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Environmental Toxicants and Lifestyle Diseases

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Contents

Emerging Toxicants

Microplastics: An Emerging Concern of Human Health

P. Said Hamid Thangal and P. A. Ahammed Shareef

Abstract

Microplastics are small plastic particles, typically less than 5 mm in size, that pose serious environmental concern and human (and animal) health risks worldwide. They are classified based on type, size, shape and chemical composition. They are divided into primary microplastics, which are purposefully manufactured as small plastics (e.g., microbeads and nurdles), and secondary microplastics, formed by the biotic or abiotic degradation of larger plastics. They are further categorized based on their size into mesoplastics, microplastics, and nanoplastics. Classification based on shape include fragments, fibers, pellets, foams, films and beads. They are also classified as thermoplastics, thermosetting plastics, elastomers and biodegradable plastics based on their chemical composition. Microplastics are formed from a wide variety of sources and enter the living system via ingestion, inhalation or dermal contact, and distribute via circulatory system. They pose varying health risks through physical blockages, chemical toxicity, bioaccumulation and biomagnification. They have significant impact on various tissues and organ systems. They persist in ecosystem for longer period of time, accumulate in food chain, and pose risks to terrestrial and aquatics animals. They also effect the environment by disrupting soil structure and ecology, and interact with organic pollutants, heavy metals and pathogens. The control measures include reduce plastic manufacture/use, improved waste management,

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regulative and legislative measures, public awareness and education, and innovative policies.

Keywords

Microplastics · Nanoplastics · Emerging contaminants · Environmental pollution · Human health · Toxicity

Introduction

Plastics are polymers synthesized by polymerization of monomers (the repeating units of long-chain polymers, composed of carbon, hydrogen, and oxygen held together by covalent bonds) extracted from petrochemicals and combined with other chemicals to improve the quality. They received wide acceptance due to their advantages over other materials, such as ease of manufacture, durability, resistance to degradation, tolerance to chemicals and higher temperatures, resistance to water, high strength, low cost, etc., made them an integral part of modern life, spanning numerous industries, including packaging, construction, healthcare, and electronics (Zhang et al. 2021).

The global production of plastics has increased from 2 million tons in 1950 to 400.3 million tons in 2022 and is expected to increase exponentially in the upcoming decades (Pilapitiya and Ratnayake 2024). Their applications range from single-use packaging to high-performance materials in industries, such as automotive and aerospace. Most of the plastics are manufactured for "single-use" with limited recyclability, resulting in increased production, leading to the generation of huge amount of waste. Their widespread use of plastics has also led to significant environmental challenges. The durability that makes plastics so useful in various applications also contributes to their persistence in the environment, resulting in pollution and the accumulation of plastic waste in landfills and oceans. This has led to growing concerns about the ecological impact of plastics, prompting initiatives for recycling, reduction, and the development of biodegradable alternatives (Zhang et al. 2021).

Microplastics

The degradation of synthetic plastics, which takes several years in nature, results in the formation of their fragments of different shapes and sizes, often called microplastics. Microplastics are small pieces of plastic, less than 5 mm in size, that occur in the environment as a consequence of the degradation of plastic. Originating from both primary sources, such as microbeads intentionally included in personal care products, and secondary sources, where larger plastic debris degrades into smaller fragments, microplastics now represent a universal pollutant (Wang et al. 2019). They have become a universal environmental concern, impacting terrestrial and aquatic ecosystems globally. This growing issue stems from their widespread use, slow degradation rates, and ability to traverse various environmental compartments, from the deepest oceans to the most remote terrestrial locations (Rillig 2012).

Microplastics have infiltrated numerous environmental settings through a variety of pathways. In terrestrial systems, they accumulate through activities such as the application of plastic protecting in agriculture, the use of soil amendments containing sewage sludge, and littering. These particles can enter the soil from atmospheric deposition, street runoff, and even wind transport (de Souza Machado et al. 2018). Once in the environment, microplastics persist due to their durable nature, with slow rates of natural degradation impairing their accumulation (Rillig 2012). Their presence is not confined to any single environment but spans a diverse range of ecosystems, including agricultural soils, freshwater systems, and marine environments. For example, microplastics have been detected in soils with concentrations as high as 30.7×10^3 particles per kg of dry sludge (Li et al. 2018), and their prevalence is increasingly noted in remote areas, often far from urban centers (Piehl et al. 2018). This widespread distribution underscores the universal nature of plastic pollution and highlights the challenges associated with managing and mitigating its impacts.

The effects of microplastics on terrestrial systems are complex and multifaceted. They can influence soil structure, nutrient dynamics, and microbial communities. For instance, microplastic fibers can affect soil aggregation and water retention, with varying effects depending on the type and concentration of microplastic present (de Souza Machado et al. 2018; Lozano et al. 2021). Similarly, the impact on soil microbial activity can be significant, with some studies showing increased mortality in soil macro-organisms and a decline in bacterial diversity due to microplastic contamination (Huerta et al. 2016). To better understand these effects, recent research has focused on evaluating the impact of different microplastic shapes and types on plant growth and soil health. Controlled experiments have tested how microplastic fibers, films, foams, and fragments of various polymer types and concentrations affect plant biomass, soil aggregation, and microbial activity. These studies aim to provide insights into the complex interactions between microplastics and terrestrial ecosystems, including the potential for microplastic particles to mediate or exacerbate environmental impacts based on their physical and chemical properties (de Souza Machado et al. 2018).

