TYPE Review
PUBLISHED 18 June 2025
DOI 10.3389/fenvs.2025.1606332

# A review of microplastic pollution and human health risk assessment: current knowledge and future outlook

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The rapid growth of the global population, coupled with the expansion of industrial, agricultural, commercial, and service activities, has led to a significant increase in microplastic contamination in aquatic environments. An estimated 265 million metric tons of plastic waste are produced globally each year, with about 4.8–12.7 million metric tons ending up in the ocean. Microplastics can infiltrate the food chain or come into contact with humans through the skin, eventually penetrating and accumulating in the body. Globally, individuals are estimated to consume between 11,845 and 193,200 microplastic particles per year, with drinking water identified as the primary source. The toxicity of microplastics stems from both their inherent properties and their ability to interact with other pollutants, such as heavy metals. Adverse health effects linked to microplastic exposure include metabolic disruptions, transport to internal organs, inflammatory responses, oxidative stress, cytotoxicity, and potential damage to the nervous and reproductive systems, along with possible carcinogenic outcomes. Despite these concerns, there are currently no standardized methods for assessing the human health risks associated with microplastic exposure. There is a critical need for in-depth research to clarify the toxicological impacts and health risks of microplastics, along with the development of reliable risk assessment frameworks. This review seeks to present a comprehensive summary of microplastic levels in aquatic systems, their possible effects on human health, and the methodologies currently used to assess these risks.

KEYWORDS

**microplastics, toxicity of microplastics, aquatic environment, human health risks, microplastic exposure**

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RECEIVED 05 April 2025
ACCEPTED 30 May 2025
PUBLISHED 18 June 2025

CITATION
Hoang HG, Nguyen NSH, Zhang T, Tran H-T, Mukherjee S and Naidu R (2025) A review of microplastic pollution and human health risk assessment: current knowledge and future outlook.
*Front. Environ. Sci.* 13:1606332.
doi: 10.3389/fenvs.2025.1606332

10.3389/fenvs.2025.1606332

## 1 Introduction

The sharp increase in plastic production and use has resulted in widespread environmental contamination, especially in marine environments (Wang T. et al., 2024). As larger plastic materials break down, they contribute substantial quantities of microplastic particles to aquatic systems, including water columns and sediments (Rezania et al., 2018). Research estimates that over 250,000 tons of plastic debris have accumulated in the oceans, primarily due to improper waste management (Kowsari et al., 2023). In 2010, more than 190 coastal nations collectively produced over 265 million metric tons of plastic waste, with an estimated 4.8 to 12.7 million metric tons entering the marine environment (Jambeck et al., 2015).

Microplastics (MPs), defined as plastic particles smaller than 5 mm, can be readily absorbed by various organisms, leading to bioaccumulation in higher organisms, including humans (Darabi et al., 2021; Prata et al., 2020). This raises concerns about the potential toxicity of MPs, which may be especially severe for human health. The most common components in the microplastics found in aquatic environments include polymers, additives, and dyes (Darabi et al., 2021; Yao et al., 2019). Common toxic substances in plastic products include polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR), polylactic acid (PLA), polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE) (Darabi et al., 2021).

Microplastics can exert two types of toxicity: direct and indirect. Direct toxicity is attributed to harmful chemicals present in plastic products and microplastic particles themselves (Thacharodi et al., 2024). This includes additives used to enhance polymer properties, such as flexibility and UV resistance (Li K. et al., 2023). Indirect toxicity arises from the interactions of MPs with organic and inorganic substances, including heavy metals and persistent organic pollutants like polybrominated diphenyl ethers (PBDEs) and polycyclic aromatic hydrocarbons (PAHs) (Santos et al., 2021).

Microplastic particles can enter living organisms and humans through ingestion, which is primarily facilitated *via* the food chain (Darabi et al., 2021; Prata et al., 2020). Once in aquatic ecosystems, MPs accumulate and subsequently enter the human body through food consumption (Al Mamun et al., 2023). This is considered as the primary pathway through which microplastics enter the human body. Although dermal contact is a less significant route, it is still a potential exposure pathway (Elizalde-Velázquez and Gómez-Oliván, 2021).

Despite the limited number of studies specifically addressing human health risks, existing research indicates that exposure to elevated concentrations of MPs may lead to various toxic effects in humans (Bexiga et al., 2011; Stock et al., 2019). Reported adverse effects include cancer, cytotoxicity, metabolic changes, organ transport, inflammation, neurotoxicity, and reproductive damage (Rahman et al., 2021). Given the scarcity of data on direct human health impacts, literature on risk assessment methodologies remains limited. The Global Average Rate of Microplastic Ingestion (GARMI) is increasingly referenced to support risk assessment efforts related to MP pollution (Senathirajah et al., 2021). Therefore, this review consolidates current knowledge on microplastic (MP) concentrations in aquatic environments, their pathways of exposure, including ingestion, inhalation, and dermal contact, and the mechanisms underlying their toxicity. It further explores the associated implications for human health, emphasizing the need for comprehensive risk assessment frameworks. In addition, this review highlights existing research gaps and offers key recommendations for future studies aimed at improving the detection, impact evaluation, and mitigation strategies for microplastic pollution in aquatic systems.

## 2 Microplastics in the aquatic ecosystem

### 2.1 Level and distribution of MPs in water and sediments

Nowadays, advanced analytical methods for microplastic (MP) detection have increasingly relied on spectroscopic and AI-based approaches to enhance accuracy, efficiency, and scalability (Jung et al., 2021). Spectroscopic techniques such as Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and near-infrared (NIR) spectroscopy are widely used for identifying polymer types based on their characteristic molecular vibrations (Prata et al., 2020). FTIR and Raman, in particular, allow for non-destructive, high-resolution analysis of MPs down to the micrometer scale, including chemical mapping and particle size determination (Wang M. et al., 2024). However, these methods can be time-consuming and data-intensive when processing large environmental samples. To address this, AI-based approaches, especially machine learning and deep learning algorithms are being integrated with spectroscopic data to automate MP classification, reduce human bias, and accelerate data interpretation (Nguyen et al., 2022). For instance, Tran et al., 2023 reported that convolutional neural networks (CNNs) have been applied to automate image-based particle recognition and distinguish MPs from non-plastic debris. Additionally, AI models can optimize spectral data analysis, enabling real-time detection, pattern recognition, and improved classification of polymer types across complex matrices such as water, and sediment.

The surge in plastic consumption has led to increased microplastic presence in aquatic environments (Jiang, 2018). Various sources release MPs into the environment, including the breakdown of larger plastic debris, industrial processes, tourism, and everyday human activities (Darabi et al., 2021; Jung et al., 2021; Nguyen et al., 2022; Rezania et al., 2018). Microbeads found in personal care products also contribute to MP pollution (Gao et al., 2020). Microplastics travel through drainage systems into rivers and ultimately the ocean. (Tran et al., 2023).

MPs manifest in numerous forms and are produced through various processes, including oxidative decomposition and friction (Yao et al., 2019). Studies indicate that microplastics in aquatic environments range in size primarily from 0.5 to 2 mm, appearing as fragments, fibers, beads, pellets, and films (Table 1). The most common colors detected include transparent, blue, green, black, white, and red (Nguyen et al., 2022).

