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Microplastics in Our Environment: Assessing Sources, Fate, and Health Impacts

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Abstract

Microplastic pollution, a pervasive environmental issue, has garnered significant global attention due to its adverse impacts on human health and ecosystems. This review paper examines the origins, environmental behaviour, and consequences of microplastics, which are plastic particles less than 5 mm in size. The ubiquitous presence of microplastics in aquatic, terrestrial, and atmospheric environments poses significant hazards to human health and biodiversity. Microplastics infiltrate the food chain by being ingested by marine organisms, accumulating in higher trophic levels, and ultimately becoming available to humans. This review focuses on the potential health impacts, environmental behavior, and numerous sources of microplastics. Additionally, it underscores existing mitigation initiatives, including the circular economy, recycling, and waste management, while advocating for more stringent regulations and public education to reduce plastic contamination. Safeguarding public health and ecosystems necessitates sustainable consumption practices, technological innovation, and global collaboration to address the microplastic crisis.

Introduction

The quantity of human-produced debris in both water and land ecosystems has surged significantly in recent decades, with around 60-80% of this debris being composed of plastic (Akdogan & Guven, 2019). Large-scale plastic production began in the 1950s and presently exceeds 280 million metric tons (MMT) globally (Plastics Europe, 2017). A study by Jambeck et al. (2015) states that coastal countries contribute between 4.8 and 12.7 MMT of improperly managed plastic waste to the oceans each year. Since 1950, global plastic production surged significantly, aimed at enhancing human well-being. By 2015, production had nearly reached 381 Million metric tons (Padervand et al., 2020). Unfortunately, this surge has resulted in widespread plastic pollution, making plastics a major issue as pollutants (MacArthur et al., 2016). In 2019, global plastic production reached approximately 368 million metric tons, with half of this production occurring in Asia (Tiseo, 2021). By 2050, it is estimated that plastic waste in landfills or natural environments will surpass 12 billion

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metric tons, marking an increase of over 250% compared to the 4.9 billion metric tons generated in 2015 (Geyer et al., 2017). The COVID-19 pandemic caused a slight de crease in plastic production in 2020, with around 367 MMT being produced, representing a 0.3% decline. However, the production of facial masks has led to a notable rise in plastic production following the COVID-19 pandemic (Lamichhane et al., 2023). Plastics are highly persistent, resulting in delayed breakdown and rapid accumulation. At present, there is growing international concern among scientists about the pervasive presence of microplastics — tiny plastic particles with significant environmental impacts, as highlighted by research from Vaid et al. (2021) and Wright et al. (2013). Microplastics (MPs) are plastic fragments that range from 5 mm to 1 µm in size, assessed along their longest dimension. The composition includes several polymers such as polyethylene (PE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) (Crawford & Quinn, 2017). MPs are small plastic particles that pollute the environment and are significantly more prevalent than other forms of plastics because of their durability.

MPs greatly influence ecosystems across marine, freshwater, and terrestrial environments globally (Prabhu et al., 2022). The term "microplastics" was initially introduced 19 years ago by Thompson et al. (2004) during their investigation of plastic pollution in the UK's oceans. Since then, MPs have garnered the interest of the scientific community, governments, non-governmental organizations, and various other entities. Evidence suggests that MPs pose serious risks to ecosystems and human health (Osman et al., 2023). Plastics emerged as novel materials in the latter part of the previous century (Gündogdu and Çevik, 2017). However, their extensive manufacturing and utilization across several industries have posed a substantial environmental hazard (Qasim et al., 2021). Due to their small size and high surface-to-volume ratio, MPs can absorb inorganic pollutants and persistent organic pollutants from their environment, potentially causing harmful effects on organisms when they are exposed (Lee et al., 2014). Various organic substances contaminate MPs, each with significant health impacts, as detailed in Table 1. MPs have a notable environmental impact, entering soil and water through wind, rainfall, surface runoff, and atmospheric deposition. The environmental behaviours of MPs, such as aggregation, migration, and degradation, are influenced by their physicochemical characteristics, including size, color, shape, density, composition, and surface charges (Lambert & Wagner, 2016). Previous studies have shown that microplastic pollution is present in various environments, such as mountainous regions, lakes (Sighicelli et al., 2018), the remote Gobi Desert with limited human influence, and karst groundwater (Panno et al., 2019).

Due to their tiny dimensions, MPs can be taken in by organisms, infiltrate the food chain, move through it, and accumulate in higher trophic levels (Deng et al., 2020). In recent decades, microplastic pollution has emerged as a major environmental issue because of its widespread presence in numerous ecosystems worldwide. The investigation of MPs is essential for understanding their impact on human health and the environment, as their repercussions can be extensive. The widespread prevalence of MPs poses substantial hazards to wildlife, as numerous marine species consume these particles, mistakenly perceiving them as food and nourishment. Ingesting MPs can cause physical injury and potentially harmful effects due to the presence of compounds, such as additives and absorbed pollutants from the environment (Campanale et al., 2020; Kaban et al., 2021). This review is driven by the growing global concern about MPs in marine, freshwater, terrestrial, and atmospheric ecosystems. The problem of microplastic pollution is internationally acknowledged as an urgent environmental issue. However, substantial knowledge gaps remain regarding the full range of its effects, especially the

Table 1 Organic substances contaminating microplastics and their health impacts

Contaminant	Source	Health Impact	Reference
Persistent organic pollutants (POPs)	PCBs, PAHs, Dioxins	Endocrine disruption, carcinogenicity, reproductive toxicity	Bakir et al. (2014)
Plastic additives	Bisphenol A (BPA), phthalates, flame retardants	Hormonal disruptions, developmental defects, cancer risks	Prata et al. (2019)
Hydrophobic organic chemicals (HOCs)	Environmental adsorption	Oxidative stress, neurotoxicity, cellular damage	Ziccardi et al. (2016)
Polycyclic aromatic hydrocarbons (PAHs)	Environmental adsorption	Immune suppression, oxidative stress	Pittura et al. (2018)
Neurotoxic and genotoxic substances	Contaminants and additives	Oxidative stress, inflammation, DNA damage, increased risk of neurodegenerative diseases and cancer	Barboza et al. (2018)

potential threats to human health. Gaining an in-depth understanding of microplastic pollution is essential to formulate effective measures and policies to mitigate their negative effects on ecosystems.

Microplastic sources in the environment

MPs can be classified into two categories: primary and secondary MPs, depending on their source (Duis & Coors, 2016; Smith et al., 2018; Avio et al., 2017). Primary MPs are tiny synthetic polymers used as exfoliants in various processes, such as the production of synthetic clothing, the upkeep of plastic items, and the creation of chemical formulations (Ziani et al., 2023). Their main sources are plastic pellets, personal care products, washing wastewater, paint, and sewage treatment plants.