The marine environment is also significantly impacted by microplastics, which enter the ocean through numerous pathways, including runoff, atmospheric deposition, and direct disposal. The scale of marine microplastic pollution is so extensive that these particles are now considered a key marker of the Anthropocene, a term used to describe the current geological age viewed as the period during which human activity has been the dominant influence on climate and the environment (Cózar et al. 2014). Microplastics in the marine environment are particularly concerning due to their potential to be ingested by aquatic animals across various trophic levels, from plankton to larger marine animals. The accumulation of microplastics in marine habitats can cause physical harm to organisms, affect nutrient cycles, and lead to the transfer of toxic pollutants up the food chain (Teuten et al. 2009). The ecological impacts of microplastics in marine environments are profound and necessitate the need for extensive research to assess and mitigate their effects (Zarfl et al. 2011).

Microplastics exhibit a high degree of physical and chemical diversity. They vary in shape, ranging from fibers and films to foams and fragments, and in polymer type, including polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) (Khalid et al. 2021). Each polymer type can contain different additives and monomers that may pose specific hazards to environmental and human health. For example, polyurethane (PU), used extensively in flexible foams, is composed of monomers known to be highly toxic (Lithner et al. 2011). These polymers can affect soil biota and plant health through their chemical leachates and physical presence in the soil matrix. The degradation process of these materials further complicates the environmental impact, as plastics weather into smaller particles that can absorb various pollutants, including heavy metals and organic chemicals. The interaction between microplastics and these contaminants can enhance the toxicity of the particles, posing additional risks to both terrestrial and aquatic ecosystems (Hodson et al. 2017; Rochman et al. 2015).

Classification of Microplastics

Microplastics are categorized into different classes based on type of origin (primary and secondary microplastics), size, shape, and chemical nature.

Classification of Microplastics Based on Types

Microplastics are broadly classified into primary and secondary microplastics based on whether they are originally manufactured of that size (primary) or formed from the breakdown of large plastics (secondary).

Primary microplastics Primary microplastics are small plastic particles having less than 5 mm in size, manufactured with a specific purpose. These are not formed by the degradation of large plastics but are purposefully made small plastic particles. They can be found in various consumer and industrial products and reach the environment/living system through their use or disposal. They include microbeads, nurdles, and microfibers.

Microbeads are tiny plastic particles commonly used in personal care products such as exfoliating scrubs, toothpaste, and facial cleansers. Their primary function is to provide texture and abrasive properties. They are washed down and end up in aquatic environments and oceans. In response to environmental concerns, several countries have implemented bans on microbeads, but their legacy preserves (Liu et al. 2021). *Nurdles* are small plastic pellets used as raw material in the manufacturing of plastic products (pre-production plastics). These are often spilled during transport or production and are regarded as a major source of microplastic pollution. They are often lost during manufacturing, handling, and transportation processes. Spills of nurdles can lead to significant environmental pollution, particularly in marine environments where they are frequently found on beaches and in water. *Microfibers* are synthetic fibers, such as those from polyester, nylon, or acrylic materials, shed from textiles during manufacturing, processing, and washing. These microplastic fibers are released into wastewater systems and are often too small to be filtered out, leading to their accumulation in water bodies (Zhang et al. 2021).

Secondary microplastics Secondary microplastics originate from the degradation of larger plastic items. They result from the breakdown of plastic products over time due to environmental factors. Larger plastic items such as bottles, bags, packaging, etc. are brokendown into smaller particles through physical weathering, UV irradiation, and chemical degradation. Plastic fragments are the larger plastic debris, like bottles, bags, and containers, which break down into smaller pieces through exposure to sunlight, wave action, and physical wear (Zhang et al. 2021). These fragments contribute significantly to the growing microplastic content in oceans and soil. Foams are the expanded polystyrene (EPS) used in packaging and insulation that degrades into smaller foam particles. These are particularly harmful in marine environments, where they can be mistaken for food by marine organisms. Films are the plastic films used in agriculture (e.g., covering films) or packaging that degrade into smaller pieces when exposed to sunlight and environmental weather. These films can persist in soil and aquatic ecosystems for longer periods of time. This fragmentation process generates secondary microplastics that contribute to pollution in both terrestrial and aquatic environments (Lebreton et al. 2017).

Classification of Microplastics Based on Size

Microplastics are generally defined as plastic particles smaller than 5 mm. They are further categorized into mesoplastics, microplastics, and nanoplastics based on their size. Though their classification is controversial, this is generally an accepted classification (Ali et al. 2024).

Mesoplastics These are plastic particles with the size range of 0.5–5 cm. These particles are larger and more visible compared to other microplastics. They typically originate from the breakdown of larger plastic debris, such as plastic bags, bottles, and other consumer products. Mesoplastics are easily ingested by aquatic animals, such as small fish and seabirds, which can mistake them for food. This leads to physical harm and potential chemical contamination within the food chain/web.

Microplastics These are the plastics that have a range from 1 μm to 1 mm. These particles are more challenging to detect and are often generated through the wear and tear of larger plastic products, as well as microbeads and synthetic fibers. The major sources of microplastics are coming from the washing of synthetic textiles, personal care products containing microbeads, and weathering of larger plastics. These smaller particles can be ingested by plankton and other small aquatic organisms, leading to potential bioaccumulation in the food chain/web.

Nanoplastics These are plastic particles smaller than 1000 nm. Due to their tiny size, nanoplastics are not easily detectable with standard equipment, but their presence in the environment is increasingly being recognized. Nanoplastics often originate from the degradation of larger plastics or are manufactured intentionally for use in industrial processes. These nanoplastics can penetrate biological tissues and cells, which is a raising concern about their potential toxicity to aquatic life and human health. They are particularly concerning due to their ability to interact with living cells at the molecular level. Moreover, the classification of microplastics by size is critical because smaller particles tend to have more significant environmental and health impacts (Ali et al. 2024).

