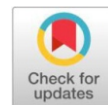


Review Article

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Microplastics in food systems: sources, detection, fate, food safety and human health risks



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ABSTRACT

Microplastics (MPs) have become ubiquitous pollutants in food and environmental systems, raising concerns about human exposure and potential health risks. This review summarises the occurrence of MPs in important dietary sources, including seafood, drinking water, beverages, fruits, vegetables and dairy products, as well as their occurrence and potential migration from food packaging materials, in addition to inhalation as a substantial non-dietary exposure pathway. Additionally, the biological fate of MPs following ingestion and inhalation is discussed, with a focus on their translocation, tissue accumulation and potential to cause endocrine disruption, oxidative stress, inflammation, gut microbiota dysbiosis, reproductive toxicity and neurotoxicity. Current techniques for MP detection and characterisation, including microscopic, spectroscopic and thermal methods, as well as emerging techniques such as surface-enhanced Raman spectroscopy (SERS), laser direct infrared imaging (LDIR), hyperspectral imaging and artificial intelligence-assisted analysis, are critically reviewed. Important analytical challenges, including contamination control, nanoplastic detection and the lack of standardized techniques, are also discussed. Despite mounting evidence of MP occurrence and biological effects, major challenges remain, including the absence of standardized analytical protocols, difficulties in identifying nanoplastics, contamination during analysis and limited evidence regarding the long-term effects on human health. This review contributes by integrating current evidence on MP occurrence in food systems, human exposure pathways, biological fate, health impacts and analytical approaches, while identifying key methodological and regulatory gaps and priorities for future research. To improve risk assessment and develop practical strategies to reduce MP exposure, further efforts towards standardised procedures, improved monitoring, realistic exposure assessment and long-term human studies are required.

Keywords: Microplastics, Nanoplastics, Food contamination, Human exposure, food safety, Drinking water, Seafood, Toxicity, Analytical methods, Detection methods, Human health

1. Introduction

Plastic production and use have expanded globally in recent decades owing to the adaptability, durability, lightweight nature, and low production costs of plastics [1,2]. However, their widespread use and improper disposal have resulted in the accumulation of plastic waste in terrestrial, aquatic, and atmospheric environments, making plastic pollution one of the most serious environmental challenges of the twenty-first century [2,3]. Among the various plastic applications, food packaging plastics, particularly polyethylene (PE), including high-density polyethylene (HDPE) and low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS), account for a significant portion of global plastic production and

consumption [4]. Owing to their persistence and resistance to biodegradation, these materials remain in ecosystems for extended periods before gradually fragmenting into smaller plastic particles through physical, chemical and biological weathering processes [1]. Microplastics (MPs) defined as plastic particles smaller than 5 mm in diameter, have emerged as a global concern because of their widespread occurrence and environmental persistence [5,6]. Atmospheric transport, habitat fragmentation, and hydrological processes facilitate their spread across ecosystems and contribute to their global distribution [7]. As a result, MPs have entered the food chain and have been detected in a wide range of food commodities and beverages, including seafood, drinking water, bottled water, table salt, sugar, honey, milk, tea, beer, fruits, vegetables and processed foods [8,9,10]. Seafood is regarded as one of the most significant dietary sources because aquatic species readily consume plastic particles present in contaminated water [11]. Human exposure to MPs occurs primarily through ingestion, inhalation and dermal contact, with food and drinking water representing the dominant exposure pathways [2,7]. Recent biomonitoring studies have detected MPs in human blood, lungs, placenta, breast milk, urine, semen and other tissues,

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indicating their ability to cross biological barriers and accumulate within the body [12,13,14]. MPs can adsorb and transport heavy metals, persistent organic pollutants, antibiotics, plastic additives and pathogenic microorganisms, potentially amplifying their adverse biological effects [12,15]. Accurate assessment of microplastic contamination requires reliable analytical methodologies. Various techniques, including stereomicroscopy, optical microscopy, scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, micro-Raman spectroscopy, pyrolysis-gas chromatography-mass spectrometry (Py-GC MS), and emerging AI-assisted and hyperspectral imaging technologies, have been developed and increasingly applied for the detection and characterisation of MPs [16,17,18]. However, the lack of standardised analytical techniques, limitations in nanoplastic identification, and insufficient toxicological data continue to impede comprehensive risk assessment and regulatory decision-making [11]. The present review provides an integrated assessment of current knowledge on microplastics in food systems, encompassing their major sources and occurrence in food commodities, environmental distribution, human exposure pathways, biological fate, health implications and detection and characterisation techniques. It further examines key methodological, toxicological and regulatory challenges, identifies important research gaps and highlights future research priorities for improving microplastic monitoring, risk assessment and food safety.