1. Plastic pellets

Plastic pellets are small, granular pieces of plastic, usually measuring 2-5 mm in diameter. They are commonly used in the production of various plastic goods (Karlsson et al., 2018). These materials are predominantly derived from petroleum and coal and are classified into two categories: thermoplastics and thermoset plastics. Plastic pellets find extensive application across multiple sectors, including consumer products, construction, and automotive industries. Due to their long-lasting nature and small dimensions, they undergo gradual degradation in the environment and pose hazards to both wildlife and human health by entering the food chain.

2. Personal care products

Microbeads are tiny, processed particles used in personal care products as alternatives to synthetic pigments for cosmetic effects like cleansing and exfoliation. They can be categorized into two types (Leslie, 2015): thermoplastics and thermoset plastics. Notably, polyethylene microbeads constitute 93% of the total microplastic beads (Gouin et al., 2012). Typical products that contain microbeads include facial cleansers, toothpaste, sunscreen, shower gel, and hair dye. Due to their tiny size, inability to dissolve, and gradual breakdown, microbeads find their way into sewage systems along with wastewater. Current sewage treatment methods fail to adequately eliminate these MPsMPs, allowing their release into the environment via sewage sludge, which is frequently utilized in agricultural practices.

3. Washing wastewater

Substantial quantities of plastic microfibers are released into the environment during the washing process, which encompasses wastewater from domestic laundry and washing facilities. These microfibers are predominantly sourced from synthetic fabrics made of polyamides and polyesters. A single wash can result in the shedding of over 1,900 microfibers from each item of clothing. Unfortunately, wastewater treatment plants are incapable of eliminating these MPs (Cheung & Fok, 2017), enabling them to infiltrate the environment via discharged effluent or sludge. Research indicates that plastic microfibers are the predominant form of MPs identified in various ecosystems, including soil, rivers, and oceans (Horton et al., 2017).

4. Paint

Pigments, fillers, solvents, and minor quantities of beneficial ingredients constitute paint in general. Depending on their intended use, coatings can be categorized into marine, automotive, architectural, and aerospace coatings. They can also be categorized based on the materials used to produce the film, including natural resin, phenolic, alkyd, epoxy, and other varieties. Research indicates that the process of painting may produce minuscule plastic particles, which are then discharged into the surroundings through aging, erosion, and abrasion. Environmental MPs are primarily caused by painting, especially from architectural coatings (such as paint peeling from buildings), maritime coatings, automobile coatings, and road-marking paint (Wang et al., 2019).

5. Sewage treatment plants (STPs)

Sewage treatment facilities are exposed to various MPs originating from plastic manufacturing, personal care items, chemical laundry products, and tire degradation. These MPs enter the system through household sewage, industrial waste, and surface water discharge. Although treatment processes remove over 90% of MPs, effluents from these facilities are one of the largest sources of microplastic pollution in natural waters, as they are directly discharged into surface water (Murphy et al., 2016). MPs in sewage sludge predominantly result from sedimentation during treatment, with over 98% of MPs in influents accumulating in sludge (Magnusson et al., 2016). However, due to the lack of standardized methods for MPsmicroplastic removal from sludge, its use in composting and agriculture results in the introduction of MPs into the soil (Corradini et al., 2019).

Secondary MPs form when macro-or mesoplastics, fragment due to various environmental processes, including biodegradation, photodegradation, thermo-oxidative degradation, thermal degradation, and hydrolysis (Sharma & Chatterjee, 2017). Their production occurs in two distinct phases: in-use fragmentation and post-use fragmentation. In-use fragmentation occurs through processes such as tire degradation, microfiber release during laundry, and the deterioration of fishing equipment (Carney et al., 2018; Welden & Cowie, 2017). Furthermore, plastics in use can degrade due to animal activity—for example, MPsdigging isopods and polychaetes create MPs while burrowing in polystyrene (PS) floats (Davidson and Dudas, 2016; Jang et al., 2018). Post-use fragmentation refers to the breakdown of abandoned or discarded plastics. Secondary sources of MPsMPs include municipal debris, fishing waste, agricultural film.

6. Municipal debris

This category includes items like plastic bottles, bags, and disposable cutlery. Plastic bags are produced by blending different types of plastic with additives and then heat-sealing or gluing the mixture. Common plastics used include PET, PE, HDPE, PVC, among others. Plastic bags are widely utilized because of their affordability, light weight, and ease of production. Global consumption of plastic bags reaches up to 5 trillion annually. Made from materials like PET, PE, and PP, plastic bottles are produced through processes such as blow moulding and injection moulding. They are primarily used as disposable containers for liquids and solids, including beverages and food items. Plastic bottles are favoured for their convenience, hygiene, affordability, and transparency. It is currently estimated that one million plastic bottles are sold globally on every minute (An et al., 2020). Single-use plastic tableware, which is manufactured through thermoplastic moulding of resin or similar materials, includes utensils, straws, plates, and lunch cases. These items are favoured worldwide for their affordability, portability, waterproof qualities, and durability.

7. Fishing wastes

A wide variety of objects, including buoys, floating containers, fishing poles, aquariums, nets, lines, and wires, make up plastic fishing waste. Every year, people around the world discard commercial fishing gear weighing anywhere from 0.13 to 135,000 tons (Merrel, 1980). The aquaculture industry contributes to marine plastic pollution by discarding excessive amounts of feed sacks, while the use and disposal of plastic fishing nets and gear add to the problem. These nets, primarily made from materials like PE, LDPE, nylon, and PP, shed fibers after entering the ocean (Lu et al., 2018; Yong et al., 2014). Maritime accidents further exacerbate the issue by releasing plastic products into the sea.

8. Farming film

Plastic films used in agriculture are a substantial source of environmental MPs. Typically produced from polyvinyl chloride (PVC), polyethylene (PE), and other polymers, these films have been employed since the 1950s to elevate soil temperature, reduce soil contamination, and enhance crop yield, thus strengthening food security. However, their extensive utilization, brief lifespan, and inadequate recycling efficiency pose challenges in recovery and contribute to the release of MPs into the soil. The largest consumer of plastic film mulch is China, with 143.37 million tons consumed in 2017 (National Bureau of Statistics of China, 2018). These MPs have the potential to negatively affect human health, enter the food chain, be ingested by crops, reduce agricultural productivity, and pollute the soil.

