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Microplastics and human health: Exposure pathways, toxicological impacts, and sustainable risk management

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Abstract

Microplastics (MPs) have become pervasive environmental contaminants, raising growing concerns regarding their implications for human health and environmental sustainability. This perspective paper explores the various ways humans are exposed to MPs, including through diet, air, and skin contact. Seafood, especially fish and shellfish, is a major source of dietary exposure, but MPs have also been found in water, salt, and other food products. The small size of MPs allows them to cross biological barriers and potentially cause harm. Once inside the human body, MPs can induce oxidative stress, inflammation, and cellular damage, and they can also act as carriers for harmful chemicals and pathogens, further increasing their health risks. Beyond characterizing health effects, this paper reviews current approaches for risk assessment and sustainable risk management, including the estimated daily intake and polymer hazard index, which are essential tools for evaluating the toxicity of different polymer types and prioritizing mitigation efforts. Despite ongoing research, significant gaps remain in our understanding of the long-term effects of chronic exposure to MPs, underscoring the need for further studies. To address these risks, this paper discusses strategies to reduce exposure, including reducing plastic use, improving food packaging, and raising consumer awareness. It also emphasizes the importance of international collaboration and policy action to mitigate the public health threat posed by MPs. Finally, we call for further research, particularly in terms of human biomonitoring and interdisciplinary collaboration, to better understand the full range of health impacts and inform effective policies.

Keywords: Microplastics; Human health; Sustainability; Toxicity; Exposure; Risk assessment

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1. Introduction

Sustainable management of plastic waste is pivotal to limiting environmental contamination and protecting human health. While recycling enables the reprocessing of plastic waste into new products, its effectiveness remains limited by technical and infrastructural constraints, particularly in developing regions, allowing plastics to persist in the environment and increase human exposure.[1] Consequently, preventive strategies such as reduction and reuse are increasingly recognized as more effective for minimizing plastic emissions at the source and lowering long-term health risks. The integrated application of the "reduce, reuse, and recycle" principles, supported by policy measures and education promoting reusable packaging, is therefore essential for advancing circular economy models while protecting public health.[2] Despite these efforts, ineffective plastic waste management continues to facilitate the fragmentation and dispersion of plastics in the environment, leading to the formation of microplastics (MPs) and increasing human exposure.[3]

Microplastics are emerging environmental concerns that pose potential risks to human health.[1] These microscopic plastic particles, often smaller than 5 mm, are ubiquitous in the environment and infiltrate ecosystems and consumer products worldwide.[4] As we become increasingly aware of the pervasive nature of MPs, understanding how they interact with human health has become a critical area of scientific inquiry.[5] Exposure to MPs occurs through various pathways, including ingestion, inhalation, and dermal contact.[6] Seafood, particularly fish and shellfish, has been identified as a primary route of dietary exposure, with MPs found in both wild and farmed varieties.[7] Additionally, drinking water, salt, and a range of other food products contain these particles, further complicating human exposure.[8] Inhalation of airborne MPs, particularly in urban and industrial areas, and dermal exposure through consumer products, such as cosmetics, also contribute to potential health risks.[9,10]

Given their small size and widespread presence, MPs can translocate across biological barriers and accumulate in human tissues, raising concerns about their toxicity.[11] Once inside the body, MPs can induce various harmful effects, including oxidative stress, inflammation, and cellular and tissue damage.[12] Furthermore, MPs can serve as carriers for toxic substances such as heavy metals, persistent organic pollutants (POPs), and pathogens, which may increase the risk to human health.[13] The ability of MPs to adsorb and transport these harmful chemicals makes them even more concerning as potential vectors of environmental toxins.[14] Despite increasing research, numerous gaps remain in our understanding of the long-term health effects of MPs, particularly regarding chronic exposure and their impact on vulnerable populations.[15]

This perspective paper examines the major exposure pathways to MPs, their toxicological effects, and current approaches used for human health risk assessment within a sustainable risk management (SRM) framework. Despite the growing body of literature on MPs, significant uncertainties remain regarding human exposure levels, health outcomes, and the establishment of safe exposure thresholds.

Overall, the objectives of this paper are to: (i) summarize the principal pathways through which MPs enter the human body; (ii) synthesize current evidence on their toxicological effects and potential health consequences; (iii) discuss existing risk assessment approaches as tools for evaluating potential human health risks; and (iv) identify key knowledge gaps and research priorities relevant to SRM and public health protection.

Rather than providing an exhaustive review, this perspective offers a concise and focused overview of current evidence, emphasizing the challenges associated with exposure assessment, hazard characterization, and the determination of safe exposure thresholds. Particular attention is given to the need for improved human biomonitoring, standardized methodologies, and interdisciplinary research to better understand the long-term health implications of MP exposure. The role of public health policies and preventive measures in mitigating these emerging risks is also discussed in the context of environmental sustainability and evidence-based decision-making.