The distribution of MPs in aquatic ecosystems hinges on numerous factors, including human activities, physical and chemical properties of the microplastics, and environmental conditions (Darabi et al., 2021). Research indicates that Asia is the leading contributor to global microplastic emissions, primarily due to activities in China (Wang M. et al., 2024). Meijer et al. (2021) showed

**TABLE 1** Distribution of MPs in water and sediments worldwide [Updated based on Elizalde-Velázquez and Gómez-Oliván (2021)].

| Country | Study area | Water | Sediments | Types | Shapes | References |
|---|---|---|---|---|---|---|
| Canada | Ottawa River and its tributaries | 0.05–0.24 fragments/L | | | Red and blue microfibers and microbeads | Vermaire et al. (2017) |
| | Wascana Creek | 0.5–9.7 particles/$m^3$ | | | Fragments, fibers, beads | Campbell et al. (2017) |
| | East coast of Vancouver Island | 139.01–1,180.75 particles/$m^3$ | <1.0–123.6 particles/kg | | Clear and blue fibers and fragments | Collicutt et al. (2019) |
| Mexico | Banderas Bay | 0.013–0.044 pieces/$m^3$ | | PP, PVC, PAN | Fragments, fibers, film, line | Xu et al. (2020) |
| | Northern Gulf of Mexico | 4.8–18.4 particles/$m^3$ | | | Fibers, Bead | Di Mauro et al. (2017) |
| US | Charleston Harbor and Winyah Bay | 3–88 particles/L | 33.7–1,389.6 particles/$m^2$ | PE, PA, PP | Black fragments, white foam, blue fibers, green spheres | Brignac et al. (2019) |
| | Hawaii Beach | | 18.1 (±22.9) particles/$km^2$ | LDPE, HPDE, PP | Foam, fragment, line, sheet, whole, pellet | |
| Norway | South and southwest of Svalbard | 0–1.31 items/$m^3$ | | PET, PA, PE, PMMA, PVC, cellulose | Fibers, fragments and films | Lusher et al. (2015) |
| Italy | Southern subalpine lakes | 1,300–93,000 particles/$km^2$ | | PE, PP, EPS | Fragments, filaments and sheets | Sighicelli et al. (2018) |
| Portugal | Antuã River | 58–1,265 items/$m^3$ | 18–629 items/kg | PE, PP, PS, PET, PVA, EVA, PTFE, Cellulose | White, black, transparent and blue foams, fibers and fragments | Rodrigues et al. (2018) |
| South Korea | Coast of South Korea | 1,051 particles/$m^3$ | | PP, PE | Fragment and fiber | Song et al. (2018) |
| China | Xiangxi River | $0.55 \times 10^5$–$342 \times 10^5$ items/$km^2$ | 80–864 items/$m^2$ | PE, PP, PS, PET | Blue and red sheet, fragment, lines and foam | Zhang et al. (2017) |
| | Three Gorges Reservoir | 1,597–12,611 n/$m^3$ | 25–300 n/kg ww | PS, PP, PE | Fiber, fragment, pellet, film and Styrofoam | Di and Wang (2018) |
| | Qiantang River and Hangzhou Bay | | 0.23 ± 0.06 and 0.15 ± 0.03 particles/g | PE, PS | Fragment, fiber | Fraser et al. (2020) |
| | Hanjiang River and Yangtze River | 1,020.9–10,561 n/$m^3$ | | PET, PP, PE, PA, PS | Transparent, blue, purple and red fiber, granule, film and pellet | Wang et al. (2017) |
| | Yangtze River | 0.48–21.52 items/L | 35.76–3,185.33 items/kg | PP | Fibers and fragments | Hu et al. (2018) |
| | Three Gorges Reservoir | 1,597–12,611 n/$m^3$ | 25–300 n/kg | PS, PP, PE | Transparent fibers | Di and Wang (2018) |
| | West Dongting Lake | 433.33–2,216.67 items/$m^3$ | 320–480 items/$m^3$ | PS, PP, PE, PVC, PET | transparent, white, blue, black and green fibers, fragment, film and pellet | Wang et al. (2018) |
| | South Dongting Lake | 366.67–2,316.67 items/$m^3$ | 200–1,150 items/$m^3$ | PS, PP, PE, PVC, PET | transparent, white, blue, black and green fibers, fragment, film and pellet | Jiang et al. (2018) |
| | Wei River | 3.67–10.7 items/L | 360 to 1,320 items/kg | PE, PVC, PS | Fiber, films, fragments, foam, pellets | Ding et al. (2019) |
| Iran | Persian Gulf | | 61 particles/kg dw | PE, PET, nylon | Fragment, films, and fibers | Naji et al. (2017) |
| India | Vembanad lake | | 96–496 particles/$m^2$ | LDPE, PS, PP | Film, foam, fragment, fiber and pellets | Naji et al. (2017) |
| Indonesia | Jakarta Bay | | 18,405–38,790 particles/kg | PP | Fibers, fragments and pellets | Sruthy and Ramasamy (2017) |

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TABLE 1 (*Continued*) Distribution of MPs in water and sediments worldwide [Updated based on Elizalde-Velázquez and Gómez-Oliván (2021)].

| Country | Study area | Water | Sediments | Types | Shapes | References |
|---|---|---|---|---|---|---|
| Malaysia | Kuala Nerus and Kuantan port | 0.13–0.69 particles/L | | PS, PA, PVC, PE, PP | filament, fragment and irregular shape | Khalik et al. (2018) |
| Philippines | Negros Oriental | | 0.082 items/g | Rayon, PE, PVC | Fibers | Bucol et al. (2020) |
| Turkey | Mediterranean Sea | 16,339–520,213 particles/km$^2$ | | PTHC resin, PS, PA resin, PE, PP | Fibers and hard plastic | Güven et al. (2017) |
| Jamaica | Kingston Harbour | 0–5.73 particles/m$^3$ | | PP, PE | Fragments | Rose and Webber (2019) |
| Kenya | Indian Ocean | 33.3–275 particles/m$^3$ | | PP, LDPE | Black, filaments, fragments granules and foams | Kosore et al. (2018) |

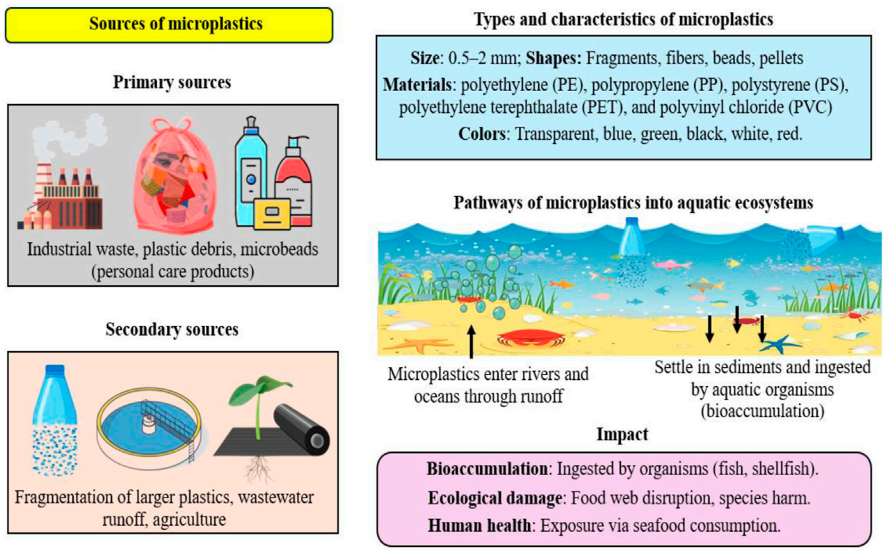


FIGURE 1
Sources, pathways, and impact of microplastics pollution on aquatic environment.

that Asia is the geographical region with the most microplastics emissions in the world (80.99%) with the main contribution coming from China. Hu et al. (2018) reported microplastic abundances of 0.48–21.52 items/L in surface water and 35.76–3,185.33 items/kg in sediments of Yangtze River. Significant amounts of MPs were also presented in Three Gorges Reservoir with concentrations of 1,597–12,611 n/m$^3$ and 25–300 n/kg, respectively (Di and Wang, 2018). Microplastic concentrations were also recorded in the range of 433.33–2,216.67 particles/m$^3$ and 320–480 particles/m$^3$ in surface water and sediments of West Dongting Lake, respectively (Jiang et al., 2018). The contributions of other continents are much less than Asia, i.e. 7.99% from Africa, 5.51% from South America, 4.5% from North America, 0.6% from Europe, 0.37% from Oceania, and 0.04% from others (Meijer et al., 2021). Meijer et al. (2021) showed that 31,904 locations released plastic wastes into the ocean with leakage into the marine environment (of 0.8–2.7 million tons) in 2015.