Properties of microplastics

The environmental behaviour and toxicity of MPs are profoundly influenced by their physical attributes—size, density, colour, shape, and crystallinity—which are often assessed using microscopes (Wright et al., 2013). The dimensions of MPs are a critical aspect of MPs study, varying according to the collection and separation techniques applied, as well as the pore size of the filter membrane used (Cai et al., 2020). Accurately measuring the dimensions of MPs is crucial in scientific investigations, as size is the primary characteristic that differentiates thisnovel form of pollutants from traditional ones (Ho et al., 2000). Research indicates that the dimensions of MPs influence counting precision: smaller particles correlate with increased error rates, while larger particles are associated with reduced error rates (Lenz et al., 2015). MPs that are less dense than water will either float on the surface or remain suspended in the water making them susceptible to consumption by creatures that inhabit the upper and middle layers of water (Hidalgo-Ruz et al., 2012). The colour of MPs can indicate their probable sources and affect their persistence and breakdown in the environment. Colourful samples are more readily identifiable, and the degree of fading can signify the duration of exposure (Andrady et al., 1993;

Turner et al., 2011). MPs, present in diverse forms such as films, foams, and fibers, significantly influence environmental adsorption, desorption, and ecological impacts. Their morphology can offer traceability and data on their existence, with pellets, thin films, pieces, foams, and fibers being the predominant categories (Muller et al., 2018). Crystallinity, a characteristic of polymers, denotes the mass or volume ratio of crystalline areas. The range is from 30% to 85%, affecting the mechanical characteristics of MPs (Guo et al., 2012). Polymers can be classified into three categories: crystalline, semicrystalline, and amorphous polymers. However, there are no crystallinity polymers. Environmental MPs undergo progressive modifications in their crystallinity over time due to the selective transformation of amorphous polymers or the rearrangement of polymer chains at the molecular level (Stark et al., 2004; Rouillon et al., 2016). The chemical composition and surface groups of MPs are the primary determinants of their chemical properties. These materials consist of polymers, additives such as antioxidants and plasticizers, and contaminants that adhere to their surface. During the manufacturing, usage, and decomposition of plastics, these chemical substances are readily released into the environment (Gandara et al., 2016; O'Connor et al., 2016). A significant portion of the environmental impact of MPs is due to their discharge, particularly PVC, which is considered highly hazardous because of its elevated chlorine content and the emission of dioxins (Paluselli et al., 2018). The physical characteristics of polymers, including molecular size, degradation level, and porosity, are associated with the rate at which chemical substances leach (Hermabessiere et al., 2017). The release of additives can be significantly enhanced by surface deterioration, with the extent of the effect depending on the concentration and distribution coefficient of the compounds within the original plastic (Hahladakis et al., 2018). The diversity of surface groups in primary MPs, influenced by artificial modifications, affects their interactions with chemicals and alters their surface oxidation capacities (Lambert & Wagner, 2016). Conversely, environmental MPs undergo ongoing oxidation processes, leading to a progressive rise in their surface group content as they age and degrade (Song et al., 2017). To evaluate the behaviour of MPs in the environment and their potential impact on human health and ecosystems, it is imperative to analyze their physical and chemical properties (Ahmed et al., 2022; Cai et al., 2019).

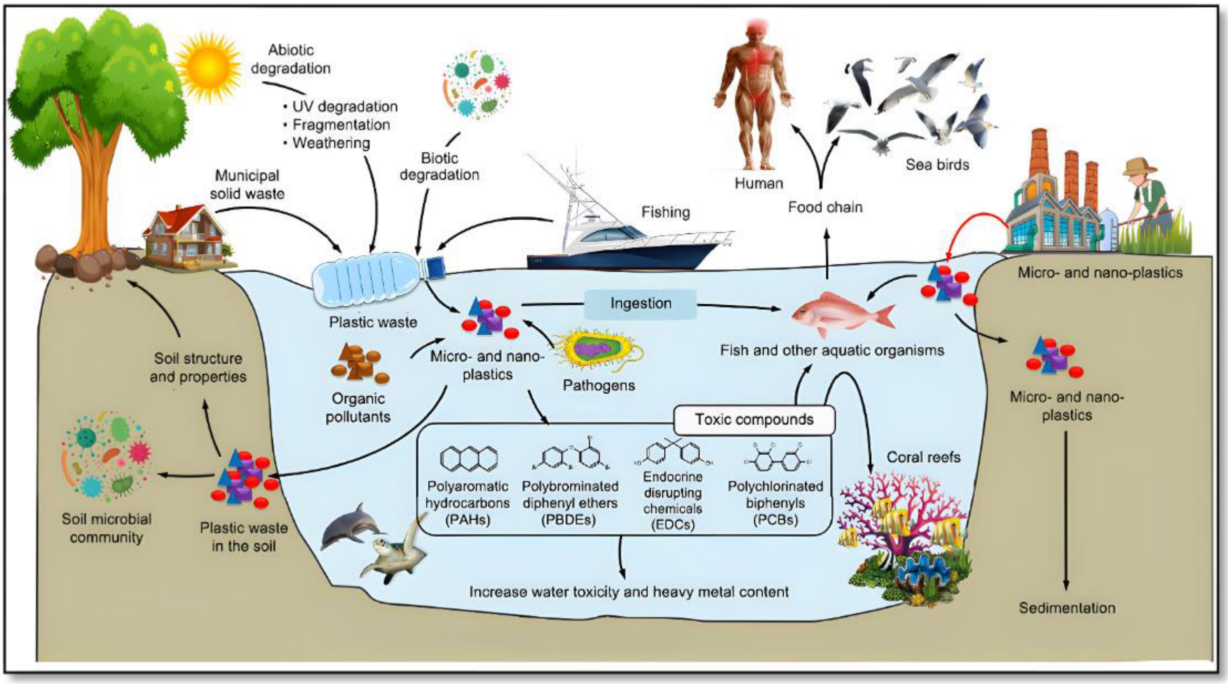

Fig. 1 Aquatic microplastics' source, life cycle, and effects on humans, animals, and plants (Ali et al., 2024, used with permission)

Microplastics in the environment

1. Aquatic environment

In aquatic systems, the spatial distribution of MPs is influenced by factors such as concentration and contamination, which affect marine species. Lower-density MPs remain buoyant, while higher-density ones settle in sediment after fragmentation (Kane et al., 2019). Subsequently, MPs are exchanged among biota, water, and sediment through bioturbation, ingestion, and excretion, as illustrated in Fig. 1.