2. New and emerging exposure pathways

2.1. Methodology and analysis of microplastics

The detection and characterization of MPs in studies investigating human exposure pathways rely on a combination of microscopic and spectroscopic techniques.[16] In dietary exposure studies, samples such as bottled water, seafood, beverages, and food products are typically subjected to chemical digestion and filtration, followed by particle identification using simple Fourier-transform infrared spectroscopy (FTIR), μ-FTIR, attenuated total reflectance-FTIR, Raman spectroscopy, or pyrolysis-gas chromatography-mass spectrometry.[17,18] In inhalation studies, airborne particles are commonly collected using active air samplers or deposition collectors and subsequently analyzed by optical microscopy coupled with μ-FTIR or Raman spectroscopy to determine particle abundance, size, morphology, and polymer composition.[9] For dermal exposure investigations, particularly those assessing MPs in cosmetics and personal-care products, optical microscopy, scanning electron microscopy, μ-FTIR, and Raman spectroscopy are frequently employed to identify and characterize plastic particles.[19,20] Despite significant methodological advances, differences in sample preparation, detection limits, particle size ranges, and identification criteria continue to hinder direct comparisons among studies, highlighting the need for greater methodological standardization in MP research.[21]

2.2. Dietary intake

Among the various pathways of human exposure to MPs, dietary intake via food and beverages is one of the most prevalent routes.[8] Seafood, particularly fish and shellfish, is a major concern because these animals often ingest MPs from their environment, which may accumulate in edible tissues and subsequently contribute to human exposure.[7] However, MPs are also found in everyday foods such as salt, honey, milk, fruits, and vegetables, especially those grown near cities or industrial areas.[22] Drinking water is also a potential source of exposure; bottled water often contains more MPs than tap water, likely because of the plastic packaging.[23] In addition, heating food in plastic containers, such as in a microwave or with acidic foods, can cause tiny plastic particles to leach into the meal.[24] Taken together, these examples show how our diet has become a steady, if unintentional, source of MP exposure.

2.3. Inhalation

While dietary intake is often considered the primary route of MP exposure, inhalation is another important pathway that often occurs unnoticed. In indoor environments, everyday items such as carpets, furniture, and especially synthetic textiles release tiny plastic fibers into the air, which then settle in house dust or float around in the air we breathe.[25] Outdoor environments also contribute substantially to airborne MP exposure. MPs can originate from tire wear on busy roads, industrial emissions, and particles falling from the atmosphere.[9] Individuals working in certain occupations, such as textile factories, construction sites, or waste processing facilities, are often exposed to much higher levels of airborne MPs. These environments can increase the risk of breathing plastic particles, which may lead to respiratory problems over time.[26]

2.4. Dermal exposure

Although it is not the main route of exposure, human skin may come into contact with MPs, especially through the use of cosmetics and personal care products.[27] In the past, tiny plastic beads were commonly added to face scrubs, body washes, and toothpastes as exfoliants.[28] These microbeads also serve as carriers for fragrances and other chemicals. While some regions have banned their use, such ingredients are still found in various products around the world. Research on skin absorption is still in the early stages. However, extremely small plastic particles, particularly nanoplastics, can potentially pass through thin or damaged skin.[27] While this type of exposure is likely less significant than swallowing or inhaling MPs, it remains a topic of interest, especially given how frequently these products are used. Figure 1 summarizes the main human exposure pathways to MPs, illustrating how these particles can enter the body through ingestion, inhalation, and dermal contact. Complementing this overview, Table 1 presents representative recent studies reporting human exposure to MPs through dietary intake, inhalation, and dermal contact, providing evidence of the prevalence and

Table 1. Representative recent studies reporting human exposure to microplastics through dietary intake, inhalation, and dermal contact

Exposure route	Matrix/population	Main findings	Relevance to human exposure	Reference
Dietary intake	Commercial bottled water (China)	Mean MP concentration of 72.3 ± 44.6 particles/L in bottled water, exceeding levels detected in tap water. Small particles (10–50 μm) predominated.	Demonstrates drinking water as a continuous source of MP ingestion and suggests packaging may contribute to contamination.	18
Dietary intake	50 packaged nonalcoholic beverages (Hong Kong)	MPs were detected in all beverage samples, with an average abundance of 42.1 ± 41.2 particles/L. Estimated annual exposure from beverage consumption reached approximately 6,200 particles per adult.	Highlights the contribution of commercially packaged beverages to dietary MP exposure.	29
Dietary intake	Seafood, poultry, pork, beef, and processed protein products	MPs were detected in all protein categories. Highly processed products contained significantly higher MP concentrations than minimally processed foods.	Suggests food processing may increase dietary exposure to MPs.	30
Inhalation	Indoor and outdoor airborne MPs (systematic review)	Indoor MP concentrations were generally much higher than outdoor levels, with synthetic fibers dominating airborne particles.	Indicates inhalation as an important and often underestimated route of human MP exposure, particularly in indoor environments.	31