Classification of Microplastics Based on Shape

Microplastics are classified into six categories based on their shapes such as fragments, fibers, pellets, foams, films, and beads.

Fragments are the irregular shaped particles resulting from the breakdown of larger plastic items, typically through mechanical, thermal, or photodegradation processes. They are originated from the larger plastic products, such as containers, packaging, consumer goods, etc. Due to their sharp and jagged edges, fragments can physically harm aquatic organisms and are often mistaken for food (Cole et al. 2011).

Fibers/filaments are the thread-like, thin strands derived from synthetic textiles or fishing gear that are predominantly invented from washing synthetic fabrics, such as polyester and nylon, and from the wear and tear of ropes and fishing nets. These fibers are widely distributed in aquatic environments and easily ingested by plankton and small fish, causing physiological and biological impacts (Browne et al. 2010).

Pellets/nurdles are the spherical or cylindrical microplastics used as raw materials in the plastic manufacturing industry, and they are released to the environment during transportation or spillage in industrial processes. These are abundantly found along shorelines and marine environments, where they can be consumed by marine animals and birds, often causing ingestion-related issues (Thompson et al. 2004).

Foams are the lightweight, porous materials, often used for packaging or insulation, that break down into small, spongy particles, which are originated due to the breakdown of expanded polystyrene foam like Styrofoam and from disposable food containers and packaging. They are highly buoyant and float in surface waters, contributing to marine debris (Hidalgo-Ruz et al. 2012).

Films are the thin, flexible sheets or membranes of plastic that tear into smaller fragments while maintaining their flat shape. They are commonly invented from single-use plastic bags, agricultural films, and plastic wraps. These are the reasons for the blocking of light and gas exchange of the surface water (Thompson et al. 2004).

Beads are the small, spherical microplastics commonly found in personal care products and industrial abrasives, and they are the exfoliating agents in cosmetics, toothpaste, and other hygiene products. These are very dangerous and can pass through water filtration systems, entering aquatic ecosystems due to small size (Fendall and Sewell 2009).

Classification of Microplastics Based on Chemical Nature

Understanding the chemical composition of microplastics is critical to assessing their environmental fate and impact. Different types of plastics have unique chemical structures and composition that affect how they degrade, interact with pollutants and accumulate in ecosystems. Some of the major keys which help to identify the microplastics based on their chemical nature. They are thermoplastics, thermosetting plastics, elastomers, and biodegradable plastics (Zhang et al. 2021).

Thermoplastics are the plastics that can be repeatedly melted and reformed upon heating. They are characterized by their linear or branched polymer chains, which allow them to soften when heated. They are one of the keys to examine the chemical nature of microplastics. They make up the majority of plastic waste found in the environment, such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC). Due to their widespread use, thermoplastics are the most commonly found type of microplastic. Their degradation in the environment is slow, and they are resistant to chemical breakdown. Thermoplastics can absorb and transport hydrophobic pollutants, acting as vectors for other harmful chemicals in ecosystems (Andrady 2011; Geyer et al. 2017).

Thermosetting plastics are the plastics once hardened, cannot be melted or reformed, and the high cross-link and inflexible structure make them resistant to heat and chemical degradation. They are typically more rigid and durable than thermoplastics. Epoxy resins, polyurethane (PUR), and phenol formaldehyde (PF) are some examples of thermosetting plastics. Often due to their chemical stability, thermosetting microplastics may remain in the environment for long periods, contributing to long-term pollution and potential ingestion by aquatic animals.

Elastomers (rubber-like polymers) are the flexible, elastic materials that can stretch and return to their original shape. Elastomers like styrene-butadiene rubber (SBR), natural rubber, and silicone are widely used in the production of tires, footwear, and industrial products. They have a cross-linked polymer structure that provides the elastic properties. They are less rigid than thermoplastics and thermosets but are more resistant to mechanical wear and tear. These are commonly ejected to the environment from tires and contribute significantly to microplastic pollution in urban and roadside environments. Tire wear particles are one of the largest sources of microplastics in the environment (Kole et al. 2017).

Biodegradable plastics are designed to degrade more quickly in the environment, typically through microbial activity or under specific conditions. Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), and starch-based plastics are some main examples for the biodegradable plastic. These are often made from renewable resources like cornstarch and are intended to reduce environmental impact. However, their degradation often requires specific industrial composting conditions, and they may persist in natural environments (Tokiwa et al. 2009; Napper and Thompson 2019).

Sources of Microplastics

Microplastics from various sources are released into the environment through the degradation of various commonly used plastic items. They contribute to the primary or secondary microplastic sources (Anik et al. 2021). Some common sources include:

- *Degradation of larger plastics*: The breakdown of larger plastics of any type/source over time due to biotic or abiotic processes poses a significant contribution to the global microplastics release.
- *Plastic packaging*: Commonly used plastic packaging materials, such as films, containers, and wrappers, degrade into microplastics, mainly by sunlight exposure and environmental stressors.
- *Large plastic items*: Bottles, cans, cups, containers, and bags are widely used, and they break down into smaller particles and microplastics due to weathering, sunlight exposure, and mechanical forces.
- *Cosmetics and personal care products*: Many commonly used cleaning, cosmetics, and personal care products, such as toothpaste, carry microbeads made of plastic. After their use and wash-off, they finally end up in water bodies.
- *Paints and coatings*: Paints, polishes, and coatings are widely used in almost all items, and they degrade and deterioration over time, particularly after disposal, forms microplastics. Paints used on ships and boats also contributes to the microplastic formation.
- *Textiles*: Synthetic textiles and fabrics release shreds of fibers like polyester and nylon during manufacturing, processing, sewing and washing.
- *Vehicle tyres*: The synthetic rubber in tyres releases microplastic particles over time, or its disposal significantly contributes to the airborne microplastics.
- *City dust*: City dust comes from a variety of sources exposed to weathering, abrasion, and detergents that create a significant amount of microplastics.
- *Agricultural plastics*: Plastic coverings, films, and textiles used in agricultural fields can degrade into microplastics because of exposure to agricultural activities, weather conditions, and improper disposal.