2. Sources and Environmental Distribution of Microplastics

Microplastics (MPs) originate from a variety of human activities and continuously enter environmental systems through both direct and indirect pathways. MPs are classified as primary or secondary microplastics based on where they come from [3]. Their widespread production, persistence and environmental mobility have resulted in substantial contamination of marine, freshwater, terrestrial and atmospheric ecosystems worldwide. Primary MPs are intentionally produced for specific applications, including microbeads used in cosmetics and microfibres released from synthetic textiles. In contrast, secondary microplastics are formed from larger plastic materials through physical, chemical and biological processes, such as exposure to sunlight, weathering, wave action and microbial activity [19,20,21]. The major sources and environmental pathways of microplastics are illustrated in Figure 1. Among primary microplastics, plastic microbeads are widely used because they are inexpensive and durable. Following use, these particles enter wastewater systems and are not completely removed during treatment, eventually reaching aquatic ecosystems [22]. Industrial plastic pellets, also known as nurdles, are small resin pellets used as raw materials in plastic production. Accidental losses during production, shipping and handling can result in substantial quantities of these pellets entering terrestrial and aquatic habitats. Owing to their small size and buoyancy, nurdles can travel long distances and accumulate in coastal and marine environments [3]. Wastewater from laundry activities is a major pathway for fibre release into aquatic environments [7]. Food packaging materials are major contributors to secondary microplastic production because physical wear and mechanical stress can release plastic particles from packaging materials. Plastic cutting boards, which have received increasing attention, can also produce microplastics that directly contaminate food items [23].

Plastic mulches, greenhouse films, irrigation pipes and other agricultural plastics degrade in the field, resulting in microplastic particles that accumulate in soil. Agricultural land receiving sewage sludge and compost may also acquire considerable quantities of microplastics, increasing soil pollution and potentially promoting plant uptake [2]. Vehicle tyres release microparticles whenever they come into contact with road surfaces. These tyre particles are recognised as a major source of urban microplastic pollution and enter aquatic bodies through surface runoff or disperse into the atmosphere [8]. Atmospheric transport has emerged as a key mechanism for microplastic dispersal. Textile fibres, traffic dust, industrial emissions, construction activities and the decomposition of plastic waste all contribute to airborne microplastics. Their ability to travel vast distances allows them to contaminate remote areas, including polar and alpine regions. Airborne microplastics also contribute substantially to human inhalation exposure [7].

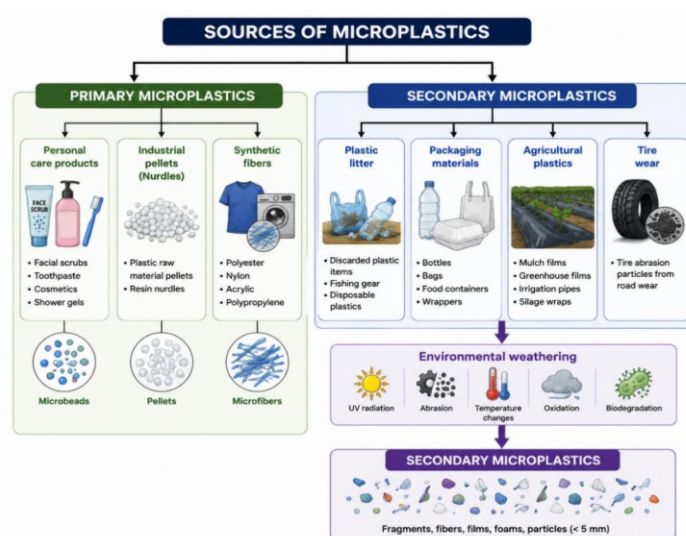


Fig. 1. Major sources and pathways of microplastics entering environmental compartments.

3. Human Exposure Pathways

Microplastics are widely distributed in the environment and in consumer products, resulting in continuous human exposure. According to [2], humans are predominantly exposed to microplastics through ingestion, inhalation and dermal contact.