Moreover, regional and socio-economic disparities significantly influence microplastic (MP) exposure through food and water. For example, in high-income areas, advanced regulations and water treatment may reduce MP levels, though high consumption of packaged foods still poses risks (Hossain et al., 2021; Ma et al., 2024). In contrast, low and middle-income regions often face higher exposure due to limited infrastructure, weak regulation, and reliance on untreated water and seafood (Kurniawan et al., 2024). Socio-economic status also affects dietary habits and access to safe food and water, with disadvantaged populations more likely to consume contaminated sources and have less awareness of MP risks (Prata et al., 2020). These factors underscore the need for context-specific exposure assessments and interventions.

## 2.2 Concerns regarding microplastics in the aquatic ecosystem

There are several critical concerns raised by microplastics in aquatic ecosystems including envirnmental health effects, bioaccumulation, ecological effects, health risks, and biodiversity

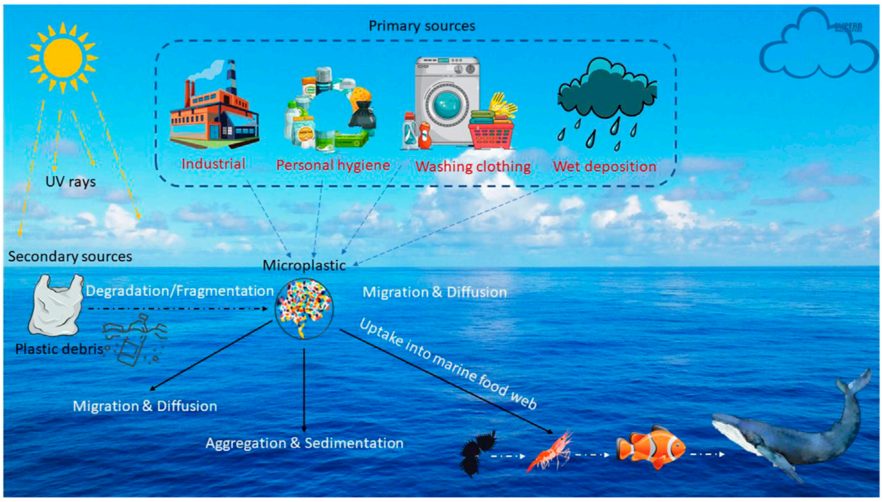


FIGURE 2
The occurrence of microplastics in aquatic environments.

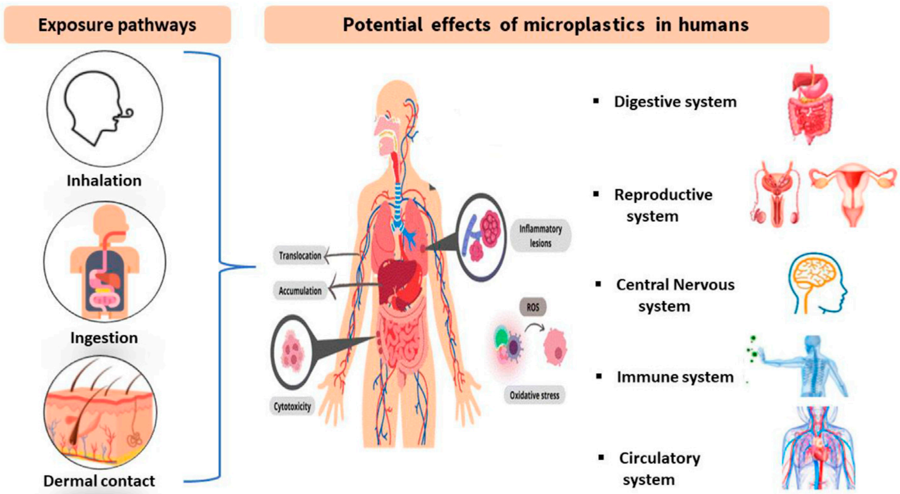


FIGURE 3
Exposure pathways and potential effects of microplastics in human.

loss (Figure 1). MPs can disrupt the self-cleaning capacities of ecosystems and alter their degradation pathways, ultimately affecting aquatic health (Prata et al., 2020). They can impair the self-cleaning ability of environments. The fate of MPs is related to their degradation pathways and interactions with aquatic ecosystems. The accumulation of MPs in sediments can harm nutrient cycles and overall ecosystem functioning, affecting a range of aquatic organisms (Rezania et al., 2018; Xu et al., 2020). MPs can accumulate in sediments and enter organisms through food webs, thereby affecting nutrient cycles and ecosystem health (Figure 2). Benthic organisms are particularly susceptible to MP accumulation, while marker species across various aquatic food webs are increasingly being documented with MP presence (Ajith et al., 2020; Darabi et al., 2021; Zhang et al., 2019). In a nutshell, microplastics pose complex challenges in aquatic ecosystems, affecting both environmental health and biodiversity. Therefore, the long-term effects of MPs on ecosystems and human health still need further investigation.

## 3 Microplastics toxicity potential

Once MPs enter the environment, humans and other organisms including aquatic and terrestrial organisms can get exposed *via* diverse pathways, directly causing health risks (Elizalde-Velázquez and Gómez-Oliván, 2021). Coupled with the small sizes of MPs, they are easily ingested by organisms at all trophic levels, causing increased bioaccumulation in higher trophic levels including humans (Figure 3). For instance, researchers have presented that human exposure to MPs mainly occurs *via* the food chain (Al

Mamun et al., 2023; Mercogliano et al., 2020; Pironti et al., 2021), implying that the severity of any associated toxicity may be higher in humans compared to other organisms. In addition, owing to the adsorption of MP particles to other inorganic and organic contaminants, for instance, heavy metals, the toxicity of MPs can also be indirect. Recently, toxicological studies increasingly use receptor-level pathways and molecular biomarkers to assess microplastic (MP) impacts on human health, focusing on mechanisms such as the aryl hydrocarbon receptor (AhR), peroxisome proliferator-activated receptors (PPARs), and estrogen receptors (ERs) that mediate oxidative stress, inflammation, and endocrine or immune disruption (Al Mamun et al., 2023; Mercogliano et al., 2020). Biomarkers like reactive oxygen species (ROS), pro-inflammatory cytokines, apoptosis proteins, DNA damage indicators, and epigenetic changes help quantify MP-induced effects, providing critical mechanistic insights for risk assessment (Zhang et al., 2020; Zimmermann et al., 2019). Accordingly, we examine recent literature findings on the toxicity of MPs in relation to chemicals in plastic products, the MP particles themselves (direct toxicity), and the indirect effects they pose to organisms.