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Table 1. (*Continued*)

Exposure route	Matrix/population	Main findings	Relevance to human exposure	Reference
Dermal exposure	Liquid soaps, micellar waters, and cleansing oils	MPs were identified in several personal-care products, with polymer type, size, and abundance varying among brands. Potential exposure through skin contact was highlighted, particularly for smaller particles.	Provides evidence that cosmetics and personal-care products remain a potential source of dermal MP exposure, although the mechanisms of absorption require further investigation.	19
Dermal exposure	Review of 46 studies on dermal uptake of MNPs in *ex vivo* human and animal skin, *in vitro* skin models, and *in vivo* animal studies	Most MNPs were retained in the stratum corneum and hair follicles, with limited evidence of penetration into deeper skin layers. Uptake appeared to be influenced by particle size, shape, surface properties, skin condition, and co-exposure factors, while significant methodological and knowledge gaps remain.	Suggests that dermal exposure is likely a minor route of systemic MNP uptake compared to ingestion and inhalation, although extremely small particles and compromised skin may increase penetration potential.	32

Abbreviations: MPs: Microplastics; MNPs: Micro- and nanoplastics.

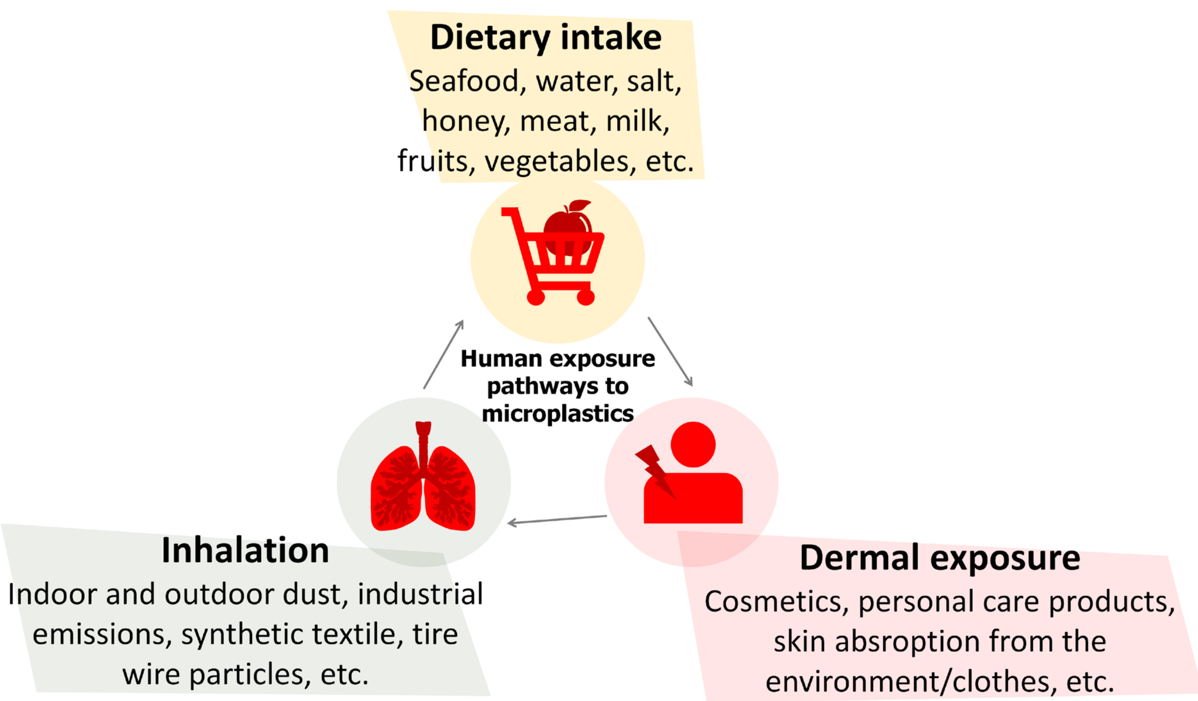

Figure 1. The main pathways of human exposure to microplastics. Image created by the authors based on information synthesized from Refs.[8,9,15,21]

diversity of these exposure routes.