The introduction of freshwater and turbulence can disrupt the migration of MPs in aquatic environments. A recent study utilizing modeling approaches found that the mobility of MPs in rivers is substantially affected by water flow, which then influences their transit into aquatic ecosystems (Besseling et al., 2017). Studies have demonstrated that invertebrates, fish, birds, and marine mammals can consume MPs in aquatic biota. Upon ingestion, they transfer toxic chemicals that are either adsorbed onto the MPs during emission and transportation or added as additives during the manufacturing process (Song et al., 2015). Despite the anticipation of substantial quantities of MPs in aquatic biota, there is no experimental evidence that MPs are capable of passing high concentrations of pollutants to tissues or impairing the functions of organisms MPsMPs (Browne et al., 2013). Consequently, this domain necessitates intensive future research. Without adequate filtration or treatment, the presence of MPs in drinking water has a direct impact on human health, potentially resulting in diseases such as cancer and genetic abnormalities (Ali et al., 2021a; Ali et al., 2021b). Both primary and secondary MPs can invade marine ecosystems. Macro- and mega-plastics occasionally find their way into the environment and break down into MPs and Nanoplastics (Fotopoulou et al., 2017). Contamination by MPs is a significant issue in marine and freshwater ecosystems, with prevalence documented in Europe, Africa, Asia, and North America. MPs have a stronger correlation with their parent materials in freshwater, underscoring the distinction between freshwater and marine environments, even though they share analogous transport mechanisms and potential impacts (Ashrafy et al., 2023; Cera et al., 2020; Galafassi et al., 2021; Onoja et al., 2022). The majority of MP particles that are discharged to land ultimately end up in the marine environment, making terrestrial sources a significant contributor to marine plastic debris. An estimated 1.15-2.41 million tons of plastic debris are transported by rivers annually, contributing between 80% and 94% of the total plastic burden that enters the seas and oceans. (Jambeck et al., 2015; Hale et al., 2020; Lebreton et al., 2017; Schmidt et al., 2017). Inadequate waste management and population density can result in elevated contamination levels. The global distribution of MP in the marine ecosystem causes high interaction with biota in surface waters, deep abysses, and sediments (Pedrotti et al., 2016; Lots et al., 2017; Zhao et al., 2015; Mathalon et al., 2014). Through ingestion and entanglement, more than 1,400 marine species interact with marine plastic debris. Due to their size and coloration, MPs are frequently misidentified as food (Vroom et al., 2017). Corals, zooplankton, phytoplankton, crustaceans, sea urchins, and fish are all susceptible to the consumption of MPs, as are larger animals such as sea turtles, whales, sharks, polar bears, and seals (Chatterjee & Sharma, 2019; Sharma & Chatterjee, 2017). Marine biota can also consume MPs through predation (Watts et al., 2014; Green et al., 2015). Predatory vertebrates may consume MPs by mistaking them for prey or by consuming invertebrates that have already ingested them, while marine species that feed on phytoplankton can ingest MPs when these particles aggregate with photosynthetic organisms. This process allows MPs to transfer between species at various levels of the food chain, exposing marine organisms from deep sea to surface habitats. Ultimately, these interactions lead to MPs entering the human food chain (Tursi et al., 2022).

Wastewater treatment plants (WWTPs) play a crucial role in managing microplastic (MP) pollution. These facilities are highly efficient, removing between 84% and over 99% of MPs in many cases. However, due to the enormous volumes of treated water processed daily, even small inefficiencies can lead to the release of millions to billions of microplastic particles into aquatic environments (Raju et al.,2018). These MPs come from diverse sources, such as industrial discharges and household activities like washing synthetic fabrics. The most common microplastic found in WWTP influent and effluent are fibers, especially those made of polyethylene and polyester (Tang et al., 2020). While WWTPs are generally effective at retaining MPs, they still serve as a significant route for MPs to infiltrate aquatic ecosystems. Discharged MPs can harm aquatic organisms by acting as carriers for toxic chemicals, amplifying their ecological impact (Leslie et al., 2017). Moreover, a large amount of MPs remains in the sediment produced by WWTPs. This sediment is often used as agricultural fertilizer, potentially transferring MPs to terrestrial ecosystems (Magni et al., 2019).

Land use patterns affect the spatial concentration of microplastic, while factors like microplastic density, land use, and hydrodynamic parameters (such as flow dynamics and tidal exchanges) influence longitudinal patterns in flowing water (Li et al., 2020; Tien et al., 2020). Rivers carry large amounts of plastic particles, causing MPs along with sinking sediment, particularly when the energy flow decreases during riverbed development (Vivekanand et al., 2021). A German study revealed that the concentration of MPs in river sediment was 600,000 times greater than in water. MPs MPs Microplastic concentrations decreased steadily from upstream to downstream due to barrage retention and limited tidal influence. However, no such trend was observed in the concentration of aqueous MPs (Scherer et al., 2020). Various studies indicate that microplastic contamination significantly impacts freshwater systems in Africa, Asia, Europe, and North America (Eerkes-Medrano et al., 2015; Khan et al., 2018; Faure et al., 2012; Imhof et al., 2013). While both freshwater and marine environments face similar transport pressures, such as surface currents, and share potential consequences like harm to organisms and the transmission of toxins, there are key differences due to the proximity of MPs to their sources. This leads to the presence of various forms of MPs in freshwater systems, such as rivers, displaying consistent patterns in their shapes, sizes, and numerical distribution (Blettler et al., 2017). Research indicates that plastic contamination is present in lakes and ponds worldwide, including remote areas like the Andes of the Patagonian region (Vaughan et al., 2017; Alfonso et al., 2020). Plastic tends to accumulate in these water bodies as it settles in sediment without further transit to the ocean, thereby accumulating over time. Although MPs have been identified in freshwater, their presence and distribution remain inadequately understood (Khan et al., 2018; Dubaish et al., 2013; Klein et al., 2015). The lack of understanding regarding the transmission of MPs from freshwater to terrestrial habitats and their potential health impacts is alarming. Allocating resources for research and promoting education and awareness, especially in developing nations, is crucial to address this issue and establish effective policies and management tools (Horton et al., 2017). In aquatic animals and mammals, MPs have been found to cause reproductive failure and can lead to mortality if the dosage exceeds a specific threshold (Gao et al., 2022). Exposure to MP results in decreased larvae growth length and lower egg hatching rates (Wu et al., 2021). Entanglement and ingestion of the remains of the MPs can directly impact aquatic organisms. Once ingested, MPs create a false sense of satiety, potentially leading to internal blockages or damage to the digestive system, and affecting appetite (Wang et al., 2018). Plastic microparticles accumulate in the digestive tract of organisms, with even smaller particles entering and persisting in the circulatory system (Jingjing et al., 2018). The accumulation of MPs, influenced by the size of the organism, negatively affects growth and reproduction of living organisms. Research shows that MPs accumulate significantly in fish tissues, especially in the liver, and are widely distributed throughout the gastrointestinal tract, muscular system, and gills. Evidence suggests that ingestion of MPs by marine creatures can lead to oxidative stress, immunological depression, growth suppression, altered gene expression, and changes in the physiology of the gastrointestinal systemMPs (Meaza et al., 2020). MPs enter the food chain and undergo biomagnification, starting with primary consumers and moving up to secondary consumers before ultimately reaching humans. Consequently, microplastic particles disrupt the food chain (van Raamsdonk et al., 2020). Additionally, MPs can act as vectors for environmental pollutants and heavy metals, adsorbing and later releasing them, thereby exposing aquatic organisms to these pollutants (Kang et al., 2019).