## 3.1 Toxicity of chemicals in plastic products

Across the globe, plastic products that are frequently used today include polypropylene, polystyrene, polyethylene terephthalate (PET), polycarbonate, polytetrafluoroethylene (PTFE–Teflon), and polyurethane (PUR) coatings) (Barnes et al., 2009; Cole et al., 2011; Lambert et al., 2013). Primary MPs originate from several types of products including plastics, synthetic textiles, abrasion of tires through driving, road markings, city dust, marine coatings, intentionally added MPs in products of personal care, for instance, engineered plastic pellets, and microbeads in facial scrubs. Most of these consumer plastic products are synthetic of various polymers, chemical additives, including antioxidants, stabilizers, plasticizers, catalysts, and flame retardants, and other byproducts (Rochman et al., 2019). These additives are added to improve the plasticity, and resistance to ultraviolet radiation, and reduce decomposition and flammability of fairly pure polymers. In addition, other desirable physical properties of the finished product are also achieved thanks to the addition of additives (Andrady and Neal, 2009; Lambert et al., 2013), and most of them are toxic *in vitro*, yet largely remain unidentified (Zimmermann et al., 2019). From the chemical composition contained in the manufactured plastic products and their combination with contaminants in the water and sediments, plastics have the potential to become a source of pollution. Thus, there is a rising concern about their toxicological influences on aquatic organisms, but also organisms that are either directly dependent on aquatic life (Teuten et al., 2009).

Owing to their small size and large surface to volume ratio, MP particles are prone to adsorption to other pollutants, thereby accumulating them from environmental media such as water (Brennecke et al., 2016; Holmes et al., 2014; Menéndez-Pedriza and Jaumot, 2020; Santos et al., 2021). This tendency for MPs adsorption to pollutants can depend on the properties of both the MPs themselves and the pollutants. Such properties include the type and age of the MPs, but also the polarities of both the MP and the pollutants. For instance, when Wang and Wang (2018) studied the sorption process of pyrene (Pyr) – a polycyclic aromatic compound in water and sediments on types of plastic particles, including polystyrene (PS), high-density polyethylene (PE), and polyvinylchloride (PVC), they reported that PE indicated the strongest connection for Pyr compared to PS and PVC. Further, results from a study that investigated the sorption actions of fuel-related water contaminants such as ethyl benzene, benzene, and xylene (BTEX) on plastic pellets showed that the formation of the oxidized facet layer on PS due to aging led to less sorption of BTEX (Müller et al., 2018). In addition to other properties such as the polarity, environmental conditions (pH and salinity) are also reported to influence the capacity of pollutants to sorb on MPs. For instance, the sorption of heavy metals, including Pb, Ni, Co, and Cd on pellets of PE have been shown to increase at high pH values (Holmes et al., 2014).

The heterogeneity of MPs is determined by their physical properties (shape, size, and color), and their chemical composition (polymers, additives, and by-products). Accordingly, the toxicity of MPs depends on the polymer types or the chemical ingredient of a plastic product, and consequently its fragments (Renzi et al., 2019). It should be remarked that high molecular mass polymers are inert, thus, not hazardous in terms of toxicity. Rather, it is the existence of the low molecular mass polymers, chemical additives, and other residual monomers that may affect the transport capacity of chemical materials from polymeric substances (Sheftel, 2000). In fact, most of the plastic monomers and additives are perilous in diverse ways to both humans and other organisms. For instance, bisphenol A and di (2-ethylhexyl) phthalate (DEHP) are toxic for reproduction; acrylonitrile, vinyl chloride, 1,3-butadiene, and benzene are carcinogenic; acrylonitrile, formaldehyde, methyl methacrylate, and toluene diisocyanate (TDI) are allergenic; phenol, benzene, and 1,3-butadiene are mutagenic; benzene also has high chronic toxicity, phosgene and TDI also has high acute toxicity, whiles others such as acrylonitrile, pentabromodiphenyl ether (PeBDE), and TDI are known to be environmentally risky and with long-term influences (Knight, 2006; Lithner et al., 2009).

Different types of plastic products that are available on the market can contain one or more varieties of chemicals that may be toxic. A recent study that analyzed the chemical signatures of plastic consumer products composed of eight major polymer types: polyethylene terephthalate (PET), polyvinyl chloride (PVC), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyurethane (PUR), polylactic acid (PLA), polypropylene (PP), and polystyrene (PS) prioritized up to 27 different chemicals (Zhang et al., 2020; Zimmermann et al., 2019). In total, the authors detected as much as 1,411 features, which included monomers, additives, and non-purposely added substances. Most chemicals contained in plastic products such as plasticizers, antioxidants, colorants, residual monomers and oligomers, polymerization byproducts, flame retardants, and other compounding impurities (Muncke, 2009) are weakly connected to the polymer matrix through van der Waals forces. This makes them easier to enter the environment

TABLE 2 Toxicological impacts of microplastics on human health [Source: Hua et al. (2022); Goodman et al. (2022); Hou et al. (2022); Zurub et al. (2024)].

| Human organ/ system | Experimental model used | Microplastic types (size) | Microplastic concentrations (μg/mL) | Exposure time | Health impacts |
|---|---|---|---|---|---|
| Forebrain | 3D structured organoids (human forebrain cortical spheroids) | Polystyrene (1 and 10 μm), and phthalates | 5, 50, and 100 | 7 and 27 days | **Short-term exposure:** Polystyrene microplastic (PS-MPs) boosted cell growth and the expression of brain progenitor genes such as Nestin and PAX6, while also elevating the oxidative stress response indicator, SOD2. **Long-term exposure**: PS-MPs lowered cell survival and changed gene expression associated with brain tissue patterning, including β-tubulin III and TBR1, indicating a possible hindrance to neural development. **Particle size and penetration:** Tiny PS-MP particles (1 μm) exhibited higher cell penetration, underscoring the potential neurotoxicity of PS-MPs. |
| Lungs/ Respiratory tract | 3D structured organoids (human airway organoids are generated from the lung tissue-resident stem cells) | Polyester fibers (700 ± 400 μm), and stabilizers (e.g., UV stabilizers, antioxidants) | 1, 10, and 50 | 7 days | **SCGB1A1 expression:** There was a decrease in SCGB1A1 expression, an important indicator of lung damage and healing, even though there was no notable inflammation. **Epithelial markers:** Other epithelial markers remained relatively stable, the reduction in SCGB1A1 indicates possible interference with lung repair processes. **Oxidative stress:** Minor elevations in markers of oxidative stress were observed, suggesting potential oxidative harm, necessitating additional investigation into the lasting effects of MPFs on lung function. |
| Heart | 3D structured organoids (cardiac organoids generated from pluripotent stem cells) | Polystyrene (1 μm), and Antimicrobials like silver nanoparticles and triclosan | 0.025, 0.25 and 2.5 | 3 days | **Cardiotoxicity:** Microplastics (MPs) can harm the heart, resulting in oxidative stress, cell death, inflammatory reactions, and build-up of collagen in heart tissues. **Cardiac hypertrophy**: MPs exposure led to higher levels of genes and markers associated with hypertrophy, suggesting possible development of cardiac hypertrophy. |
| Kidney | Human embryonic kidney 293 cells (HEK 293) | Polystyrene (1 μm), and Flame Retardants (e.g., brominated compounds, organophosphates) | 5 | 3 days | **Cellular proliferation:** Exposure to 1 μm PS-MPs caused a notable decrease in cell growth **Morphological changes:** PS-MP particles exhibit significant morphological alterations, and absorptionwas observed in both cell types after 3 days. **Reactive Oxygen Species (ROS):** Elevated levels of ROS were seen in both cell types, suggesting the presence of oxidative stress. **Gene expression:** Exposure to enzymes leading to a reduced capacity of cells to detoxify ROS. |
| Liver | Human hepatocellular carcinoma cells (Hep G2 or HEPG2) | | | | |
| Intestine | Intestinal organoids | Polystyrene nanoparticles (PS-NPs) (50 nm), and | 10 and 100 | 2 days | **Selective accumulation:** PS-NPs preferentially target endocrine, |