3.1 Dietary Exposure

Dietary consumption is regarded as the primary route of human exposure to microplastics because these particles have been detected in a wide range of food and beverage products consumed regularly. Microplastics can enter food chains through environmental pollution, food processing, packaging materials and food preparation practices [24,25].

Seafood

Seafood is regarded as one of the main dietary sources of human exposure to microplastics because aquatic animals readily ingest microplastics, which may subsequently accumulate in edible tissues. Microplastics, alone or in combination with other pollutants, can cause a variety of adverse effects in aquatic organisms. These effects range from physiological and biological disturbances to behavioural disorders, growth retardation and neurotoxicity. The occurrence of MPs in fish muscle is of particular concern because muscle is the principal edible portion consumed by humans.

Numerous studies have reported microplastics in both pelagic and demersal fish species, including herring, mackerel, cod, sole and sardines, from water bodies such as the Atlantic, Pacific and Indian Oceans and the Mediterranean Sea [26]. In the central Adriatic Sea, MPs were found in 26% of red mullet (*Mullus barbatus*) and 20% of European hake (*Merluccius merluccius*), confirming that commercially important fish species can be frequently contaminated. Consumption of molluscs and crabs can further increase human exposure because these organisms may be consumed whole, allowing microplastics present in their gastrointestinal tracts to enter the diet. In India, the prawn species *Fenneropenaeus indicus* from Cochin contained an average of 0.39-0.6 MPs per individual, with 83% being fibres [27]. Canned fish from the Turkish market was also found to contain polyolefin MPs, potentially associated with processing and packaging [28]. Mussels, specifically *Mytilus edulis* and *Mytilus galloprovincialis*, have been shown to contain MPs in several European countries. Belgian mussels contained up to 0.51 MP particles per gram, demonstrating persistent contamination of commercially harvested shellfish [29]. Similarly, oysters (*Crassostrea gigas*) and mussels from Apulia were reported to contain 790 and 270 plastic particles, respectively, primarily in the 5-500 µm size range. Mussels and oysters exhibited different particle compositions, with mussels containing predominantly nylon and polyamide, whereas oysters contained mainly polypropylene [30]. The widespread occurrence of microplastics in crustaceans, bivalves and fish makes seafood an important dietary source of human microplastic exposure, particularly in populations with high seafood consumption.

Drinking Water

Drinking water is an important pathway of human exposure to microplastics because it is consumed daily and represents a major component of the human diet. MPs have been detected in a variety of water sources, including groundwater, surface water and treated drinking water [31,32]. Concentrations in treated water ranged from 338 ± 76 to 628 ± 28 particles/L, compared with 1473 ± 34 to 3605 ± 497 particles/L in raw water, with particle sizes ranging from 1 to 10 µm [33]. Similar findings have been reported elsewhere, including concentrations of approximately 700 microplastic particles/L [31]. Mineral water from reusable PET bottles contained approximately 4889 ± 5432 microplastics/L, compared with 2649 ± 2857 particles/L in single use PET bottles, glass bottles also contained microplastics in the 1-5 µm size range [34]. FTIR analysis detected PE, PET and PP in the water samples [25]. In a zebrafish model used to assess MP toxicity, several bottled water brands were found to contain PS, PE and PA, and exposure was associated with oxidative stress, raising concerns about potential health effects [35]. Raman microspectroscopy detected MPs up to 100 µm in size, mainly polyethylene (PE) and polypropylene (PP) [36]. Concentrations of 0.02 ± 0.03 MP/L in samples from drinking water treatment plants and 0.01 ± 0.02 MP/L in tap water samples have also been reported. Regardless of polymer type or sampling frequency, 80% of the identified MPs were between 10 and 50 µm in size [37,38]. Due to variations in sampling plans, analytical methods, contamination control protocols and particle size detection thresholds, reported MP concentrations in drinking water vary considerably among studies. Consequently, direct comparison remains difficult, underscoring the need for standardised analytical procedures.

Salt, Honey and Tea

Microplastics have also been detected in several commonly consumed foods, including table salt, sugar, milk, honey and tea, indicating that dietary exposure is widespread [2,3]. Marine salt produced by the evaporation of seawater may be particularly vulnerable to contamination by suspended plastic particles. Honey from Ecuador was also found to contain microplastics at concentrations of 67 and 54 particles/L in artisanal and industrial honey, respectively. Atmospheric deposition onto flowers and contamination during honey processing are considered major sources of microplastics in honey [39]. Similarly, tea bags containing plastic materials can release substantial quantities of microplastic particles during brewing [40]. Collectively, these findings demonstrate that microplastics are present in numerous staple foods consumed on a daily basis.

