into the sediments. Sediments can act as reservoirs of microplastics and can also re-release them into the water column [18,19].

4. Atmospheric environment:

Microplastics can also be found in the outdoor air. Synthetic clothing fibres, tyre and road wear particles, and plastic fragments are significant sources of atmospheric microplastics. Microplastics can be transported in the atmosphere as airborne particles over long distances and then removed by dry or wet deposition onto the ground, water surfaces,

plants, and other surfaces [2].

5. Freshwater environments:

Freshwater environments such as rivers, lakes, reservoirs, and streams can be important microplastic reservoirs and conduits. Microplastics can enter freshwater environments through urban runoff, effluents from wastewater treatment plants, industrial inputs, domestic waste, and recreation. Organisms living in freshwater habitats can be exposed to microplastics in the water column and in the sediment [3,4].

6. biota and food webs:

Microplastics have been found in drinking water, bottled water, seafood, salt, agricultural products, and other food items. They can enter the food chain at several points, such as from the environment, food-processing equipment, packaging, storage containers, or atmospheric deposition. Microplastic contamination of food and water has raised concerns about human exposure [15,17].

7. Dietary Exposure to Microplastics:

Microplastics have been found in drinking water, bottled water, and other foodstuffs. Contamination can come from the environment, food-processing equipment, packaging, storage, or atmospheric deposition. Microplastic contamination of food and water has raised concerns about human exposure [15-17].

Migration, fate and transformation of microplastics

Microplastics are generally persistent like other plastic wastes; therefore, wastewater, agricultural activities, and various sources of pollution from which they originate can transfer them through different environmental matrices such as water, soil, sediments, and atmosphere. Microplastics can originate from different sources such as tyre debris, synthetic textiles, and degraded plastics and can be transported short or long distances depending on their physicochemical properties [2].

In water bodies, rivers, streams, oceanic currents, tides, and runoff can transport microplastics. Microplastics from wastewater treatment plants can be partially removed through wastewater treatment processes, but significant amounts of microplastics can still be discharged into the water bodies through effluents. Rainfall and runoff from cities and agricultural lands can also transport microplastics from the land into water bodies. Additionally, in the oceans, currents and waves can redistribute microplastics. Microplastics can be suspended in the water column or settle on the sediment bed [3,4].

The fate of microplastics in the environment is determined by their size, shape, density, physicochemical properties, and polymer composition, as well as environmental factors like water flow, particle interactions, and biological processes. Microplastics with low polymer density can float on water surfaces, while those with high polymer density can sink and accumulate in the sediment bed. However, the density of microplastics can also change due to colonisation by microorganisms and the formation of biofilms on their surfaces, allowing them to vertically migrate through the water column or eventually settle on the sediment bed [15-17].

In addition, the interactions of microplastics with other environmental contaminants should also be considered, as they can play an important role in determining their fate and impact.

Sampling, Extraction, and Identification of Microplastics

Microplastics analysis involves a series of steps that are performed in a systematic manner and require specific skills, knowledge, and equipment. In general, sampling, preparation, and analysis of microplastics are done with careful handling to avoid contamination from airborne fibres, plastics, and other materials [11].

Environmental matrices such as water, soil, sediment, air, and biota can be sampled using standard analytical procedures suitable for the target microplastic size. During the extraction stage, microplastics are removed from the sampled matrix using filtration, density separation, and careful digestion of organic matter. The extracted plastics are then cleaned and dried, and their colour is analysed under a microscope, although this method cannot identify the polymer, and they are then prepared for analysis. Preliminary polymer analysis can be done using [11].

On the other hand, instrumental analysis is more appropriate for the identification of microplastics. Infrared spectroscopy (FTIR) and Raman spectroscopy are commonly used for polymer identification, while thermal analysis techniques like py-gc-ms are used. In summary, it is important to note that proper microplastic analysis requires correct sampling, preparation, and identification techniques to ensure that reliable results are achieved [8,9].