In addition to the above, natural disasters, medical applications, like dentist tooth polishing, artificial grasses (turf) in the football pitch, unwise dumping of plastic garbage and landfill, etc., also significantly contribute to the production and release of microplastics into the environment (Anik et al. 2021).

Formation of Microplastics

Plastics are resistant to degradation and are known to have a longevity of hundreds or even thousands of years, depending on environmental conditions (Zhang et al. 2021). Still, various biotic and abiotic degradation processes do occur to form plastic fragments and microplastics, which are illustrated in Fig. 1.

Biotic Degradation of Microplastics

This is the deterioration of plastic due to the activities of microorganisms or biological products such as enzymes, resulting in the formation of microplastics. Microorganisms such as fungi and bacteria, and insects substantially contribute to this process. Physical degradation by biting, cutting, chewing, or digestive processes and biological degradation by various biochemical processes. Hydrolysis and enzymatic oxidation lead to chain scission and fragmentation of plastic. The plastic degraded by abiotic processes facilitates and increases the biotic degradation process and the formation of microplastics.

Abiotic Degradation of Microplastics

This is the change in physical or chemical properties of plastic by abiotic factors and processes resulting in the formation of microplastics. They include chemicals, heat, water, photodegradation, UV irradiation, and mechanical stress resulting in the oxidation, cross-linking, dehydrochlorination, chain scission, fragmentation and ablation processes, contributing to plastic degradation and microplastic formation.

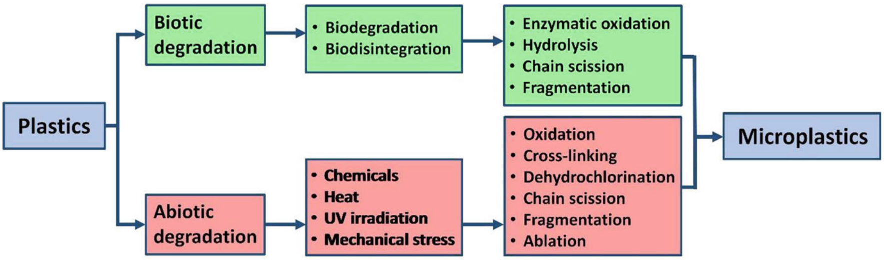

Fig. 1 Schematic diagram showing the processes involved in the biotic and abiotic degradation of plastic

Among these, photo degradation by solar irradiation is regarded as the most important contributing factor. The exposure of plastic to high temperature leads to a thermo-oxidative reaction causing the plastic to break down, which is related to the availability of oxygen and thermal properties of plastic. The photochemical reactions due to repeated exposure cycles (day-night cycle) for longer periods substantially contribute to the degradation process. In addition, the plastic degraded by biotic processes also facilitates the abiotic degradation process.

Entry of Microplastics to the Human Body

Microplastics can enter living organisms through several pathways, primarily through ingestion, inhalation, and dermal contact. These entry routes raise concerns about the bioaccumulation and potential toxic effects of microplastics and the chemicals they carry in the living system (Zhao et al. 2024). The potential routes of entry of microplastics and their distribution in the body have been illustrated in Fig. 2.

Ingestion

This is the entry of microplastics via the oral route by terrestrial and marine organisms, including plankton, fish, larger animals, and humans. These particles

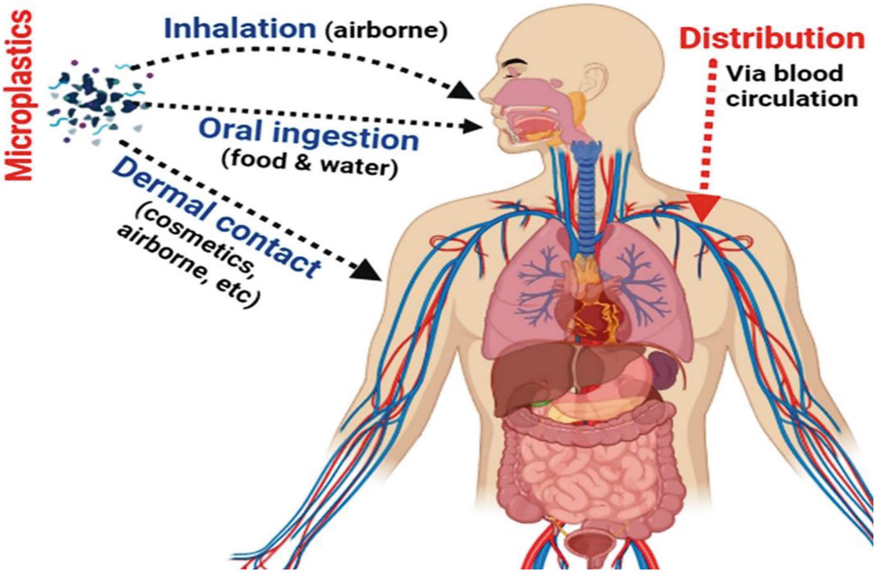

Fig. 2 Schematic diagram showing the pathways of entry of microplastics and their distribution in human body

are mistaken for food due to their small size and resemblance to prey (Cole et al. 2011). Once ingested, microplastics can accumulate in the gastrointestinal tracts of animals, leading to physical blockages, reduced feeding, and impaired growth. More alarmingly, microplastics can bioaccumulate and move up the food chain/web, affecting larger predators, including humans who consume seafood. Studies have documented the presence of microplastics in fish and shellfish, which are part of the human diet, raising concerns about their transfer into human bodies (Galloway et al. 2017). Once absorbed from the gastrointestinal tracts, they are distributed by the blood circulatory system to various parts of the body.