2. Terrestrial environment

MPs enter terrestrial environments through various methods, including landfills, atmospheric fallout, and agricultural practices like plastic mulching (Geyer et al., 2017). Agroecosystems are significant entry points, especially when wastewater treatment sludge is applied to soil (Corradini et al., 2019). Additionally, direct littering and poorly managed waste, such as industrial spillages and landfill discharges, exacerbate MP pollution (Hale et al., 2020). Furthermore, the deliberate or accidental incineration of plastics can emit particles into the atmosphere and surrounding environment, which may subsequently enter nearby rivers. Effective waste management and disposal are essential to mitigate the detrimental effects of plastic pollution (Hale et al., 2020). The primary sources of microplastic pollution in the terrestrial environment include plastic debris, microfibers from synthetic textiles, and the degradation of plastic fertilizers used in agriculture. According to recent research, agricultural settings are major recipients of micro and nanoplastic pollution (ECHA., 2019), primarily from sources such as sewage sludge biosolids, plasticulture, synthetic polymers, plastic litter decomposition, and irrigation with microplastic-contaminated water. These sources significantly exacerbate pollution in agricultural environments (Kallenbach et al., 2022). Urban environments are crucial for the release and cycling of plastic debris due to high population densities and industrial activities involved in plastic production or manufacturing. MPs can be dispersed through textile disintegration, environmental degradation, and industrial emissions. Three studies in Iran identified MPs in urban dust samples, primarily originating from road sources such as tire rubber, with concentrations ranging from 2.9 to 166 particles per g. This underscores road environments as key contributors to urban microplastic pollution (Abbasi et al., 2019; Dehghani et al., 2017). In terrestrial environments, MPs are transported by physical, chemical, and biological mechanisms (Du et al., 2020). Airflow and water flow are environmental forces that drive physical migration, while degradation and adsorption are the primary drivers of chemical migration. Biological migration involves the assimilation, metabolism, growth, and movement of organisms. The biological migration of MPs is significantly influenced by their accumulation within the food chain (Yu et al., 2024). Low-density MPs on soil surfaces can be released into the atmosphere through direct emission, bombardment during saltation, and aggregate disintegration. Upon exiting the atmosphere, MPs migrate to distant terrestrial regions and re-enter the Earth's surface through precipitation (Allen et al., 2019). Their dispersion, migration, and sedimentation are influenced by atmospheric parameters, surface characteristics, and MP characteristics (Bento et al., 2017). MPs can infiltrate soil, sediments, and pollutants in the terrestrial environment through various processes and pathways. The dynamics of nutrients can be altered by priming effects (PEs) (Zhang et al., 2023; Yang et al., 2025). Degradable MPs can significantly impact the decomposition rate of soil organic carbon. They can be transported from urban areas, agricultural fields, or landfills by wind and water discharge. According to Kumar et al. (2023), MPs can alter the physicochemical characteristics of soil, such as its structure and nutrient cycling. Consequently, they can influence the growth of vegetation and soil-dwelling organisms. Physiological and behavioral alterations, as well as the transmission of MPs through various food chains, can result from the absorption of MPs by organisms such as earthworms and insects. Traceable microplastic particles have been identified in terrestrial organisms, particularly urban and agricultural ravens in California, USA, where plastics have become entangled and integrated into their nests (Townsend & Barker, 2014). In the gastrointestinal tracts of birds of prey from central Florida, Carlin et al. (2020) observed an average of 6.22 microplastic particles. However, many of these particles were identified as rayon, which is sometimes excluded from microplastic counts due to its classification as a synthetic polymer. The gut contents of bird species now commonly contain MPs (Holland et al., 2016).

Soil, an essential environmental matrix, facilitates the functions and services of ecosystems (Bardgett & van der Putten, 2014). MPs can significantly impact soil physicochemical properties, including bulk density, water retention capacity, water stable aggregate distribution, and pH. These changes depend on the concentration, polymer type, and morphology of MPs (Lozano et al., 2021; Zhang et al., 2019). Recent research has revealed that fibers have a more substantial influence on the formation of macropores, aggregate distribution, and soil bulk density. The physicochemical properties of soil can also be influenced by interactions with soil-dwelling organisms, including fungi and plants (Liang et al., 2019; Wang et al., 2020). Significant contributors of MPs to soil ecosystems include sewage sludge, plastic film mulching, inadequate plastic waste management, and agricultural amendments, posing serious environmental hazards (Guo et al., 2020; He et al., 2022). Inefficient waste management and the unauthorized dispersal of plastic waste are substantial contributors to land pollution (Prokic et al., 2018). Current literature indicates that soil is a more significant reservoir of MPs than oceanic basins, as the majority of plastic waste is generated and disposed of on land. Vertical transfer of MPs into soil aggregates is facilitated by various mechanisms, including soil fissures, agronomic techniques, plant root elongations, and soil-burrowing animals (He et al., 2018; Rillig et al., 2017). Due to their inherent and ubiquitous presence in the environment, MPs act as vectors for soil contamination. MPs can significantly impact microbial communities that are essential for nitrogen cycling, carbon digestion, and other biogeochemical processes by altering soil structures (Rong et al., 2021; Rillig et al., 2021). Research has shown that MPs can significantly affect nutrient cycling by influencing soil microbial activity (Machado et al., 2019; Machado et al., 2018; Liu et al., 2017). The potential of MPs to alter the performance of microbial communities and influence nutrient accumulation is demonstrated by the correlation between increased microbial activity associated with MPs and elevated soil-water dissolved nutrient concentrations (Liu et al., 2017). The accumulation of MPs in soil adversely affects the animals inhabiting the pedosphere. These animals struggle to digest MPs, resulting in the accumulation of undigested MPs MPsin their bodies (Ju et al., 2019; Kim et al., 2019; Peng et al., 2017). While smaller organisms like earthworms can digest MPs, this can damage their intestinal tract and impact their survival MPs (Zhu et al., 2018; Rillig et al., 2012). Biopores that facilitate the profound infiltration of MPs into the soil can be generated by specific soil organisms, such as *Lumbricus terrestis* L. (earthworm), as demonstrated by a study. Various organic pollutants that are adsorbed onto the surface of the MPs are also transported through these biopores (Rillig et al., 2017). Consequently, the intrusion of MPs into soil, which involves deposition, translocation, erosion, deterioration, and percolation to groundwater, poses a threat to microorganisms. Ultimately, all living organisms are impacted by this interference through indirect utilization (Hurley et al., 2018).