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TABLE 2 (*Continued*) Toxicological impacts of microplastics on human health [Source: Hua et al. (2022); Goodman et al. (2022); Hou et al. (2022); Zurub et al. (2024)].

| Human organ/ system | Experimental model used | Microplastic types (size) | Microplastic concentrations (μg/mL) | Exposure time | Health impacts |
|---|---|---|---|---|---|
| | | Antimicrobials like silver nanoparticles and triclosan | | | goblet, and Paneth cells in the intestine, indicating variable susceptibility among cell types. **Oxidative stress and inflammation:** PS-NPs induce oxidative stress and inflammation, resulting in cellular damage. **Apoptosis:** PS-NPs induce apoptosis in intestinal cells, highlighting the detrimental effects of nanoplastic accumulation. **Prolonged exposure:** Increased exposure time and concentration of PS-NPs heighten the risk of cellular damage. **Endocytosis inhibition:** Chlorpromazine (CPZ) inhibitor reduces PS-NP uptake, leading to decreased apoptosis and inflammation in intestinal organoids. |
| Placenta | Maternal surface, maternal-fetal exchange region, and fetal surface | Polystyrene (PS), polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC) (2–60 μm), and Colorants like dyes, pigments. | - | - | **Fetal growth and development:** PS-MPs in the placenta suggest a potential disruption of normal fetal growth and development, raising concerns regarding the possibility of long-term developmental effects. |

and be absorbed by organisms in the aquatic environments (Oehlmann et al., 2009).

In relation to aquatic environments, major contaminants that have been detected in plastic materials include phthalates, polybrominated diphenyl ethers (PBDEs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), bisphenol A (BPA), organochlorine pesticides (OCPs), alkylphenols, as well as heavy metals such as Zn, Al, and Zn (Engler, 2012). Different types of plastic materials have different rates of sorption to chemical compounds in aquatic environments. Owing to the low solubility of hydrophobic compounds such as PCBs, PAHs, and OCPs, they tend to partition to plastic debris in aquatic environments (Engler, 2012). For instance, results from a study on contaminant sorption to plastic materials indicated that compared to PET and PVCs, PCBs sorbed more easily to low- and high-density polypropylene and polyethylene (Rochman et al., 2014b). Due to the persistence of plastic materials in the aquatic environment, the chemicals, and other ingredients such as monomers and additives may easily leach into surrounding waters, thereby serving as sinks for accumulation of other chemicals such as persistent, bioaccumulation, and toxic (PBT) pollutants (Engler, 2012). Further, these plastic compounds can be toxic to aquatic organisms when consumed. For example, a study that investigated the hazardous chemical emissions of plastic products to water found that leaching of these chemical compounds from plastic consumer products into the aquatic environments led to acute toxic influence for *Daphnia magna* in 9 out of 32 products and the leachates ranged between 5 and 80 g plastic material per liter (Lithner et al., 2009).

## 3.2 Particle toxicity of MPs

Due to their microscopic size and omnipresence in different media, MPs are bioavailable to many organisms (Table 2). Organisms can easily interact with MPs, thereby consuming them together with their food. The literature is replete with reports of ingestion of MPs by different types of organisms, for instance bivalves, zooplankton, and vertebrates (Wieland et al., 2022). Upon ingestion, these MP particles are known to enter circulatory systems and tissues of organisms (Lu et al., 2016). In aquatic ecosystems, filter-feeding organisms such as mussels have been reported to ingest MP particles in large amounts as they feed on particulate matter (Moore, 2008), potentially causing adverse effects. Toxic effects of consumed MP particles that have been shown in the previous studies include reduction in number of offspring and changes in the proteomic profiles in the mussel *Dreissena* and *Daphnia*, as well as changes in the antioxidative capacity of *Dreissena* (Trotter et al., 2021; Weber et al., 2021). Further, when Wieland et al. (2022) exposed *Dreissena bugenis* (*D. bugenis*), a freshwater mussel to fragments of polyamide, polylactic acid, polystyrene, and polyethylene terephthalate from drinking bottles, the authors reported that ingestion of these fragments caused polymer type-dependent negative effects such as proteomic alterations and antioxidant enzymes, which were associated to chemicals and residual monomers such as BHT–a synthetic phenolic antioxidant that is used as a thermostabilized in the production of plastics, as well as modifiers like isophthalic acid (IPA) and diethylene glycol (DEG), and phenylene-bis-oxazoline (PBO) that are found in MPs. In addition to ingestion by organisms, humans can also consume MPs through contaminated food such as

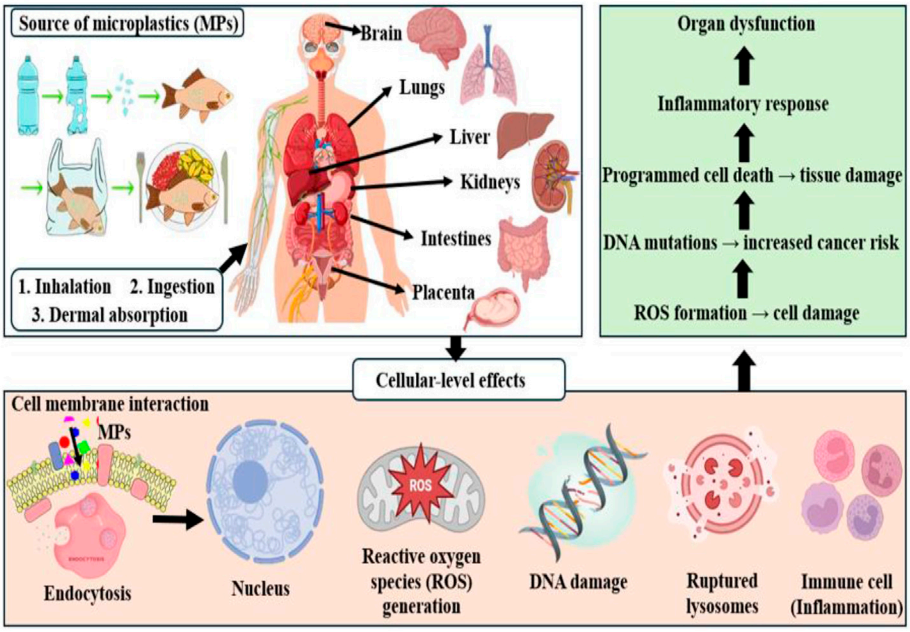


FIGURE 4
Impact of microplastics on human organ systems and cellular functions.

seafood and plastic packaging containing drinks and foods (Jadhav et al., 2021), and these pose risks to human health and food security (De-la-Torre, 2020).

Plastic is not digested by organisms and humans but remains in body parts. Thus, they can cause gastrointestinal dysmotility and obstruction (Figure 4). In aquatic environments, interactions of MP particles with other impurities could harm organisms, thereby affecting humans when consume. Studies has shown that MP particles with sizes 1.5 μm can dause direct damages to cells by penetrating tissues (Revel et al., 2018). Through consumption of seafoods such as fish, crabs, and oysters, the average person is reported to ingest approximately 11, 000 MPs and nanoplastics annually (Galloway, 2015; Van Cauwenberghe and Janssen, 2014). Moreover, apart from these direct toxic effects, findings from a recent study suggest that MPs have the potential to exert damaging effects to humans by modifying the dynamics of vector-borne diseases and the exposure to pathogens (Loiseau and Sorci, 2022).