Inhalation

This is the entry of airborne microplastic particles, from synthetic clothing or dust from degraded plastics, via inhalation by humans and animals. Studies have shown that microplastics are present in indoor and outdoor air, especially in urban environments and near industrial activities (Dris et al. 2016). These particles can reach the respiratory system, leading to potential respiratory issues, especially with long-term exposure. In addition, the microplastics are absorbed from the lungs and respiratory tracts; they are distributed to various parts of the body by the blood circulatory system and make it available for exposure to other tissues as well.

Dermal contact

This is the absorption/entry of microplastics via penetrating the skin or absorption through open wounds. This could be active (using products that contain microplastics) or passive entry (via unintentional exposure). The presence of microplastics in air, dust, cosmetics, personal care products, etc., makes its way to the human body via skin contact. Once absorbed/entered, they are distributed by the blood circulatory system to various parts of the body (Zhao et al. 2024). The potential toxicity is, therefore, not just in the skin but to the entire body, the details of which have been given in the preceding section.

Potential Toxicity and Impact on Health

Impact on Animals

The intake of microplastics making a serious impact on the living organism is mainly based on their physical and chemical nature. Many animals, particularly aquatic organisms, mistake microplastics for food and ingest them. Ingested microplastics can cause physical blockages in the digestive system, leading to reduced feeding, impaired digestion, and malnutrition. Studies on marine species like fish, seabirds, and turtles have documented the accumulation of plastic particles in their stomachs, which can reduce the ability to digest the food and absorb nutrients and affect their survival (Lusher et al. 2017). In smaller organisms, such as plankton, microplastics can physically obstruct the feeding apparatus, reducing energy intake and growth (Cole et al. 2013). Moreover, microplastics can adsorb toxic chemicals, such as persistent organic pollutants (POPs), heavy metals, and other hazardous substances from the environment. When animals ingest microplastics, these absorbed chemicals can be released into their bodies, leading to potential toxic effects. Research has shown that microplastics can transfer harmful chemicals through the food chain, potentially impacting predator species and, ultimately, humans who consume contaminated seafood (Teuten et al. 2009). Some certain chemicals associated with plastics, such as bisphenol A (BPA) and phthalates, are known endocrine disruptors. When animals are exposed to these chemicals, they can interfere with hormonal regulation, affecting growth, reproduction, and development (Gallo et al. 2018).

Microplastic exposure has been linked to reduced reproductive success in animals. Studies have shown that invertebrates like oysters and fish species may suffer from reduced egg production, lower hatching success, and impaired larval development after exposure to microplastics (Sussarellu et al. 2016). These effects are likely due to both physical interference from microplastics and chemical toxicity. Also the intake of microplastics can cause physical damage to tissues when ingested or inhaled by animals. Studies have found that microplastics can lead to inflammation and oxidative stress in various organs, including the liver, intestines, and gills. For instance, in fish, microplastic exposure has been linked to liver stress and reduced immune responses (Lu et al. 2016). Inflammation and tissue damage caused by microplastics can impair an animal's overall health, making them more susceptible to diseases. Bioaccumulation and biomagnification are other serious issues for the animals due to the intake of microplastics. Microplastics and the chemicals they carry can accumulate in an animal's body over time, a process known as bioaccumulation. As smaller animals are eaten by larger predators, the concentration of microplastics and toxic chemicals can increase through biomagnification. This process is particularly concerning for top predators in marine and terrestrial ecosystems, including humans, as they can end up with high levels of toxicants due to their consumption of contaminated preys (Carbery et al. 2018). Also microplastics are causing behavioral changes in some animal species. Research on fish has shown that exposure to microplastics can alter normal feeding behaviors, making them less efficient at capturing prey or leading them to consume less nutritious food. These behavioral changes can reduce their overall fitness and survival chances (Savoca et al. 2016).

Impact on Humans

Microplastics are known to have potential toxicity to multiple organ systems in humans, which have been briefly described below and illustrated in Fig. 3. Studies