3. Recent toxicological impacts

Once MPs enter the body, whether through food, water, or air, their subsequent fate largely depends on their size and morphology. Research suggests that particles smaller than 150 μm may cross the gut lining, whereas those less than 10 μm may even enter the bloodstream or the lymphatic system.[33] From there, they may travel to different organs, with studies detecting MPs in the liver, kidneys, brain, and even the placenta.[34] Both *in vivo* and *in vitro* research help scientists better understand where these particles travel and what effects they might have. Several factors seem to influence how much the body absorbs, such as whether the particle is a fiber or a fragment, its surface chemistry, and whether it is carrying a layer of bacteria or other substances forming biofilms.[35] These variables play a role in how MPs behave within the body and in the harm they might cause. Other important factors influencing the uptake and distribution of MPs include their hydrophobicity, which affects their interactions with cell membranes and digestive components such as bile salts, and their persistence, as some particles resist enzymatic degradation and may remain in tissues for extended periods.[4,36]

3.1. Physical and cellular effects

Microplastics can trigger a range of harmful effects at the cellular level, even without releasing any chemicals. One key mechanism is oxidative stress: when cells are exposed to MPs, they may begin producing excess reactive oxygen species, which can damage cellular components and lead to mitochondrial dysfunction.[37] This stress often initiates inflammatory responses as the immune system tries to eliminate foreign particles. As a result, the body releases signaling molecules such as cytokines, which can further escalate inflammation.[38] In some cases, MPs have also been shown to cause genotoxic and cytotoxic effects. This includes DNA damage, disruption of cell membranes, and even programmed cell death (apoptosis), all of which may have serious consequences for tissue health and organ function over time.[10,39]

3.2. Chemical vector potential

In addition to their physical effects, MPs can act as carriers of other harmful substances. Owing to their large surface area and chemical properties, MPs can readily adsorb environmental pollutants, including heavy metals such as cadmium and lead, POPs such as polychlorinated biphenyls and polycyclic aromatic hydrocarbons, and endocrine-disrupting chemicals like bisphenol A.[40] Once inside the body, the gut may promote the release or desorption of these substances, increasing their bioavailability and potential toxicity.[14,34] Additionally, MPs can serve as habitats for microorganisms. When covered by biofilms, MPs may carry pathogenic bacteria such as *Vibrio* or *Escherichia coli*, potentially introducing new microbial threats into the body alongside chemical contaminants.[41] Overall, the health risks associated with MPs may be amplified by their ability to act in synergy with other contaminants. When coexposed to substances such as heavy metals or POPs, MPs can increase overall toxicity through combined or synergistic effects.[40]

3.3. Organ-specific effects

The effects of MPs are not limited to the cellular level; they can also impact entire organ systems, with increasing evidence of multiorgan toxicity. In the gastrointestinal system, MPs have been linked to alterations in the gut microbiota and damage to the intestinal lining, impairing both nutrient absorption and intestinal barrier integrity.[37] Recent findings have led to the emerging concept of "plastic-induced liver injury," highlighting the need for further research to clarify causal relationships, improve exposure assessment methodologies, and better understand the long-term implications of MNP accumulation leading to human liver disease.[32] Inhaled MPs can accumulate in the lungs, where they may provoke local inflammation and, over time, contribute to fibrotic changes and respiratory complications.[42] Notably, recent studies have highlighted their ability to infiltrate skeletal tissues, including bones, cartilage, and intervertebral discs, via the bloodstream. In these tissues, MPs accumulate in region-specific patterns and induce inflammatory responses by activating proinflammatory cytokines, potentially leading to tissue degradation. Moreover, they interfere with bone morphogenetic protein signaling, which is essential for bone formation and repair, thereby posing risks to skeletal integrity.[43]

Animal experiments have further revealed the neurotoxic and endocrine-disrupting potential of MPs, with observed changes in behavior, brain function, and hormone levels.[44] MPs can disrupt the endocrine system by interfering with thyroid-stimulating hormone, disturbing the thyroid hormone balance (T3 and T4), and altering sex steroid hormones such as testosterone, estrogen, and progesterone.[45] Disruption of cortisol and other adrenal hormones also suggests potential impacts on stress regulation and metabolism. These endocrine disturbances are accompanied by reproductive disorders, including testicular abnormalities, impaired sperm morphology and vitality, ovarian dysfunction, and uterine structural changes.[45,46]

Additionally, the immune system may be compromised, as indicated by findings of hepatic fibrosis, hypersensitivity reactions, persistent inflammation, and facilitation of tumorigenesis.[38,45] MPs are also implicated in metabolic imbalance, particularly through disruption of glucose and lipid metabolism, increased risks of atherosclerosis, and interference with adrenal steroidogenesis.[5,46] Furthermore, neurological dysfunctions such as cerebral thrombosis and increased mortality risks have been reported, highlighting the extensive and systemic health impacts of MP exposure.[12,47] While further research is necessary to fully understand the long-term consequences, current evidence strongly suggests that MPs represent a widespread threat to human health across multiple physiological systems. Figure 2 provides a schematic overview of the main toxicological