Recently, emerging evidence indicates that microplastics (MPs), especially those smaller than 10 μm, may penetrate the placental barrier, leading to potential fetal exposure during gestation (Anifowoshe et al., 2025). For instance, Ragusa et al. (2021) evaluated microplastic observation in six human placentas. In this study, Raman Microspectroscopy detected 12 microplastic fragments (5–10 μm) in four out of six human placentas, including the fetal side (5), maternal side (4), and chorioamniotic membranes (3). These particles have been identified in human placental tissue, where they may interfere with essential biological processes like nutrient transfer and immune system modulation (Paul et al., 2024). Furthermore, the chemical additives and pollutants carried by MPs can function as endocrine disruptors, raising concerns about their effects on fetal development. Early studies also associate MP exposure with oxidative stress, inflammation, and changes in gene expression within placental cells, underscoring the need for more in-depth investigation into their prenatal health implications.

## 3.3 Indirect effects of MPs

Over the years, researchers have observed MPs of varying characteristics in different compartments of the environment such as the ocean (Andrady, 2011), in freshwater resources (Sarijan et al., 2021), floodplains (Scheurer and Bigalke, 2018), in soils (Rillig, 2012), and in the atmosphere (Chen et al., 2020). Due to the ubiquity of MPs in all these compartments, several organisms can be directly or indirectly exposed to either the MP particles themselves, or the chemical contaminants they are associated with. As already indicated, MPs have been in detected several marine organisms including commercial edible bivalves such as mussels, clams, and oysters all over the world. Apart from the direct negative effects of MPs on activities such as filtration, feeding behavior, and reproductive health in these organisms, other indirect effects could occur as a result of the organism's association with MPs. Indirect effects that have been reported in bivalves include changes to the structure of their sedimentary habitats, impairment of their food resources, and delivery of persistent organic pollutants (Zhang et al., 2020). Further, since these organisms and potentially several other aquatic organisms are produced at commercial scales such as in aquaculture for human consumption, this has indirect impact on food safety in relation to human exposure to MPs, consequently posing risks to human health.

MPs can also worsen the toxic effects of chemicals on organisms as they enhance the bioaccumulation of toxic chemicals. Results from the work of Rochman et al. (2013) indicated that mean concentrations of hydrophobic compounds including polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons, and PCBs in a fish sample with MPs were between 1.2 and 2.4 times higher compared to concentrations in fish samples without MPs. Moreover, just as the polymers and additives, heavy metals could also be added during the manufacture of plastic products (Nakashima et al., 2012). In addition to those added during manufacturing, metals already present in water column and sediments can sorb to MPs. Several types of heavy metal ions including Fe, Cu, Pb, Co., Mn, Al, Cd, and Zn have been reported to sorb to plastic debris (Beaman et al., 2016; Rochman et al., 2014a; Rochman et al., 2014b). These results imply that MPs can be important sources of heavy metal contamination in aquatic environments.

Apart from indirect effects on aquatic organisms and potentially humans, organisms in other environments such as soils are also known to be affected indirectly by MPs. That is, by modifying the physicochemical and soil biological properties, organisms that live in soils tend to be affected indirectly. For instance, the tensile strength and aggregate formation of soils are reported to be influenced by MPs (de Souza Machado et al., 2019).

Further, by causing changes in the physiological properties of soils, MPs could also pose indirect threats to the survival of plants in terrestrial environments, and potentially reduce crop yield. Studies have reported detection of MP particles in soils from diverse areas including industrial zones and farmlands (Fuller and Gautam, 2016). In farmlands, MP contamination arises from abandoned agricultural film degradation after being used to minimize soil moisture loss and protect crops against changes in ambient temperature (Chen et al., 2013). These practices are known to indirectly influence crop yield. For instance, up to 15% reduction in the production of cotton in China has been attributed to long-term coverage of agricultural topsoil with such plastic films (Liu et al., 2014). Thus, seeing as plastics are used for similar purposes in agricultural lands all over the world, it is possible that MPs from those plastic films might be indirectly affecting crop yield. MP pollution in agricultural soils could also be caused by other common agricultural activities, for instance, the use of sewage sludge as fertilizer, application of organic manures, and plastic mulching (Watteau et al., 2018). It has shown that when MP particles sizes are much bigger (e.g., 100 nm–5 mm), they can indirectly harm plants through modifications or disruptions in the soil structure, clogging of seed pores, inhibition of water uptake (Bosker et al., 2019). According to these authors, up to 78% reduction in seed germination occurred after exposing the seeds of *Lepidium sativum* to MPs in different sizes for 8 h.

Dong et al. (2020) studied the effects of polytetrafluoroethylene and polystyrene on Arsenic (As) contents in the roots and the leaves of rise seedlings, the researchers reported that samples treated with a combination of MPs and As demonstrated more changes in physiological and biochemical features compared to those tread with only As. In addition, the authors found that As adsorption in the roots of the seedlings decreased with increasing concentrations of the MPs. Since As is one of the most harmful environmental pollutants, the decrease in its uptake by plants potentially caused by MPs may be an advantage. Nonetheless, this also highlights the adsorption capabilities of MPs to As and possibly other harmful metals in the soil. That is, this demonstrated ability of MP particles to take over available adsorption sites on the roots could inhibit relevant root activities such as water and nutrient uptake, but also microbial activities on the roots, consequently affecting crop yield. Moreover, MPs have the potential to increase soil temperature by absorbing and transmitting solar radiation. This could increase the temperature of the microclimate of root zones of crops, which may enhance evaporative water loss, potentially inhibiting growth, and crop yield.

Microplastic waste intersects with climate strategies and lifecycle pollution in multiple, interconnected ways. From the extraction and refining of fossil fuels used in plastic production to the manufacturing, transportation, and eventual disposal of plastic products, each stage contributes significantly to greenhouse gas emissions (e.g., $CO_2$, $CH_4$, $N_2O$) (de Souza Machado et al., 2019). These emissions exacerbate climate change, undermining efforts to achieve net-zero targets (Nakashima et al., 2012). Additionally, the persistence of plastic in the environment leads to widespread pollution across terrestrial and aquatic ecosystems, often degrading into microplastics that pose chronic risks to human and ecological health (Rochman et al., 2014a; Rochman et al., 2014b). The incineration of plastic waste further contributes to air pollution and climate-forcing emissions, while landfilling can result in leachate and methane release (Sarijan et al., 2021). Addressing plastic pollution, therefore, is not only an environmental imperative but also a critical component of integrated climate strategies that consider the full life cycle of materials and their cumulative impacts on planetary health.

## 4 Routes of exposure

The main routes of exposure of microplastics in aquatic environments to humans include ingestion and dermal contact (Enyoh et al., 2020; Prata et al., 2020). Microplastics are ingested by humans through the consumption of contaminated water and food products, for instance, fish, shrimp, and crabs, and are absorbed through dermal contact (Prata et al., 2020). The following sections will provide more information about these exposure pathways (Figure 3).