Fruits and Vegetables

MP contamination has expanded beyond aquatic ecosystems to terrestrial food sources such as fruits and vegetables through various pathways, including uptake from contaminated soil and water, atmospheric deposition and contact with plastic materials during growth, harvesting, processing, and packaging. Several studies have confirmed the occurrence of MPs in fruits and vegetables. Microplastics have been detected in apples, tomatoes, cucumbers, onions and potatoes, with tomatoes showing the highest estimated intake at 398,000 particles per person per year [41]. Microplastic contamination is not restricted to the plant growth stage but may also arise during post-harvest processing and handling. Concentrations of up to 29 MP g⁻¹ in lettuce grown in an urban garden of Portugal exhibited microplastic particularly in locations with high human activity [42]. Urban agriculture may be particularly susceptible to MP contamination because of increased exposure to atmospheric pollution and contaminated water sources. Studies have shown that MP uptake by plants is influenced by particle size, morphology, and absorption patterns. Smaller particles may penetrate more deeply into root tissues. Particle uptake is size dependent, as shown by [43] in carrots: 0.2 µm particles could enter leaves, whereas 1 µm particles could enter the intercellular spaces of roots but not the cytoplasm. Particles of approximately 607 nm were mostly absorbed through leaves, while larger particles (up to 1220 nm) entered both roots and leaves. Similarly, apples and carrots showed higher microplastic contamination when particles smaller than 10 µm were included, highlighting the importance of analytical detection limits in estimating dietary exposure [44]. Plant morphology also influences the uptake of micro and nanoplastics. Plants with broad, rough leaf surfaces and larger stomatal openings facilitate greater retention and foliar deposition, whereas roots act as a major entry route for plastic particles. In addition, the hydrophobic nature of microplastics may promote their adherence to wax coated leaf surfaces, increasing the likelihood of foliar retention and uptake [45]. These findings highlight the need for further research on food safety and plant uptake and demonstrate that fruits and vegetables should be considered important dietary sources of MPs.

MPs in beverages

Alcoholic and non-alcoholic beverages constitute a significant portion of the human diet. Because of their frequent consumption and direct route of exposure through ingestion, the presence of microplastics (MPs) in these beverages has received increasing attention.

An estimated 123.1 billion litres of non-alcoholic beverages were consumed in Europe in 2021, corresponding to an average annual intake of approximately 235 litres per person [46]. Among beverages, dairy products particularly milk and milk derived products, have attracted attention because of their high daily consumption. MP contamination in dairy products may originate from animal feed, water, milking equipment, packaging materials and storage conditions. MPs smaller than 4 µm have been detected in milk and dairy products using sophisticated analytical techniques such as micro-Raman spectroscopy [47]. Skimmed milk powder samples have been found to contain microplastics composed of PE, PP, PET and PS. The particles exhibited a variety of colours and morphologies, including fibres, spherical particles and irregular fragments [48]. In addition to dairy products, MP contamination has been reported in several widely consumed beverages. Average concentrations of MPs in soft drinks, cold tea beverages, and energy drinks were approximately 40, 14, and 11 MP L⁻¹, respectively, indicating the widespread occurrence of MPs across beverage categories [49]. Microplastics have also been reported in German beer with quantities ranging from 2-79 fibres L⁻¹ and 12-109 fragments L⁻¹, indicating possible contamination during brewing, filtration or packaging [50].

Food packaging

Food packaging has emerged as a major secondary source of microplastic (MP) contamination because food-contact materials may release plastic particles during processing, storage, transportation and consumer use. The migration of MPs from packaging into food is influenced by temperature, mechanical stress, storage conditions and the type of packaging material [51]. MP migration from food packaging can occur through mechanical stress, UV exposure, thermal degradation, physical abrasion and repeated use. Particle release into food may be further increased by high temperatures, prolonged storage, acidic or fatty food matrices and frequent opening or handling of packaging materials [52].