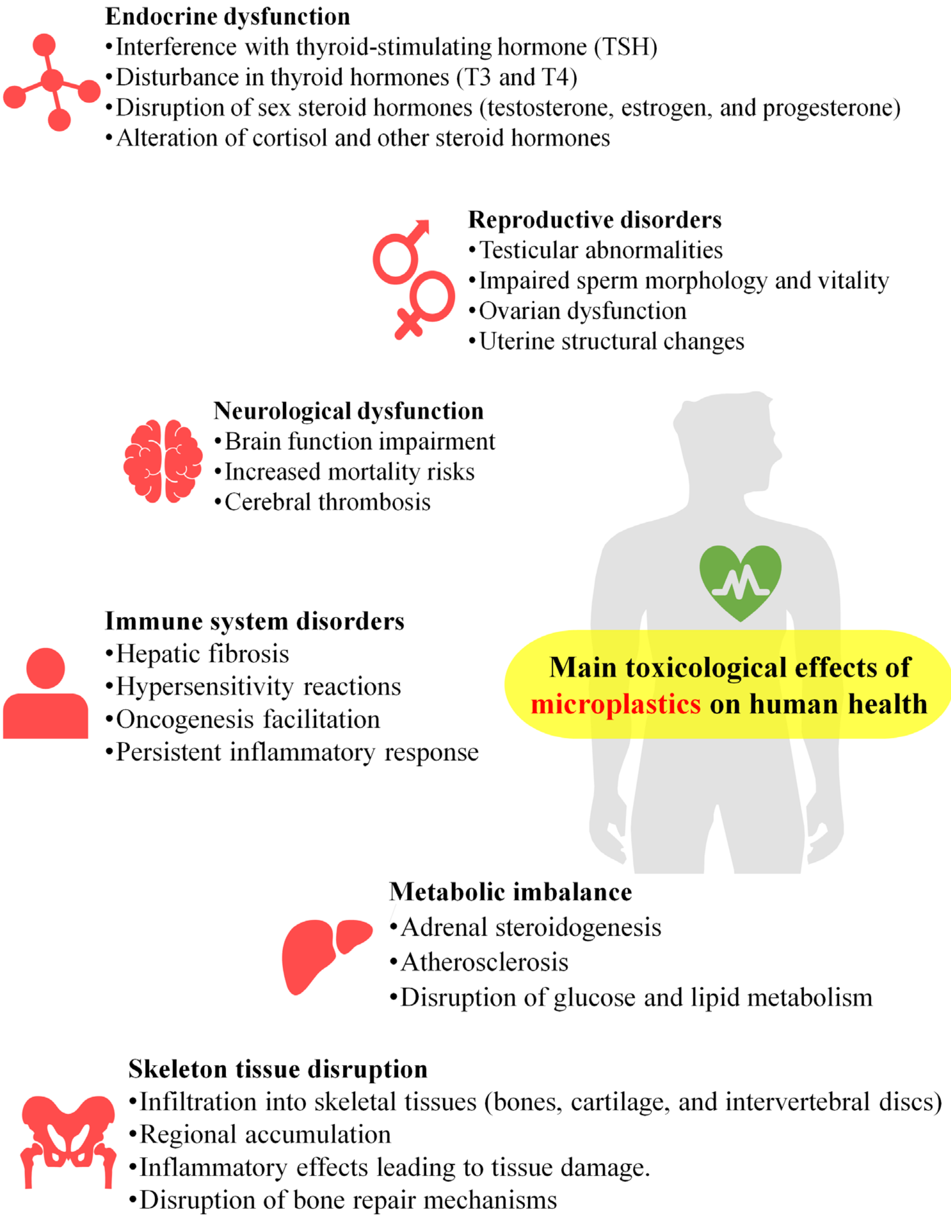

Figure 2. The main toxicological effects of microplastics on human health. Image created by the authors based on information synthesized from the studies cited in Section 3.

effects of MPs on humans, as confirmed by the literature.