### 4.1 Ingestion

Ingestion can be considered the main route of entry of MPs from aquatic environments into the human body (De-la-Torre, 2020; Elizalde-Velázquez and Gómez-Oliván, 2021). These particles can enter the human body through drinking contaminated water, incidentally drinking water while swimming, and consuming foods (Elizalde-Velázquez and Gómez-Oliván, 2021; Prata et al., 2020). Of these three pathways, food consumption is the most common route of exposure based on the low concentrations of MPs found in drinking water and the infrequency of incidental ingestion while swimming (Prata et al., 2020). Food chain exposure is based on human consumption of MP-contaminated aquatic organisms. Through this process, people may have introduced plastic particles into their bodies. Based on food consumption, microplastic intake is estimated to be 39,000–52,000 particles per person per year (Enyoh et al., 2020; Prata et al., 2020). There are many previous studies that have reported the presence of MPs in various aquatic organisms ranging from plankton to invertebrates and vertebrates (Darabi et al., 2021; de Souza Machado et al., 2019; Issac and Kandasubramanian, 2021). In particular, shellfish consumption is the route through which MPs are absorbed into the body most effectively (11,000 microplastics per person per year) due to the high accumulation of MPs in these species (Smith et al., 2018). In addition, salt consumption is also reported to be a route for introducing MPs into the human body (Prata et al., 2020; Yang et al., 2015). Yang et al. (2015) estimated that in China, each person ingested 100 microplastic particles per year through salt consumption.

### 4.2 Inhalation

Inhalation of microplastics (MPs) is an emerging pathway of exposure that raises significant health concerns (Chen et al., 2025). Airborne MPs are generated from various sources, including synthetic textiles, vehicle tire degradation, plastic breakdown, and industrial activities (Santizo et al., 2025). Research indicates that indoor air can have MP concentrations ranging from 0.1 to 1.2 particles per cubic meter, with urban areas often showing higher levels due to plastic waste degradation (Li et al., 2021). The size of inhaled MPs can vary, with fine particles (less than 10 μm) reaching the lungs, and even smaller particles (below 1 μm) potentially penetrating deeper into the respiratory system and entering the bloodstream (Ageel et al., 2024). These particles are particularly concerning as they can be inhaled during everyday activities, especially in indoor environments where MPs accumulate in dust and air.

Health risks linked to inhaling MPs include respiratory inflammation, oxidative stress, lung fibrosis, and potential damage, with long-term effects such as asthma, chronic obstructive pulmonary disease (COPD), and even cancer (Geng et al., 2023). Research has demonstrated that inhaled MPs can trigger inflammatory responses in lung tissues, which are worsened by their small size and large surface area (Cao and Cai, 2023). Particularly small MPs (less than 0.1 μm) can move to other organs, potentially leading to systemic health issues, including neurotoxicity, immune disruption, and cardiovascular damage (Lu et al., 2023). Studies suggest that individuals living in urban environments may inhale between 39,000 and 52,000 microplastic particles annually through the air, with additional exposure from food and beverages adding up to an estimated total of around 74,000 particles per year (Eberhard et al., 2024; Tomonaga et al., 2024). This exposure, coupled with the increasing presence of microplastics in the environment, highlights the pressing need for more detailed research on inhalation risks, exposure levels, and potential chronic health consequences (Soo et al., 2024).

### 4.3 Dermal contact

MPs can be absorbed through the skin when humans come in contact with contaminated water or sediment (Galloway, 2015). MPs particles will penetrate through skin pores to penetrate inside the human body (Galloway, 2015; Prata et al., 2020). Therefore, this exposure route depends on the sensitivity as well as the skin structure characteristics of each person. MPs fibers with very small sizes (<25 μm) can penetrate skin pores (Sharma and Chatterjee, 2017). MPs with sizes smaller than 100 nm can penetrate the skin barrier (Revel et al., 2018). Microplastics can enter the human body through dermal contact, though this route is less significant than ingestion or inhalation. Exposure can occur *via* personal care products containing microbeads, which may adhere to the skin or enter through pores or hair follicles, especially if the skin is damaged (Naji et al., 2017; Rahman et al., 2021). Contact with microplastic-contaminated water during bathing or swimming, particularly in warm conditions, may also increase skin exposure (Zhao et al., 2024). Wearing synthetic clothing can release microplastic fibers that accumulate on the skin, especially in hot, humid environments (Enyoh et al., 2020; Prata et al., 2020). In occupational settings, repeated skin contact with microplastic dust may allow limited penetration into the outer skin layers, particularly when the skin barrier is compromised (Yuan et al., 2022). There is still a lack of comprehensive studies on human dermal exposure to MPs. Nonetheless, the dermal contact exposure pathway to microplastics cannot be ignored.

Dermal absorption of microplastics (MPs) is an emerging research area, with *in vitro* studies using reconstructed human epidermis (RHE) models showing limited penetration of particles larger than 1 μm, primarily accumulating on the outer skin layers (Abafe et al., 2024; Li et al., 2024). Nanoplastics (<100 nm) exhibit greater absorption potential, potentially inducing oxidative stress or skin damage (Yang et al., 2025). *In vivo* studies with animal models confirm minimal absorption in healthy skin but suggest that damaged or inflamed skin may allow deeper penetration, particularly of smaller particles (Liu and You, 2023). Key knowledge gaps include a lack of standardized testing methods, limited data on chronic exposure, and insufficient understanding of how MP size, shape, and surface chemistry affect absorption. Further research, particularly on nanoplastics and aged MPs, is needed to better assess dermal risks.

## 5 Potential health impact and health risk assessment

### 5.1 Potential human health risks

Microplastics pose several potential health risks to humans, although research is still ongoing. When ingested or inhaled, they can accumulate in the gastrointestinal tract or lungs, potentially causing inflammation, oxidative stress, and disruption of the gut microbiota or respiratory function (Enyoh et al., 2020; Prata et al., 2020). Microplastics often contain chemical additives, such as phthalates and bisphenol A, and can also absorb environmental pollutants like heavy metals and persistent organic pollutants (Prata et al., 2020). These chemicals may leach into the body, potentially interfering with the endocrine system and contributing to reproductive, neurological, and immune disorders, as well as increasing cancer risk (Rahman et al., 2021). Research has demonstrated that MPs smaller than 10 μm can penetrate organs and cellular structures (Zhao et al., 2024). Studies indicate that smaller MPs can infiltrate the circulatory system, affecting lymph nodes (Yuan et al., 2022). Although there is limited direct research on the impact of MPs on human health, evidence suggests that high concentrations may result in toxicity (Naji et al., 2017; Rahman et al., 2021). For instance, exposure to polystyrene at elevated levels has been linked to cell death through apoptotic mechanisms (Maity et al., 2023). Moreover, exposure of human brain cells to polyethylene and polystyrene has been correlated with increased levels of reactive oxygen species (Zhao et al., 2024).

As shown in Figure 4, microplastic exposure has been associated with various health effects, including oxidative stress, inflammatory responses, neurotoxic effects, and reproductive and developmental toxicity (Chelomin et al., 2024; Liu and You, 2023). Research suggests that microplastics can induce oxidative stress in cells and organs, significantly impairing cellular functions and promoting chronic diseases (Osman et al., 2023). For instance, Chen et al. (2022) reported that a total of 65 microfibers were detected in one hundred lung tissue samples from humans, which included 24 microplastics measuring greater than 25 μm in size. Moreover, the presence of microplastics can trigger an inflammatory response, which is a key factor in numerous chronic diseases, including cardiovascular conditions, diabetes, and potentially cancer (Zhao et al., 2024). Furthermore, microplastics are capable of crossing the blood-brain barrier, potentially leading to neurotoxicity (Li Y. et al., 2023). Preliminary evidence suggests that microplastics can adversely affect reproductive health and fetal development (Figure 3).