3. Atmospheric environment

Atmospheric MPs are associated with human activities, although few studies have explored their occurrence (Frere et al., 2017). Dris was the first to study MPs in the atmosphere, discovering that they are easily dispersed by wind and can have long-term ecological consequences (Dris et al., 2015). According to this research (Dris et al., 2015), MPs can be transported to remote regions through wind and atmospheric deposition, ultimately entering marine environments, and posing health hazards to humans and animals through potential inhalation (Prata, 2018). Research on airborne MPs is categorized into three types: suspended atmospheric MPs (SAMPs), atmospheric deposition, and dust (both indoor and outdoor). The density of MPs is a critical classification factor, as higher particulate density leads to a faster deposition process (Evangeliou et al., 2020). MPs present in the air can enter the human body through inhalation and ingestion, leading to cytotoxicity, oxidative stress, and inflammatory lesions (Stapleton, 2021; Abbasi et al., 2021). They have the potential to accumulate in organs, translocate to tissues, and remain unaltered for extended periods (Rahman et al., 2021). The immune system's inability to eliminate MPs can lead to chronic inflammation and the risk of neoplasia (Prata et al., 2020). The presence of MP fibers (MFs) in urban air is a significant characteristic of MP pollution. MFs are produced from various ground sources, including city pollution, erosion of rubber tires, and synthetic textiles. Reports indicate that in 2011, the production of textile fibers exceeded 90 million metric tons, with two-thirds being synthetic and plastic (Zhou et al., 2017; Liu et al., 2019). In recent decades, the fibrous plastic has experienced a 6.6% annual increase (Geyer et al., 2017). Both indoor and outdoor environments can exhibit fiber-dominated MPs. The commercial use of fine-diameter (1–5 mm) plastic fibers, particularly in sportswear, may influence the prevalence of microfiber in the atmospheric environment (Gasperi et al., 2018). A study found that the concentration of microfibers in indoor air (1–60 fibers m^{-3}) was considerably higher than that in outdoor air (0.3–1.5 fibers m^{-3}) (Dris et al., 2016). Consequently, indoor exposure to ambient MP fibers or particles may impact human health (Chang et al., 2006). The primary sources of airborne MPs in outdoor environments are synthetic garments, textile abrasion, plastic waste incineration, municipal solid waste, dust storms, rubber tire abrasion, scaffolding mesh, and synthetic turf for ground cover (Cai et al., 2021; Hu et al., 2022; Sun et al., 2022). The discharge of microscopic fibers from furniture, draperies, carpets, and other objects is a significant source of MPs in indoor air (Abad López et al., 2023). MP concentration is also influenced by factors such as the type of flooring, paint coatings, and air conditioners (Chen et al., 2022; Uddin et al., 2022). MPs are generated as a result of the opening and handling of plastics, such as containers or packaging. Their concentrations in the atmosphere depend on the plastic content of objects, interior activities, and the presence of individuals (Bahrina et al., 2020; Sobhani et al., 2020). Waste disposal, vehicular traffic, and anthropogenic activities are the primary contributors to microplastic pollution in metropolitan environments. Open landfills substantially contribute by releasing plastic waste into the atmosphere. Continuous exposure further increases the probability of coarse plastic fragments disintegrating and releasing MPs (Andrady, 2011; Cole et al., 2011). Additionally, ground activities such as industrial cutting, mowing, and tire wear contribute to the release of MPs, which are subsequently transported into the atmosphere (Liu et al., 2019). The abundance of MPs in atmospheric environments depend on factors such as altitude, latitude, climatic conditions, and the season of the year (Yang et al., 2021). MP levels fluctuate seasonally, with the maximum levels occurring in the spring, summer, and winter, and the minimum levels occurring in the autumn (Zhou et al., 2017). Elevated levels of MP in densely populated regions are associated with the density of plastic usage. However, other variables such as waste incineration, construction materials, industrial operations, soil suspension, deforestation, infrastructure, and macroplastic breakdown also influence the abundance of MPs (Klein & Fischer, 2019; Wright et al., 2020). Airborne MPs can contaminate both terrestrial and aquatic ecosystems due to their low density and light weight, enabling dynamic exchanges among various environmental systems (Prata, 2018). Wind, precipitation, and atmospheric disturbances can facilitate the transportation of MPs in urban environments (Abbasi et al., 2019). Recent research indicates that the morphology and chemical composition of marine and terrestrial MPs are comparable, suggesting that they may have originated from terrestrial environments through atmospheric transportation and deposition (Free et al., 2014). In terrestrial ecosystems, wind erosion is crucial for the transportation of MPs, as higher wind velocities lead to reduced concentrations of these particles in the atmosphere (Rezaei et al., 2019). The dispersion of MPs in the atmosphere may be affected by urban topography, including the spacing of structures, local meteorological conditions, and thermal circulation (Fernando et al., 2001), particularly for low-density polymers (Horton et al., 2017; Nizzetto et al., 2016). Studies confirm that atmospheric MPs contaminate terrestrial ecosystems through both dry and moist deposition, (Klein & Fischer, 2019). Effluent from tires can be discharged into the soil near roads and beyond. In the terrestrial environment, MPs introduced from the atmosphere either remain in the soil layer for an extended period or undergo gradual degradation (Baensch-Baltruschat et al., 2020). MPs accumulate in significant quantities in the soil, posing a threat to terrestrial ecosystems (Li et al., 2020).

Impact of microplastics on human health

MPs pose a potential threat to human health due to their reported toxic effects and pervasive presence in the environment. Understanding the extent of human exposure to MPs is of utmost importance, with oral ingestion being the primary pathway, followed by inhalation and skin contact (Prata et al., 2020). The incorporation of MPs into the intestinal microbiome can disturb the equilibrium between beneficial and harmful bacteria, resulting in gastrointestinal complaints such as stomach discomfort, bloating, and altered bowel habits (Jin et al., 2019). MPs can induce chemical toxicity by incorporating and accumulating MPsenvironmental pollutants such as polycyclic aromatic hydrocarbons and heavy metals. When ingested, these toxins can cause abdominal pain, vomiting, and nausea, impacting the digestive system (Abbasi et al., 2021). The persistence of MPs in the intestine can lead to intestinal oxidative injury, characterized by an imbalance in the production and detoxification of reactive oxygen species. If left unchecked, this can result in the destruction of cell structures, including DNA, proteins, and lipids (Shan et al., 2022). This, in turn, can lead to severe inflammatory bowel disease and colon cancer (Hettiarachchi et al., 2023). Airborne MPs have the potential to impact respiratory health through inhalation (Emenike et al., 2023). Shortness of breath, coughing, wheezing, and exacerbation of pre-existing respiratory conditions, such as asthma, are potential symptoms of the irritation and inflammation that these small contaminants can induce in the respiratory tract (Abbasi et al., 2019; Sangkham et al., 2022). In workers in the synthetic textile and flock industries, exposure to airborne MPs may lead to respiratory symptoms that are associated with the development of airway and interstitial pulmonary diseases (Atis et al., 2005; Ahmad et al., 2023). An examination of the lungs of flock workers exposed to nylon flock revealed that some individuals developed persistent interstitial lung disease and experienced a progressive decline in lung function. This condition ultimately led to secondary pulmonary hypertension and respiratory failure, even after they left the work environment (Turcotte et al., 2013). These airborne fibrous MPs can absorb contaminants from their surroundings due to their hydrophobic surface (Endo et al., 2013).