3.4. Polymer-specific health impacts of microplastics

Polystyrene MPs have been widely associated with oxidative stress, immune activation, and vascular toxicity, and they represent the most extensively studied polymer, particularly in nanoplastic form, accounting for over 90% of reported nanoplastic toxicity studies.[48,49] Similarly, polyethylene particles can induce inflammation, apoptosis, and epigenetic dysregulation in human cells, although their effects may vary depending on particle size, environmental origin, and exposure conditions.[48,50] In contrast, polyvinyl chloride poses additional risks due to its chemical additives and has been linked to metabolic and oxidative disturbances *in vivo*.[51] More broadly, comparative evidence across multiple polymer types, including polypropylene and polyethylene terephthalate, indicates that toxicity is influenced not only by polymer composition but also by particle size (micro versus nano), morphology, and biological context.[48] Notably, nanoplastics tend to exhibit greater toxicity than MPs, with oxidative stress among the most frequently reported mechanisms, while most observed effects are sublethal rather than directly lethal.[4,40,48,52]

3.5. Excretion pathways of microplastics in the human body

Although MPs can enter the human body and potentially accumulate there, some are also excreted, primarily through feces. Studies have confirmed the presence of MPs in human stool samples, indicating that the gastrointestinal tract plays a key role in eliminating ingested particles.[53] However, excretion efficiency largely depends on particle size, shape, and surface properties. In addition to fecal elimination, human urine has also been identified as a potential excretion route for MPs, particularly for the smallest particles.[54] The detection of MPs in urine raises important questions about their ability to cross biological barriers and suggests that small particles, especially those in the nanometer-to-low-micrometer range, may be transported to the bladder via renal filtration. This highlights the need for further investigation into the mechanisms and efficiency of MP clearance through both the digestive and urinary systems.

4. Sustainable risk management

4.1. Risk assessment approaches

4.1.1. Estimated daily intake

One common way to assess the risk of MPs is by calculating the estimated daily intake (EDI), which estimates how much MP a person consumes daily through food.[55] This is typically calculated by multiplying the number of MPs per gram of food by the amount of that food an average person eats each day (**Equation 1**).

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{IR}}{\mathrm{BW}} \tag{1}$$

where: C = MP concentration (particles g^{-1}), IR = ingestion rate (g day^{-1}), and BW = body weight (kg).

However, the EDI can vary depending on several factors. For example, children, who tend to consume more food relative to their body weight, may have higher exposure levels than adults. Similarly, people living in coastal areas, where seafood consumption is relatively high, might ingest more MPs than those in inland areas, where seafood consumption is relatively low. This approach helps us estimate potential risks based on dietary habits and population characteristics.

4.1.2. Polymer hazard index

Another important tool for assessing MPs' risk is the polymer hazard index (PHI; **Equation 2**), which considers the type of plastic and its associated chemical additives.[56] Different polymers pose varying risks depending on their chemical composition.

$$\mathrm{PHI} = \sum\left(\mathrm{P_n} \times \mathrm{S_n}\right) \tag{2}$$

where: P_n = proportion of polymer n and S_n = hazard score of polymer n.

For example, plastics such as polyvinyl chloride and polystyrene are assigned a relatively high PHI because they contain toxic monomers and additives, which can leach out once inside the body. This index helps prioritize which types of plastics may be more dangerous based on both their chemical structures and potential toxicity, providing researchers and regulators with a clearer idea of where to focus efforts.

4.1.3. Other metrics and models

In addition to the EDI and PHI, other metrics and models can help assess the risks posed by MPs. One such metric is the margin of exposure, which compares actual exposure levels to known safety thresholds for various chemicals or substances.[57] Another approach is the use of probabilistic models, which account for the uncertainty and variability in exposure data, providing a range of potential risks rather than a single estimate.[58] There is also a need for toxicological reference values, such as oral reference doses, which indicate safe exposure levels.[59] However, for MPs, these values are currently lacking, making it difficult to establish firm safety limits and further highlighting the need for more research in this area.

4.2. Implications for public health policy and sustainable risk management

Reducing human exposure to MPs requires adopting an SRM framework that integrates public health protection with environmental sustainability and socio-economic considerations (**Figure 3**). From an SRM perspective, prevention at the source represents one of the most effective strategies to minimize exposure. Reducing plastic production and consumption, encouraging alternatives to single-use plastics, improving recycling practices, and promoting safer food storage behaviors can substantially decrease overall human exposure to MPs.[1] These measures not only mitigate health risks but also promote responsible consumption patterns aligned with sustainability principles.

Policy interventions are a central pillar of SRM and play a critical role in controlling MP pollution. Regulatory actions such as banning microbeads in personal care products, strengthening plastic labeling requirements, and restricting the production of polymers associated with higher toxicological risks can reduce environmental emissions of MPs and limit their entry into the food chain.[24] Within an SRM framework, risk assessment tools such as the EDI and PHI can support evidence-based policymaking by identifying priority polymers and vulnerable populations requiring targeted interventions.