Previous study have demonstrated that microplastic exposure can disrupt reproductive hormones and lead to developmental abnormalities (Wang M. et al., 2024). For instance, Zurub et al. (2024) noted that microplastics were found to accumulate in placental tissue at levels between 0.28 and 9.55 particles per Gram of tissue. This accumulation significantly impacted normal fetal growth and development by disrupting the metabolism of amino acids, glucose, and cholesterol, which in turn led to imbalances in uterine and placental immune cells. While definitive evidence in humans is still emerging, the potential for long-term health impacts from chronic microplastic exposure is a growing concern.

## 5.2 Health risk assessment

As previously mentioned, ingestion is the primary route for MP accumulation in humans (Table 2). Due to a lack of studies directly linking MPs to human health outcomes, risk assessment methodologies remain underdeveloped. Currently, the a global average rate of MP ingestion (GARMI) is being explored as a means to evaluate health risks resulting from MP consumption Senathirajah et al. (2021). GARMI is calculated based on the formula:

$$\text{GARMI} = \text{ANMP} \times \text{AMIMP}.$$

Where ANMP represents the average number of MPs ingested, and AMIMP indicates the average mass of individual microplastics. Based on data from Senathirajah et al. (2021), annual ingestion rates vary widely depending on the source, with commonly consumed items such as shellfish, table salt, drinking water, and beer used to calculate the Global Average Rate of Microplastic Ingestion (GARMI, expressed in g/year/person) due to the availability of reliable data. Microplastics are now recognized as pervasive throughout the food chain. Drawing from diverse datasets on MP quantity and mass, recent studies like Zhao et al. (2024) have sought to identify gaps in current knowledge, refine future research priorities, and estimate a global average for MP ingestion. These findings are intended to support comprehensive human health risk assessments and inform targeted policies. Globally, individuals may ingest between approximately 11,845 and 193,200 MP particles annually, with drinking water representing a major exposure pathway. AMIMP values were categorized based on particle size, typically within the 0–1 mm range (Senathirajah et al., 2021). Under different modeling scenarios assuming spherical and cubic shapes typical of aquatic microplastics, estimated weekly intake ranges from 0.1 to 5 g. However, this intake is influenced by a range of highly variable factors, including MP characteristics and personal attributes such as age, body size, location, diet, lifestyle, and environmental context (Lee and Jeong, 2023).

However, GARMI model has limitations in accounting for variations in microplastic (MP) characteristics, such as shape, polymer type, and surface chemistry, which can significantly affect dose-response relationships (Zhuo et al., 2025; Chen et al., 2025). Different MP shapes influence ingestion rates and toxicity, with fibers posing higher risks than spheres. Polymer types, like polystyrene and PET, vary in toxicity due to differences in chemical composition and additives. Surface chemistry, including roughness and charge, affects interactions with biological systems, while adsorbed contaminants can alter toxicity (Mutlu et al., 2025). These factors can lead to differing bioaccumulation and toxicity, highlighting the need for GARMI refinement to incorporate these variations for more accurate risk assessment (Opitz et al., 2025). In recent years, other risk assessment models have been widely used, such as Hazard Quotient (HQ) models, which compare exposure levels to reference doses, and Weight-of-Evidence frameworks, which integrate diverse data to provide a more nuanced understanding of biological impacts (Gangula et al., 2023; Ruijter et al., 2020). Integrating GARMI with these models could lead to a more robust and comprehensive approach to microplastic risk assessment.

# 6 Conclusions and future recommendations

Microplastics pose a significant environmental challenge, with concentrations in marine surface waters reaching up to 1.9 million particles/$m^3$ in heavily polluted areas and sediments containing over 500,000 particles/kg. In freshwater systems, levels can range from 100 to 100,000 particles/$m^3$. Human exposure is estimated at 39,000 to 52,000 particles annually through food and beverages, with additional inhalation contributing up to 74,000 particles per year. Their pervasive presence in water systems necessitates a comprehensive understanding of their sources and pathways. The scientific community must prioritize targeted strategies to combat this pressing issue through:

- To address existing knowledge gaps, interdisciplinary integration is essential, linking microplastic research with climate science, food security, and public health policy. This approach can help assess broader implications, such as the potential contribution of microplastics to chronic health conditions like cardiovascular disease, which remain poorly understood. Moreover, advancing this field requires overcoming methodological limitations, particularly in detecting and characterizing particles smaller than 1 µm, which are likely more biologically active and capable of systemic translocation. Integrating scientific, technological, and policy perspectives will be critical for developing comprehensive risk assessments and effective mitigation strategies.

- Conducting more specific tests on the toxicity of each type of microplastic to establish a clearer foundation for assessing their impact on human health. Toxicological studies should consider individual properties, various environmental conditions, and effects on different organs. It is essential to gain a deeper understanding of the critical doses at which microplastics can cause adverse effects on human health.
- Standardized testing protocols and regulatory thresholds for microplastics (MPs) are still in development, with international efforts by ISO, OECD, ASTM, and the U.S. EPA aiming to harmonize sampling, identification, and quantification methods. While ISO 21960 and EU REACH initiatives offer early frameworks, no globally accepted thresholds exist, and most methods target particles >1 µm using spectroscopic techniques. Proposed benchmarks, such as the EU's 10 µg/L for drinking water and California's pilot limits, highlight growing regulatory interest. However, key challenges remain, including inconsistent methodologies, limited toxicological data, and the need to address microplastics. Further progress requires validated protocols and health-based risk assessments.
- Encouraging research and development of biodegradable alternatives such as natural fibers and, bioplastic for products like packaging, textiles, and microbeads can significantly reduce dependency on synthetic plastics (Osman et al., 2025). Additionally, further study will highlight the environmental and economic advantages of upcycling, such as minimizing plastic waste, conserving natural resources, lowering carbon emissions, and promoting the circular economy.
- Extended Producer Responsibility (EPR) schemes, plastic taxes, and compostable certifications are key tools to reduce plastic pollution. EPR holds producers accountable for waste, plastic taxes discourage single-use items, and certifications ensure true biodegradability. Their impact depends on strong regulation and supporting infrastructure, which need to be clarified in further studies.
- Recommending additional studies on the effects of microplastics on various human organs, exploring both carcinogenic and non-carcinogenic effects of microplastic accumulation in the body. Developing standardized methods for characterizing, analyzing, quantifying, and assessing potential human health risks from microplastic pollution.
- The implications of microplastic exposure on human health are profound, necessitating urgent attention from researchers, policymakers, and healthcare providers to develop strategies for mitigation and prevention. Understanding the mechanisms of toxicity is crucial for establishing effective public health guidelines and protective measures against this pervasive environmental issue.

These initiatives are crucial for mitigating the negative impacts of microplastics, fostering a healthier environment and promoting sustainability for future generations.

## Author contributions

HH: Writing – original draft, Formal Analysis, Visualization, Data curation, Validation, Conceptualization. NN: Investigation, Writing – original draft, Validation. TZ: Writing – original draft, Conceptualization, Visualization. H-TT: Writing – review and editing, Conceptualization, Writing – original draft, Data curation, Validation. SM: Conceptualization, Writing – original draft, Data curation. RN: Supervision, Conceptualization, Writing – original draft, Funding acquisition.

## Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

## Acknowledgments

H-TT gratefully acknowledges the time, support, and research facilities provided by Van Lang University, Vietnam. The authors also sincerely appreciate the constructive feedback, valuable suggestions, and efforts of the reviewers and the Editor, which have significantly contributed to improving the quality of this manuscript.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note

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