STAGE METHOD/TECHNIQUE

Sampling: Grab sampling, filtration, nets, sediment/ soil collection
Sample preparation: Drying, sieving, homogenisation
Density separation: Density-based separation using suitable solutions
Organic matter removal: chemical or enzymatic digestion
Microscopic examination: optical microscopy/stereomicroscopy
Thermal analysis: py-gc-ms and related techniques

ENVIRONMENTAL, ECOLOGICAL AND BIOLOGICAL EFFECTS OF MICROPLASTICS

Microplastics are ubiquitous contaminants that can interact with terrestrial and aquatic ecosystems and affect plants, animals, microbes, and food webs. Their impact can depend on various factors like particle size, shape, polymer type, surface properties, concentration, exposure duration, and the environment, such as soil, water, and sediments. Microplastics can be physically and physiologically damaging to most organisms and can be transported through various environmental media, contaminating different ecological compartments [12-14].



EFFECTS ON PLANTS

Microplastics entering agricultural lands or natural terrestrial ecosystems can affect the physicochemical properties of the soils and consequently plant growth and development. Their impact can depend on the type of microplastic, size, surface properties, and concentration. There is evidence that microplastics can affect seed germination, root development, plant biomass, photosynthetic rates, nutrient uptake, and mineral contents. For instance, smaller microplastic particles can physically adhere to root surfaces and, depending on the type, penetrate and be translocated within the plant. However, the extent to which different plant species can absorb and translocate microplastics depends on the type of microplastic and environmental conditions [13, 14].

MICROPLASTICS IN FOOD AND FOOD WEB

Microplastics can affect food webs when animals mistake them for food and ingest them or consume animals contaminated with microplastics. Microplastics have been detected in various food wastes and aquatic organisms and have been found in food products like seawater, drinking water, freshwater, and agricultural products. Zooplanktons, mussels, snails, and other aquatic organisms can be exposed to microplastics in food and water. Once ingested, microplastics can be transferred from one organism to another, facilitating their entry into food webs and affecting their distribution patterns, especially in aquatic food webs [18,19].

ECOTOXICOLOGICAL EFFECTS

Research on the ecotoxicological effects of microplastics has intensified due to their potential to cause mechanical and physiological damage to organisms. Ecotoxicological effects of microplastics depend on the exposure conditions and the physiological response of the organism. Most studies have shown that microplastics can cause oxidative stress, inflammatory responses, physiological disruptions, impaired reproduction, reduced growth rate, and altered behaviour in exposed organisms. The absorption of toxicants adsorbed onto the surface of microplastics can also contribute to their toxicological effects, although the extent of impact depends on the target organism [20].

Effects on aquatic organisms

Fish, plankton, crustaceans, molluscs, and other aquatic invertebrates can be exposed to microplastics in the water column and sediment bed. Microplastics can affect aquatic organisms by causing blockages in the alimentary canal and reducing the energy available for other physiological functions. Some of the reported effects of chronic exposure to microplastics on aquatic organisms include physiological disruption, impaired reproduction, changes in behaviour, impaired growth rate, and altered metabolism. Microplastics can also accumulate in the sediment bed and act as an additional source of exposure for benthic organisms [20].

Effects on soil organisms and microorganisms

Soil organisms such as earthworms, nematodes, insects, and microorganisms can be exposed to microplastics through ingestion and direct contact. Agricultural plastic films, sludge and wastewater, compost, atmospheric deposition, and plastic waste disposal are some of the ways microplastics can enter the soil. Once in the soil, microplastics can affect soil organisms directly and indirectly by interacting with chemical and physical properties of the soil [12-14].

Earthworms: Microplastics can reduce the growth rate and reproduction of earthworms, affect their feeding behaviour, and disrupt the microbial community in their gut.

Soil insects and arthropods: Microplastics can affect the energy budget of soil insects, reduce their weight, and alter their feeding behaviour.

Soil microorganisms: Microplastics can affect the abundance, diversity, and composition of microbial communities in the soil and affect microbial processes such as decomposition and nutrient cycling.

Bacteria and fungi: Microplastics create a unique environment called the plastisphere on their surfaces that can favour the colonisation and proliferation of certain bacteria and fungi.

Enzymatic activity: Exposure to microplastics can affect the activity of various enzymes in the soil, especially those involved in nutrient cycling.

Nutrient cycling: Microplastics can indirectly affect nutrient cycling in the soil by affecting microbial processes and enzyme activities.

Soil structure: Microplastics can alter the physical properties of the soil, thereby affecting aeration, water retention, and other physical processes.