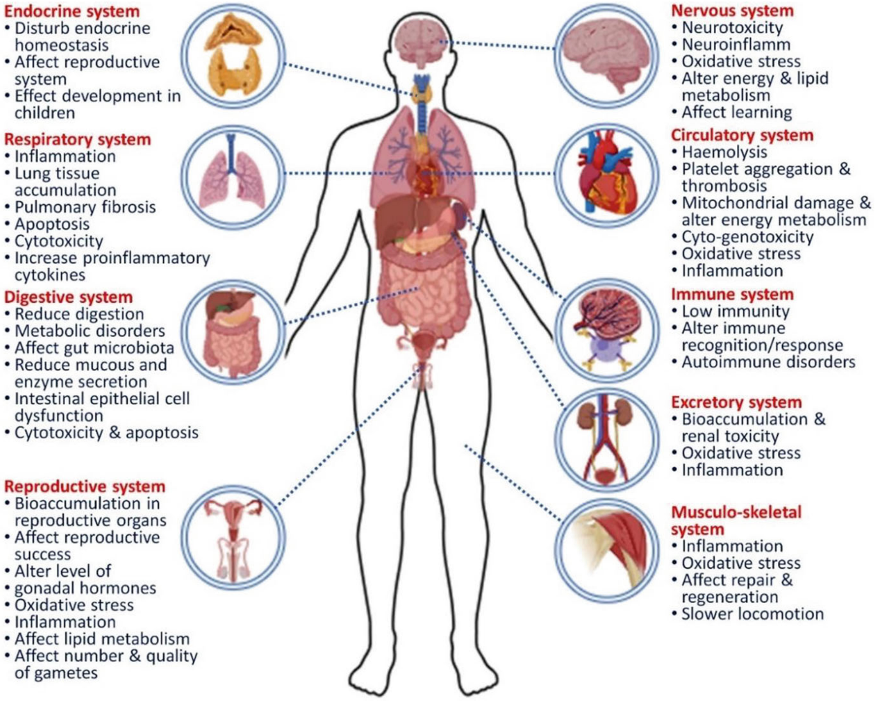

Fig. 3 Potential toxic effects of microplastics and impact on various physiological systems and human health

on naturally exposed animals and experimental conditions reported the toxicity to various physiological systems associated with the exposure to microplastics (Ali et al. 2024; Zhao et al. 2024).

Digestive System

The gastrointestinal tract serves as a predominant site of entry and accumulation of orally ingested microplastics along with the food. As discussed earlier, a wide variety of food materials serve as a potential source of microplastics and their entry to the living system. Microplastics liberated from the digested food can induce toxicity right within the intestine itself and other parts of the body after its absorption and distribution via blood circulation. The effects of microplastics associated with the digestive system include low mucus secretion in the intestine, intestinal barrier/epithelial cell dysfunction, hepatic metabolic disorders, inflammation, altered intestinal mucosal immunity, affected gut microbiome, oxidative stress, DNA damage, genotoxicity, and apoptosis. These effects were widely studied in a number of species, both naturally exposed animals and those under controlled experimental conditions.

Respiratory System

The airborne microplastics constantly enter the human body during respiration and absorb into the blood of alveolar capillaries and distribute to various parts of the body via systemic circulation. The immune system clears much of these entered microplastics but still retains a part of it, particularly the larger particles, which persist for longer periods. They can induce effects in the respiratory system and elsewhere. They can induce or worsen respiratory airway (nasal cavity, trachea, and bronchi) and interstitial lung diseases, such as asthma, bronchitis, emphysema, pneumonia, interstitial fibrosis, granuloma, and even cancer. Experimental studies showed that the inhaled microplastics cause lung injury and affect the integrity of the epithelial cell barrier, inflammation, ventilatory airway dysfunction, fibrosis, enhanced mucus secretion, oxidative stress, genotoxicity, and even death of epithelial cells.

Circulatory System

Microplastics enter to human body via inhalation, oral ingestion, and dermal contact and finally reach the cardiovascular system, and therefore, significant toxicity is obvious. Experiments conducted in different animals following microplastic exposure showed cardiovascular dysfunction, impaired cardiac output, pericardial edema, disturbed angiogenesis, endothelial dysfunction, generation of ROS, oxidative stress, systemic inflammation, interstitial hyperplasia, collagen deposition and apoptosis in cardiomyocytes, mitochondrial dysfunction, promote aortic inflammation, vascular injury, and coagulation dysfunction. These toxic effects of microplastic exposure observed in zebra fish, rat, and chicken could be correlated with human physiology and therefore similar effects are apparent.

Reproductive System

The detection of microplastics in the gonads is a clear indication that microplastics can cross the blood barrier within the gonads (Zhao et al. 2024). The effects on gonads and the whole reproductive system in males include affecting reproductive fitness, declining the number and quality and mortality of sperm, malformation, DNA damage, and abnormal testosterone levels. Toxicity to the female reproductive system includes impaired follicular growth, decreased follicular cell production and oocyte maturation, necrosis, apoptosis, inflammation, and oxidative stress.

Nervous System

Experiments conducted in animals showed microplastics accumulation in the cerebral cortex hippocampus, and cerebellum after oral exposure and consequently showed effects on the normal functioning of the nervous system. These include reduced learning and memory, low production of neurotransmitters and synaptic proteins, neuroinflammation, behavioral changes, neurodegeneration, affected protein and energy metabolism, neuronal damage, variation in cytokine production, and apoptosis.

Immune System

It has widely been reported that the microplastics compromise the immune system. It causes a local immune response in the intestine to the orally ingested microplastics, excessive mucus secretion, affects lymphocyte and neutrophil activation, alters gut microbiome and inflammatory disorders, alters serum cytokine levels, affects the complement system, inhibits T cell activation and differentiation, etc. Moreover, the affected immune system compromises the normal immunity and can cause other infections and diseases as a secondary consequence of the microplastics exposure.

In addition, the exposure of microplastics can affect the endocrine system, both at the level of gland and target tissue, by altering the hormone production and action, affecting hormone receptors, affecting hormone gene expression and overall endocrine homeostasis. Moreover, plastic monomer additives such as phthalates and bisphenol A are known endocrine disruptors. In the excretory system, renal toxicity, oxidative stress, bioaccumulation, and inflammation are reported, which again affect the overall physiology of the body. Effects on the musculoskeletal system include inflammation, oxidative stress, altered repair and regeneration processes and lower locomotion.