Public health strategies must also emphasize risk communication and consumer awareness, which are essential components of sustainable risk governance. Clear, transparent communication about potential health risks enables individuals to make informed choices and supports behavioral changes that reduce exposure. At the international level, organizations such as the United Nations Environment Programme, the World Health Organization, and the European Food Safety Authority have increasingly recognized MPs as an emerging public health concern and are actively working toward the development of clear guidelines and regulatory frameworks.[60]

In summary, integrating SRM into public health and policy responses to MPs aligns closely with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (good health and well-being), SDG 12 (responsible consumption and production), and SDG 14 (life below water). By linking scientific risk assessment with preventive measures, policy action, and public engagement, SRM provides a robust pathway for mitigating the health impacts of MPs while promoting long-term environmental and societal sustainability. To illustrate the practical implementation of these strategies, Table 2 summarizes representative global case studies highlighting diverse approaches to managing MP exposure and mitigating associated human health concerns across different

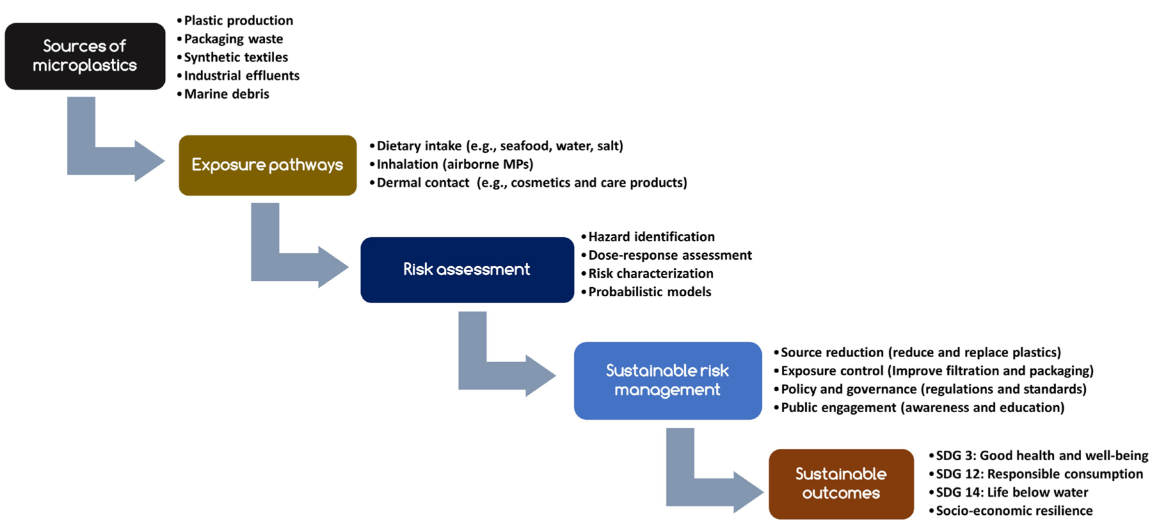

Figure 3. Integrated framework for microplastics risk assessment and sustainable management pathways. Image created by the authors based on information synthesized from Refs.[1,21,40]
Abbreviation: SDG: Sustainable Development Goal.

Table 2. Representative global case studies illustrating different approaches to managing microplastic exposure and associated human health concerns

Region	Environmental context	Main exposure concern	Management approach	Key lessons for human health protection	Reference
European Union (microbead restriction policies)	Widespread occurrence of primary microplastics in personal care products and aquatic environments	Dermal, indirect dietary, and environmental exposure from intentionally added microplastics	Regulatory restrictions on microbeads and broader restrictions on intentionally added microplastics through chemicals legislation	Prevention at the source can reduce environmental emissions and future human exposure before contamination becomes widespread.	61
China (drinking water and urban exposure studies)	High population density, urbanization, and documented microplastic contamination in bottled and tap water	Dietary exposure through drinking water and food products	Expansion of monitoring programs, improved waste management strategies, and increased research on exposure assessment	Continuous environmental surveillance is essential for identifying major exposure pathways and supporting evidence-based public health interventions.	62
United States and Canada	Significant microplastic contamination in freshwater ecosystems is linked to urban and industrial activities	Dietary exposure through aquatic food webs and inhalation in urban environments	Integrated watershed management, public awareness campaigns, and research-driven risk assessment initiatives	A multidisciplinary approach combining environmental monitoring, public education, and health-risk assessment is needed to address complex exposure scenarios.	63

regulatory, technological, and public health contexts.