Chemical interactions: Microplastics can affect the adsorption and desorption properties of the soil, thereby altering the availability of nutrients and other chemical elements in the soil. In addition, they can also affect the leaching of certain elements in the soil.

Ecological consequences: Microplastics can indirectly affect the structure and function of soil food webs by affecting the soil organisms' abundance, diversity, and behaviour. However, the extent of impact depends on the type of polymer, microplastic size and shape, and the environmental conditions.

Microplastics as Carriers of Other Contaminants

Microplastics, as persistent particles in the environment, can provide suitable surfaces for the accumulation of various chemical and biological contaminants. As a result of the relatively large surface area, hydrophobicity, uneven surface, and weathered functional groups, microplastics can provide sites for the attachment of contaminants in water, soil, and sediments. After associating with particles, their impact on the environment, persistence, distribution, and biological availability may change. The tendency for interaction depends on polymer type, particle size, surface ageing, environmental conditions, and contaminant properties, and the presence of biofilms. [21]

Interaction with Heavy Metals

Microplastics can interact with heavy metals such as Pb, Cd, Hg, Cr, Cu, Zn, Ni. While freshly produced plastic surfaces may have limited metal-binding capacity, the weathering process increases the surface roughness and introduces oxygen-containing functional groups. These factors may provide additional sites for metal adsorption. Similarly, biofilms that develop on microplastic surfaces can change their ability to retain metals. [21]

The association of metals with microplastics can influence their distribution in aquatic and terrestrial environments, but microplastics should not be considered permanent carriers of metals. Indeed, changes in pH, salinity, dissolved organic matter, ionic strength, and competing ions can lead to metal detachment from the particles. Therefore, the environmental relevance of microplastic–metal interactions strongly depends on local environmental conditions. [11]

Interaction with Persistent Organic Pollutants

Microplastics can accumulate persistent organic pollutants as many of them have hydrophobic properties and tend to adhere to organic polymer surfaces. The most common pollutants are polychlorinated biphenyls, polycyclic aromatic hydrocarbons, organochlorine pesticides, and other hydrophobic chemicals. [21]

The interaction mechanism depends on polymer properties and pollutant characteristics. For example, polyethene and polypropylene can interact differently with contaminants than other polymers with more variable or polar groups. Weathering and biofilm development can also change contaminant adsorption on microplastics. Therefore, microplastics can contribute to the redistribution and accumulation of hydrophobic pollutants.

The potential for microplastics to facilitate biological exposure is more complex. While the association of microplastics with contaminated particles can contribute to their ingestion, it does not necessarily mean that the chemicals will be desorbed in biologically relevant concentrations. Indeed, desorption can be affected by digestion conditions, temperature, pH, lipids, and other factors. Thus, the carrier effect should be considered under environmentally relevant conditions. [15–17]

Interaction with Pharmaceuticals

Pharmaceutical residues get into water and landfills with domestic wastewater, hospital waste, pharmaceutical manufacturing, agricultural runoff, and improper disposal. Drugs such as antibiotics, anti-inflammatories, antidepressants, and other compounds can interact with microplastic surfaces. [22]

Microplastics can adsorb pharmaceuticals through various mechanisms, including hydrophobic interactions, electrostatic attraction, hydrogen bonding, and surface partitioning. The process can be facilitated by the weathering of plastics and the creation of additional binding sites. [22]

The presence of pharmaceuticals on microplastics can alter their environmental behaviour, while microplastics can also affect the distribution of medicines in water, sediments, and organisms [22]

conclusion

Microplastic pollution has become a serious environmental problem as these small particles can come from various sources and persist in the environment. Their presence has been detected in water, sediments, soil, air, food, and organisms. The behaviour of microplastics is governed by particle size, shape, polymer properties, surface characteristics, and environmental conditions. As a result, they can be transported over long distances and transform the ageing process.

The ubiquitous nature of microplastics also creates opportunities for interactions with chemical contaminants and microorganisms. Their surfaces can accumulate metals, organic pollutants, pharmaceuticals, and support microbial colonisation. These associations can affect the distribution and environmental behaviour of microplastics, as well as the fate and biological availability of various substances. Laboratory and field studies have demonstrated that microplastics can induce various biological effects, including oxidative stress, inflammation, cellular impacts, and changes in growth and physiological processes. However, the mechanistic and quantitative understanding of these

effects under environmentally relevant conditions is still limited.

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