In urban areas, MPs present alongside vehicular contaminants MPshave the potential to transport polycyclic aromatic hydrocarbons and toxic metals. The release of contaminants from MPs can cause genotoxicity and lung health issues. Additionally, studies have demonstrated that environmental MPs may disrupt circadian rhythms and melatonin synthesis, leading to sleep disruptions and an increased risk of sleep disorders (Melendez-Fernandez et al., 2023; Moralia et al., 2022;

Sinha et al., 2022). The presence of MPs has been suggested to disrupt hormone regulation and metabolism, potentially contributing to weight gain and obesity, according to evidence from numerous studies (Ghosh et al., 2019; Landrigan et al., 2023; Sinha et al., 2014). There is a potential correlation between higher susceptibility to diabetes and exposure to MPs (Huang et al., 2022). Experimental evidence has demonstrated the MPs induce oxidative stress and inflammation, both recognized as risk factors for diabetes MPs (Zhao et al., 2022; Caputi et al., 2022). Numerous endocrine disorders, including metabolic, developmental, and reproductive disorders, can be caused by MPs, which can disrupt the production, release, transport, metabolism, and elimination of hormones (Vandenberg et al., 2017; Lee et al., 2023). The absorption of environmental hazardous substances, such as bisphenol A, through MPs (MPs) can lead to specific disorders affecting the endocrine and reproductive systems. MPsPrevious research has demonstrated that exposure to MPs can result in structural abnormalities in testicular and sperm cells, decreased sperm viability, and disturbance of the endocrine system in males (He et al., 2023). The detrimental effects caused by MPs on the male reproductive system could lead to reproductive dysfunction and decreased fertility (Grechi et al., 2022). A recent study using Raman micro spectroscopy found MPs in the placentas of six expectant women MPs (Ragusa et al., 2021). Research findings suggest that the prevalence of MPs may contribute to the development or exacerbation of cardiovascular diseases, including hypertension, atherosclerosis, and abnormal cardiac rhythms (Persiani et al., 2023; Zhao et al., 2021). MPs have been observed to induce oxidative stress, inflammation, endothelial dysfunction, and disruption of normal cardiac function, thereby elevating the risk of cardiovascular complications (Prata, 2018; Chang, 2010). MPs have been associated with cardiovascular disease in recent research. Human kidney and liver cells exhibit altered gene expression, decreased proliferation, structural abnormalities, and elevated reactive oxygen species levels (Goodman et al., 2022). When microplastic particles come into contact with the epidermis, they can trigger allergic responses. This occurs because the body's immune system recognizes these foreign particles as hazardous and releases histamines and inflammatory substances, inducing allergic symptoms (Tiwari et al., 2023; Kershaw & Rochman, 2015). MPs have also been found to contribute to the development of antibiotic resistance, as they may serve as breeding grounds for bacteria that can eventually develop resistance. This is an important global health problem with profound consequences for human health (Shi et al., 2021; Dong et al., 2021).

Microplastics mitigation

Global plastic production presents significant control challenges, with source control being the most acceptable approach (Ruan et al., 2018). It is essential for society to minimize the use of unnecessary plastic items, including straws, water bottles, plastic bags, and utensils. Governments should prioritize recycling and refuse collection systems to mitigate environmental waste (Lamichhane et al., 2023). Promoting environmentally favourable and cost-effective alternatives to plastics is crucial (Zhang et al., 2018). Researchers must develop techniques to decompose plastics into their basic constituents for reconstitution into new materials in the coming years (Thompson, 2018). Unlike the centuries it takes for plastic beverage bottles to decompose in oceans, researchers have identified a mutant enzyme that can decompose them in just a few days (Carrington, 2018). Recycling conserves resources and energy while decreasing harmful emissions, benefiting both society and the environment (Prata et al., 2019). The recovery process fundamentally relies on using plastics for energy production or creating new raw materials (Quesada et al., 2019). Various mechanical, biological, and caloric systems can be employed to recover the energy inherent in residual materials. These systems convert, reprocess, and decompose plastic waste into new materials or energy when it is not practicable to reuse or recycle plastic products (Calero et al., 2021). The circular economy is essential for reducing the prevalence of secondary MPs in the environment MPs (Munhoz et al., 2023). The mechanical properties, shelf-life, and recyclability of the products can be enhanced through the use of alternative materials and green design for single-use plastic items (Rajmohan et al., 2019). Fundamental behavioural adjustments and multi-layered governance at the level of the general population, governments, industries, NGOs, academia, fishermen, and local communities are necessary to prevent the discharge of MPs into the environment (Rochman et al., 2016). It is, therefore, crucial to implement measures that focus on enhancing environmental knowledge among young people (Kuo et al., 2014) and adults (Brennan et al., 2019), and involve stakeholders in advocating for the reduction of plastic pollution to effectively address the issue of littering (Clausen et al., 2020). To advance toward circularity and reduce plastic waste, the plastics industry must be continuously reinvented within the context of a circular economy (Jia et al., 2019). Key strategies include the prohibition of single-use plastics, the extension of producer responsibility, the redesign of plastics for circularity, the reduction of preproduction plastic particle loss, and the support of the market for recycled plastics (Civancik-Uslu et al., 2019; Czarnecka-Komorowska & Wiszumirska, 2020; Nahman, 2010). The degradation or elimination of MPs from soil and water has been achieved through various methods, including advanced oxidation processes (Ye et al., 2021), photocatalysis (Jiao et al., 2020), microwave treatment (Jie et al., 2020), and bioremediation. During photocatalysis, plastic particles undergo degradation and create cavity structures surrounding the catalysts, which trigger oxidation. This results in the formation of carbonyl and carboxyl groups, which are subsequently photo-oxidized to transform them into volatile organics, specifically CO_2 and H_2O (Hu et al., 2021). A microwave-assisted catalytic procedure using an iron-based catalyst took about 30–90 sec to transform powdered plastic into hydrogen and mostly carbon nanotubes (Watt et al., 2021). The removal of MPs, whether synthetic or biodegradable, from soil or water (Bhatt et al., 2021; Mohanan et al., 2020) can be achieved by microorganisms through a four-step bioremediation process: biodeterioration, bio-fragmentation, assimilation, and mineralization. Microbes initiate physicochemical degradation, fragmenting polymers into oligomers and monomers, integrating molecules into microbial metabolism, and ultimately liberating oxidized metabolites (Roy et al., 2022). Preventing microplastic leakage into the environment requires effective waste management, which includes planning, infrastructure development, education, and community involvement to minimize the environmental impact. Secured landfills and alternative disposal methods, such as incineration or pyrolysis, are also crucial (Nikpay et al., 2024). The continuous struggle against microplastic pollution necessitates the promotion of educational initiatives and increase in public awareness. Communities must be informed about the environmental repercussions of MPs through public awareness campaigns. These campaigns utilize a diverse array of strategies, such as videos, infographics, social media, and community events, to disseminate information about the sources, hazards, and consequences of MPs. These efforts encourage individuals to adopt practical measures to mitigate microplastic contamination, such as minimizing single-use plastics and engaging in responsible waste disposal (Felipe-Rodriguez et al., 2022). Integrating MPs into educational courses, from primary schools to universities, is essential for comprehending the emerging environmental challenge. This not only explains the influence of MPs on the ecosystem but also fosters a sense of environmental stewardship and responsibility in the younger generation. By doing so, we empower environmentally conscious citizens to address microplastic contamination (Araujo et al., 2023). Recent research has shown substantial progress in implementing biodegradable plastics as a sustainable solution to plastic waste. The biodegradable nature of bioplastics, including polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), has led to their integration into applications such as agriculture and packaging. However, significant obstacles persist, including the necessity of specific environmental conditions for effective degradation, limited recycling infrastructure, and high production costs (Keith et al., 2024). It has been shown that bioplastics make up less than 2% of the world's plastic production and are mostly employed in low-value sectors. Advancements in the creation of bio-based elastomers and other polymers are facilitating high-value applications that conform to circular economy concepts (Burelo et al., 2024). Additionally, innovative chemical recycling techniques, including pyrolysis and depolymerization, are emerging as viable alternatives for managing PLA and other biodegradable polymers (Shareefdeen & ElGazar, 2024). The transition to bioplastics is also being supported by policy measures. Certain nations are implementing legislative instruments to reduce the use of single-use plastics and encourage the adoption of biodegradable alternatives. However, there is a substantial void in the standardization of biodegradation protocols, infrastructure development, and consumer education to facilitate the efficient processing of waste (Mhaddolkar et al., 2024).