Packaged meat and processed foods may contain microplastics as a result of direct contact with polystyrene trays, plastic wraps and other food contact materials. Packaged fish and poultry have been reported to contain 4.0-18.7 particles kg⁻¹, while items kept in expanded polystyrene (EPS) containers may show greater contamination during transportation and storage [53]. Infants are considered one of the most vulnerable groups because of their high food intake relative to body weight. Polypropylene newborn bottles have been demonstrated to release up to 16.2 million MPs L⁻¹ when heated to 100 °C, which may result in substantial MP exposure during bottle feeding. The detection of MPs in infant formula, baby foods and milk stored in plastic containers has increased concerns regarding early life exposure [54]. MP concentrations in powdered milk have been shown to be higher than those in fresh liquid milk, indicating that packaging and additional processing stages may contribute to particle release. This suggests that food processing may further increase contamination [55]. Single use cups, takeaway containers and plastic wraps have also been identified as potential sources of MP contamination. Particle migration from these materials into foods is significantly increased by heat exposure, prolonged storage and mechanical stress [56,57]. Consequently, the use of plant based and biodegradable packaging materials may be a viable strategy for reducing MP exposure. Overall, food type, processing, storage, temperature and packaging material all influence MP migration and food packaging represents a significant secondary source of MP contamination. Reducing dietary exposure to MPs will require safer packaging materials and standardised monitoring techniques.

The increasing detection of microplastics in food and beverage products necessitates reliable methods for their identification and characterisation. Various analytical techniques have been employed to determine the occurrence, size, morphology and polymer composition of MPs, ranging from microscopy-based approaches to advanced spectroscopic and chromatographic methods, as summarised in Table 1.

Table 1: Analytical techniques to determine the occurrence, size, morphology and polymer composition of MPs

Food category	Food sample	MP concentration	Dominant polymers	Detection method	Reference
Drinking water	Tap water	44.7 MP/m ³	PS	-	[58]
Drinking water	Bottled water	1014 MP particles/2 L of water per day	PET	SERS	[54]
Beverages	Soft drink, cold tea	9.94 ± 0.33 MPs/L	-	Fluorescence microscopy	[47]
Beverages	Beer, mineral water and tea	20–80/mL of mineral water; 200–500/g of tea	PS, PP, PET, PE	Raman spectroscopy	[59]
Frozen water products	Packaged food ice cubes	19 ± 4 and 178 ± 78 MPs/L	PP, PE, PVA, tygon polymer	Microscopy, ATR-FTIR	[60]
Dairy	Skimmed milk powder	466–5764 MPs/kg	PP, PE, PS, PET	ATR-FTIR	[48]
Dairy	Milk	6 ± 5 particles	PET, PE	FTIR spectroscopy	[61]
Honey	Honey and beehive products	-	PE,PCL,PTFE	Micro-FTIR spectroscopy	[62]
Seafood	Salted and sun-dried fish	99 ± 18.91 MPs/g	PP, PE, PS	Micro-FTIR spectroscopy	[63]
Seafood	Clam meat	59.472 microplastics/person tested	PE,PET,PS	FTIR spectroscopy	[64]
Seafood	Commercial fish	1.7–11 MPs per individual	PE, PP	FTIR	[65]
Seafood	Swordfish	2.5 ± 6.1–3.3 ± 8.0 MPs/fish	PRT PE, PS,	Micro-FTIR spectroscopy	[66]
Meat	Chicken meat	-	PS, PVC	Attenuated total reflection mid infrared (ATR-MIR)	[67]
Edible oils	Edible oil	1140±350 MPs/L	PE, PP	µ-FTIR spectroscopy	[68]
Meat and meat products	Beef hamburgers	200.00 to 30,300 MPs/kg	PC, PE, PP	µ-FTIR spectroscopy	[48]
Dietary supplements	Protein supplements	3.8 million microplastics/ year	PET, PE	Raman spectroscopy	[69]
Seafood	Edible seaweeds	5.7 x 104 ± 4.9 x 104 MPs per year	PE, PP, PET	FTIR spectroscopy	[70]

3.2 Inhalation Exposure

Human exposure to microplastics (MPs) through inhalation has become increasingly significant, especially in urban and indoor settings where airborne plastic particles are continuously produced and suspended. Inhalation is an important exposure pathway for airborne MPs originating from textile fibres, tyre wear, road dust, industrial emissions, building activities and the fragmentation of plastic waste [71,72]. Human intake of microplastics has been estimated at between 35,000 and 69,000 particles per year, although exposure varies considerably according to age, occupation, lifestyle and geographical location [73]. Indoor environments are usually the primary source of inhalation exposure because people spend most of their time in homes, workplaces, schools and public transportation, where textile fibres and household dust continuously contribute to MP exposure.