5. Current evidence and knowledge gaps

Despite growing concerns, the full impact of MPs on human health remains poorly understood, primarily due to the limited availability of human-based evidence.[4] Most research on the effects of MPs comes from *in vivo* or *in vitro* studies. This reliance on indirect data makes it harder to draw definitive conclusions about how MPs affect humans specifically.[34] Another significant challenge is the difficulty in detecting small or even nanoplastic particles that may accumulate in tissues. Their tiny size makes accurate measurement and tracking of their presence in the body difficult, adding another layer of uncertainty to our understanding.[12]

We also face a lack of dose-response data, which is crucial for determining safe exposure levels. Without these data, it is impossible to know at what point MPs' intake becomes harmful or what threshold we should be concerned about. Additionally, many ecotoxicity studies are based on animal models. While they provide valuable insights, applying these findings to humans is a complex challenge, as MPs' interactions with different species can vary significantly.[5,52]

Moreover, the long-term effects of chronic low-dose exposure to MPs remain largely unexplored. It remains unclear how prolonged accumulation may impact human health over years or decades. Emerging studies suggest that MPs may penetrate multiple organ systems beyond the gut and lungs, including the liver, kidneys, brain, placenta, and even skeletal tissues. This raises concerns about the possible impacts on neurodevelopment, fetal growth, metabolic function, and immune homeostasis. Addressing these knowledge gaps requires substantial methodological improvements. Standardization across research methods is critical, including the development of consistent protocols for sampling, detecting, characterizing, and testing the toxicity of MPs. Harmonized methodologies would improve comparability among studies and strengthen the reliability of risk assessments. Longitudinal studies are also needed to better understand the effects of chronic exposure over extended periods and to determine whether prolonged ingestion or inhalation contributes to cumulative health impacts. Human biomonitoring represents another key research priority. The analysis of biological matrices such as blood, urine, feces, and placental tissues could provide valuable insights into the uptake, distribution, accumulation, and excretion of MPs in the human body. Furthermore, interdisciplinary collaboration among chemists, toxicologists, biologists, clinicians, epidemiologists, and regulators will be essential for advancing knowledge and developing comprehensive strategies for monitoring and managing MP-related risks.

6. Conclusion

Microplastics represent an emerging environmental and public health challenge due to their widespread occurrence and multiple exposure pathways, including ingestion, inhalation, and dermal contact. Current evidence suggests that these particles can induce oxidative stress, inflammation, cellular damage, and other adverse biological effects, although significant uncertainties remain regarding long-term human health consequences. Despite growing scientific attention, important gaps persist in exposure assessment, toxicological characterization, and the establishment of health-based threshold values. Given the global nature of MP pollution, reducing human exposure will require coordinated efforts involving governments, industries, researchers, and consumers. SRM strategies, supported by improved scientific evidence and effective policy interventions, are essential to mitigate potential health risks. Continued international collaboration will be crucial for advancing knowledge, informing regulation, and protecting both environmental and human health.

From our perspective, the next phase of MP research should prioritize translating environmental exposure data into clinically relevant health evidence. We believe the greatest challenge is no longer documenting MPs' widespread presence, but rather establishing biologically meaningful exposure metrics and linking them to measurable health outcomes. Future studies should integrate human biomonitoring data, mechanistic toxicological evidence, and epidemiological findings within a unified framework for health risk assessment. To achieve this, urgent efforts in the medical and public health domains should focus on strengthening the evidence base needed for human health risk assessment. Clinicians and medical researchers should prioritize identifying and validating biomarkers of MP exposure and its biological effects, including indicators of oxidative stress, inflammation, and metabolic disruption, to facilitate early detection of potential health impacts.

Hospitals and public health institutions should establish human biomonitoring programs capable of assessing MP burdens in biological matrices, including blood, urine, placenta, breast milk, and tissues. In parallel, epidemiologists should conduct large-scale prospective cohort studies to clarify associations between chronic MP exposure and adverse health outcomes affecting the liver, cardiovascular, respiratory, reproductive, and nervous systems. Occupational health specialists should evaluate exposure levels and associated risks among highly exposed populations, particularly workers involved in plastic manufacturing, recycling, and waste management. However, such investigations should also be interpreted within the context of widespread daily exposure experienced by the general population through multiple pathways, including inhalation of airborne MP particles, use of synthetic textiles such as polyester clothing and undergarments, and consumption of contaminated food and beverages. Understanding the relative contribution of occupational and non-occupational exposure sources will be essential for accurately assessing cumulative human exposure and associated health risks.

To improve the relevance of experimental evidence, medical researchers and toxicologists should develop physiologically realistic models and exposure scenarios that better reflect human conditions. Health authorities should incorporate MP exposure into environmental health surveillance programs and develop evidence-based recommendations for vulnerable populations, including pregnant women, infants, children, and individuals with chronic diseases. Furthermore, medical and public health organizations should promote interdisciplinary collaborations that integrate environmental monitoring data with clinical and epidemiological findings to strengthen risk assessment frameworks and support effective disease prevention strategies.

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