Future perspectives

Future studies must focus on the potential health hazards associated with MPs pollution and its interactions with environmental pollutants. Developing integrated MP treatment technologies, effective management strategies, and laws is essential for mitigating negative impacts. To mitigate MP pollution, it is necessary to adhere strictly to the "Reduce, Reuse, Recycle" principle. Additionally, research should investigate the toxic impacts of MPs, develop sustainable alternatives to single-use plastics, and improve recycling and reuse methods while maintaining a low carbon footprint. The current state of MP removal efforts is underdeveloped, but there is potential for development by integrating various methods. Future research may explore the potential for organic integration between different technology categories (Nasir et al., 2024). Well-designed human studies are essential to establish evidence regarding the health hazards associated with MPs exposure, particularly through long-term studies on chronic exposure. Such evidence would help develop interventions and inform policy to alleviate the effects of MPs on human health. Additionally, spreading knowledge within educational institutions, organizations, and campaigns on reducing plastic use through rejection, reduction, reuse, and recycling can effectively address the issue of microplastic pollution (Lamichhane et al., 2023). There is an urgent need for standardized techniques to collect, extract, and identify MPs during sampling. Improving data quality will enable cross-comparison of various research, therefore facilitating a comprehensive picture of the worldwide scope of microplastic pollution. The long-term health consequences of microplastic exposure should be the primary focus of research, with a particular emphasis on vulnerable populations, such as expectant women and young children. Gaining insight into the interactions between MPs and other environmental contaminants is crucial, especially their role in the transportation of hazardous chemicals and diseases. Developing effective methods for eliminating and accelerating the degradation of MPs in various environments is imperative to mitigate ecological and health risks. Research should prioritize the development of cutting-edge, environmentally sustainable methods for preventing microplastic contamination. Future endeavours to address microplastic contamination should prioritize the establishment of international monitoring networks to optimise data exchange and enhance the understanding of microplastic distribution and effects on a global scale. This collaborative strategy will facilitate thorough evaluations and guide the development of policies. Facilitating collaborations between scientists from a variety of fields, including public health, toxicology, and environmental science, would promote comprehensive research and generate more robust solutions. Developing standardized international guidelines for microplastic research and management is crucial to ensure consistent and efficient solutions to this global problem, supporting regulatory frameworks and best practices. Enhancing public awareness, promoting sustainable practices, and empowering global efforts in tackling microplastic pollution can be achieved by engaging local communities, industries, NGOs, and supporting research in low-income countries through capacity-building interventions.

Conclusion

In summary, microplastic pollution is a substantial and expanding hazard to both human and environmental health. Global ecosystems have been infiltrated by microplastic pollution, which has reached alarming levels. This pollution poses significant risks to both human and environmental health. The persistence of MPs in water, soil, and air allows them to disrupt food chains, impact wildlife, and expose humans to potentially hazardous chemicals. Wildlife is affected by the widespread presence of MPs through ingestion and entanglement, which may result in toxic effects due to chemical contaminants that are absorbed onto plastic surfaces. These pollutants not only impair ecosystems but also present health hazards to humans through skin contact, inhalation, and ingestion. To decrease microplastic pollution, it is imperative to prioritize the reduction of plastic production and consumption, with a particular emphasis on single-use plastics. Advancements in sustainable alternatives, recycling technologies, and plastic degradation methods present potential solutions.

Various techniques, such as microwave-assisted catalysis, advanced oxidation processes, and bioremediation, can be employed to degrade and remove MPs from soil and water. These processes convert into volatile compounds such as CO_2 and H_2O. Powdered plastics are swiftly converted to hydrogen and carbon nanotubes through microwave-assisted catalysis, which employs an iron-based catalyst. Bioremediation involves microorganisms degrading plastics through a four-step process: biodeterioration, bio-fragmentation, assimilation, and mineralization. The results in the conversion of MPs into innocuous metabolites. These strategies for mitigating microplastic pollution in the environment are promising when combined with effective waste management practices.

Furthermore, to effectively address this global issue, it is essential to improve waste management systems and raise public awareness. Future research should focus on the health hazards associated with MPs, their interactions with environmental contaminants, and the development of integrated technologies for microplastic removal. To safeguard the public welfare and the environment for future generations and prevent microplastic pollution, it is crucial that governments, industries, and communities participate in a global collaborative effort. Moreover, the most effective approach to reducing future pollution will be to increase awareness through education and enforce more stringent regulations on plastic production and disposal. Addressing the microplastic crisis will necessitate comprehensive, interdisciplinary endeavours that encompass community action, science, and policy.

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