Interaction with Organic Pollutants, Heavy Metals, and Pathogens

Microplastics can also interact with organic pollutants, heavy metals, and pathogens and cause secondary effects too. Due to strong hydrophobicity and large surface area, they can adsorb and act as vectors to carry the pollutants and pathogens to humans. Microplastics and organic pollutants often co-exist in the same environment, and therefore, they simultaneously enter the living system together, and consequent bioaccumulation and toxic effects are obviously far higher. Heavy metals such as arsenic, cadmium, and lead can adsorb on microplastics, and they enter the human body together. Consequently, their additive toxic effects are extremely high. Studies suggest that microplastics carry and transport viral (e.g., SARS-Cov-2) and bacterial (e.g., *Helicobacter pylori*, causing peptic ulcers) pathogens, indicating the capacity of microplastics to transmit infectious diseases too (Zhao et al. 2024).

Impact on Ecosystem and Environment

Microplastics have become a universal pollutant in both aquatic and terrestrial ecosystems, posing significant risks to the environment. The environmental health issues caused by microplastics stem from their persistence, ability to transport harmful chemicals, and their detrimental effects on ecosystems and organisms. They are commonly found in soils and terrestrial ecosystems due to activities like plastic waste dumping, agricultural practices, and the use of plastic covering films. When microplastics accumulate in the soil, they can alter its physical and chemical properties. Microplastics can change soil structure by affecting porosity and water retention capacity. They can reduce water infiltration, which impacts soil aeration and water availability for plants. Earthworms, insects, and soil microbes are essential for nutrient cycling and soil health. Studies have shown that microplastics can negatively affect earthworms by reducing their growth and reproductive capacity (Rillig et al. 2017). Previous studies show that polyethylene microplastics reduce the survival and burrowing behavior of earthworms, which can affect soil aeration and nutrient availability (Huerta et al. 2016). Some microplastics are affecting plant growth by altering nutrient availability and by causing physical barriers to root growth. Some studies suggest that plants exposed to microplastics may exhibit stunted growth, reduced seed germination, and lower yields (Boots et al. 2019).

The most significant and well-documented impact of microplastics occurs in marine and freshwater ecosystems. Microplastics are now ubiquitous in oceans, rivers, and lakes, and their persistence in these environments has far-reaching consequences. Many aquatic organisms, from plankton to fish and marine mammals, mistake microplastics for food. Ingestion of microplastics can lead to blockages in the digestive system and reduced feeding and energy intake, which can impair growth and reproduction. The ingestion of microplastics has been observed in species as diverse as zooplankton, shellfish, and seabirds (Lusher et al. 2017). This has cascading effects on the food web, as compromised species can reduce the availability of prey for predators. Also microplastics, particularly floating types, can accumulate on the surface of water bodies, forming floating “plastic soups.” These floating particles can block sunlight penetration, disrupting photosynthesis in aquatic plants and phytoplankton. Reduced sunlight can affect the entire aquatic ecosystem, leading to decreased oxygen production and altered food chains (Thompson et al. 2004).

Microplastics not only pose physical threats to ecosystems but also act as vectors for harmful chemicals. These particles can absorb/adsorb pollutants from their surrounding environment, including heavy metals, persistent organic pollutants, and endocrine-disrupting chemicals. When organisms ingest microplastics, these absorbed toxins can enter their bodies and accumulate in tissues, leading to bioaccumulation and biomagnification through the food chain (Teuten et al. 2009). Moreover, microplastics in the marine environments have been shown to carry chemicals such as polychlorinated biphenyls and polycyclic aromatic hydrocarbons. These chemicals are linked to a range of adverse effects, including immune suppression, reproductive issues, and developmental problems in marine life (Koelmans et al. 2015). As microplastics are consumed by smaller organisms, they can accumulate and concentrate in the bodies of these organisms. Predators that feed on these contaminated species may, in turn, ingest larger amounts of microplastics and the toxic chemicals they carry. This process, known as biomagnification, causes the concentration of microplastics and toxins to increase as they move up the food chain, potentially affecting larger predators such as fish, birds, and even humans (Carbery et al. 2018). The presence of microplastics in natural habitats can contribute to a decline in biodiversity. As species ingest microplastics or experience habitat degradation, their populations may suffer, leading to reduced biodiversity. Some species may be more vulnerable than others, and microplastic pollution could push already threatened species toward extinction. Decreased biodiversity weakens ecosystem resilience, making ecosystems less capable of withstanding additional environmental stressors such as climate change (Galloway et al. 2017).

Microplastics are not limited to terrestrial and aquatic environments; they have also been found in the atmosphere. Wind and air currents can carry microplastic fibers and fragments across vast distances, depositing them in remote regions, including mountains and polar areas. Airborne microplastics may contribute to air pollution and be inhaled by both animals and humans, leading to respiratory issues (Dris et al. 2016). Moreover, the abundance of microplastics in the atmosphere does cause climate change. Plastics, when exposed to sunlight, release greenhouse gases such as methane and ethylene. As microplastic pollution increases, the amount of plastic exposed to sunlight in oceans and terrestrial ecosystems may contribute to rising greenhouse gas emissions, exacerbating climate change (Royer et al. 2018).

Control Measures

The widespread presence of microplastics in both terrestrial and aquatic environments poses significant threats to ecosystems and human health. Effective control measures are essential to reduce their impact, focusing on preventing plastic waste generation, improving waste management systems, and implementing policy and technological innovations.

Decrease Plastic Manufacture and Use

A crucial strategy to control microplastic pollution is reducing the overall production and use of plastic materials, particularly single-use plastics. By minimizing the amount of plastic that enters the environment, the generation of microplastics can be significantly reduced. Banning single-use plastics is one of the easy methods to reduce the microplastic accumulation. Many governments have already enacted bans on single-use plastic products like plastic bags, straws, and cutlery. These items are major contributors to plastic waste, which eventually degrades into microplastics. For instance, the European Union implemented the Single-Use Plastics Directive, which aims to reduce the consumption of such plastics across member states. Along with banning, encouraging the development and use of biodegradable or compostable materials as alternatives to conventional plastics can mitigate the formation of microplastics. Biodegradable plastics derived from natural sources, such as starch and cellulose, degrade more quickly in the environment and produce fewer harmful byproducts (Napper and Thompson 2019). Extended producer responsibility (EPR) is the program that holds producers accountable for the end-of-life management of their products, incentivizing companies to design products that are easier to recycle or that generate less waste. This can help reduce the overall amount of plastic waste that becomes microplastic over time (Organization for Economic Cooperation and Development (OECD) 2016).

Enhanced Waste Management Systems

Improving waste management infrastructure is vital for reducing the release of microplastics into the environment. Ineffective waste management, particularly in low- and middle-income countries, leads to the breakdown of plastic waste into microplastics. The advanced recycling technologies, such as chemical recycling, can improve the recycling rates of plastic waste and reduce the amount of plastic that ends up in landfills or the environment. Chemical recycling breaks down plastics into their chemical components, which can be reused to create new plastics without producing microplastics (Geyer et al. 2017). Moreover, implementing better landfill containment measures, such as proper lining and covering, can help reduce the leakage of plastic particles into the environment. Additionally, regulating plastic waste disposal and promoting waste diversion through recycling and composting can significantly decrease the amount of plastic that decomposes into microplastics (Browne et al. 2010).

Upgrading Wastewater Treatment Plants

Wastewater treatment plants are critical in preventing microplastics from entering aquatic ecosystems. However, current filtration technologies are often insufficient to capture the smallest microplastic particles. Technologies such as membrane bioreactors (MBRs), sand filtration, and nanofiltration are more effective at capturing microplastics from wastewater before it is released into rivers and oceans (Carr et al. 2016). Incorporating these technologies into existing wastewater treatment plants can significantly reduce microplastic pollution. Also, governments can implement policies that limit the permissible levels of microplastics in treated wastewater. Some countries, such as Germany, have already set limits on the release of microplastics from wastewater treatment plants (Magnusson and Norén 2014).

Control of Microplastic Pollution from Textiles

The synthetic fibers from textiles, such as polyester, are a significant source of microplastic pollution, especially when released during washing. Installing filters in washing machines to capture microfibers is an effective way to reduce the release of microplastics from synthetic textiles. Some countries are exploring regulations that would require new washing machines to be equipped with microfiber filters (De Falco et al. 2018). Manufacturers can design textiles that shed fewer microfibers during washing by using tighter weaves or blended natural fibers. Research has shown that garments with tighter construction and natural materials produce significantly fewer microplastic fibers compared to synthetic alternatives (Hartline et al. 2016).

Regulation on the Use of Microplastics in Cosmetics

Microbeads, commonly used in personal care products like exfoliants and toothpastes, are a well-known source of microplastic pollution. Countries like the United States, Canada, and the United Kingdom have enacted bans on the use of microbeads in cosmetics and personal care products. These bans are effective in preventing microbeads from entering aquatic systems, where they are difficult to remove (Oberoi and Garg 2021).

Public Awareness and Education

Educating the public about the environmental and health impacts of microplastics can drive behavior change and increase support for plastic reduction initiatives. The governments, NGOs, and environmental organizations can launch campaigns that inform consumers about the sources of microplastics and how to minimize plastic use. Public pressure can encourage companies to reduce plastic packaging and adopt more sustainable practices (Oberoi and Garg 2021). Labeling products that are free from microplastics or that contain sustainable materials can help consumers make informed choices. Eco-labeling schemes, such as the Blue Angel label in Germany, guide consumers toward environmentally friendly products (Gasperi et al. 2018).

Future Perspectives of Research

Future research on microplastic control is likely to focus on several innovative approaches aimed at preventing, mitigating, and remediating plastic pollution (Anik et al. 2021). One promising avenue is the development of advanced biodegradation technologies, such as the use of plastic-degrading enzymes like PETase, which could be engineered to break down microplastics more effectively in natural and engineered environments (Austin et al. 2018). Further research into nanotechnology and catalytic processes may also yield new methods for accelerating the degradation of microplastics at a molecular level, turning them into non-toxic substances. Improving wastewater filtration systems to capture smaller plastic particles, such as nanoplastics, is another priority, with innovations in membrane filtration and adsorbent materials showing potential for more efficient microplastic removal. Additionally, interdisciplinary research exploring the ecotoxicological impacts of microplastics on ecosystems and human health will be essential to inform regulatory frameworks. Ultimately, addressing microplastic pollution will require a combination of technological innovation, policy development, and public awareness, making it a vital area for future scientific inquiry.

Conclusion

Microplastics pose significant environmental and health risks, primarily due to their persistence, small size, and ability to carry toxic chemicals. Classified into primary and secondary microplastics, they originate from a variety of sources, including personal care products, industrial processes, and the breakdown of larger plastics. Microplastics are further categorized by size, shape, and chemical composition, influencing their behavior in ecosystems and living organisms. They enter the food chain through ingestion, inhalation, or skin contact, leading to bioaccumulation and toxic effects in animals and potentially humans. Microplastics also disrupt ecosystems by affecting soil health, marine life, and biodiversity. Effective control measures, such as reducing plastic waste, improving waste management, and implementing policy changes, are crucial to mitigating the impacts of microplastics on the environment and human health.

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