In contrast, distant and rural areas generally have lower exposure levels, frequently below 5 MPs kg⁻¹ body weight day⁻¹. Inhalation exposures have been estimated at 507 MPs kg⁻¹ body weight day⁻¹ for adults and 1,835 MPs kg⁻¹ body weight day⁻¹ for infants based on population based research. This suggests that children's higher breathing rates relative to body weight may result in greater exposure [74,75,76]. Improved workplace safety measures are necessary because workers in plastic recycling facilities were estimated to inhale up to 22,531 MPs kg⁻¹ body weight day⁻¹, while injection moulding workers were exposed to approximately 535 MPs kg⁻¹ body weight day⁻¹ [77]. The major environmental exposure pathways and subsequent distribution of microplastics within the human body are illustrated in Figure 2.

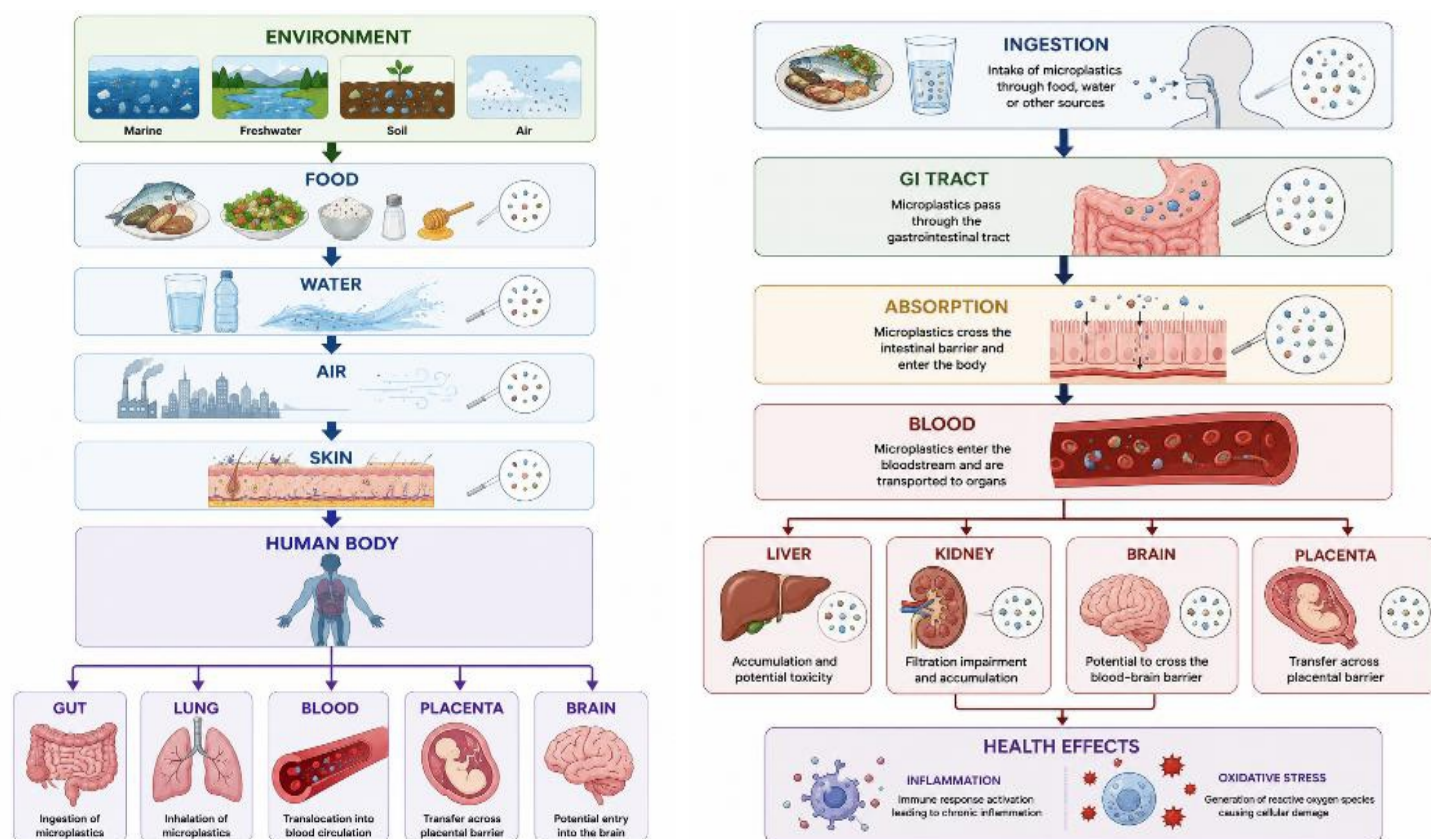


Fig. 2. Environmental exposure pathways and biological distribution of microplastics in the human body.

4. Fate and Behaviour of Microplastics in Biological Systems

The gastrointestinal (GI) tract is the primary site where microplastics interact with the human body after contaminated food and water are consumed [9,78]. The gastrointestinal fate of MPs is significantly influenced by their size, shape, surface charge and polymer composition. Larger MPs are usually retained within the intestinal lumen whereas smaller MPs and nanoplastics can cross the intestinal barrier through several mechanisms, including transcytosis by enterocytes, uptake by M cells in Peyer's patches via micropinocytosis, phagocytosis, receptor-mediated endocytosis, paracellular transport and persorption through temporary gaps in the intestinal villi [79]. Nanoplastics have reported bioavailability rates of approximately 2-7%, making them more readily absorbed into the circulation, where they can interact with proteins, lipids and other biomolecules in the gastrointestinal tract and generate a 'protein corona' that influences their absorption and biological

behaviour [80]. After absorption, MPs can spread to secondary organs, including the liver, spleen, kidneys, lungs, brain, placenta and reproductive tissues, through the circulatory and lymphatic systems. Particle size and shape also have a significant impact on the deposition of inhaled microplastics in the respiratory system. In humans, approximately 30-54% of spherical particles measuring 2.5-5 μm reach the alveolar region and particles smaller than 5 μm are more likely to penetrate deep into the lungs. Larger particles (>5 μm), on the other hand, are mostly retained in the upper respiratory tract or pulmonary capillaries and show limited alveolar deposition. Fibres 8-17 μm in length can also penetrate deep into lung tissues because of their elongated form, as evidenced by their presence in human lung samples obtained from autopsies and surgical procedures [81,82]. MPs are more prevalent in the lower lung lobes of people over 60 years of age, smokers and individuals with impaired lung function [80].

Although dermal exposure is not considered a major route of MP uptake, it has been demonstrated that plastics smaller than 100 nm can pass through the stratum corneum and enter the viable epidermis and dermis [83]. This penetration is enhanced when particles are coated with hydrophilic polymers, such as PEG, or when the skin barrier is compromised [84]. In contrast, particles larger than 500 nm exhibit poor penetration into deeper epidermal layers, while particles between 100 and 500 nm are mainly retained within hair follicles. Positively charged and rough surfaced particles may disturb the skin barrier more strongly, but their ability to move across the skin remains limited [52]. In addition to environmental exposure routes, intravenous medications have recently been identified as a direct source of systemic MP exposure. Polypropylene (PP) fragments ranging from 1 to 62 μm in size have been found in fluid bags at concentrations as high as 7500 MPs L^{-1} , indicating a potential direct introduction of MPs into the bloodstream [85]. Following absorption, microplastics have been detected in human tissues from the reproductive system (placenta, testis, ovary), respiratory system (lung, sputum, bronchoalveolar lavage fluid), digestive system (liver, colon), cardiovascular system (blood, vein tissue, heart) and nervous system (olfactory bulb, brain). Brain tissue (4,917 $\mu\text{g/g}$) had higher MP accumulation levels than the liver (433 $\mu\text{g/g}$) and kidney (404 $\mu\text{g/g}$), suggesting tissue specific accumulation patterns [86]. These findings indicate that MPs can cross biological barriers and accumulate in multiple organs. Smaller MPs and nanoplastics are generally more physiologically hazardous and bioavailable.

5. Human Health Impacts of Microplastics

Microplastics may be harmful to human health because they contain polymer-associated compounds (PACs), plastic additives and adsorbed environmental contaminants that may have a range of toxicological effects. More than 25% of the over 16,000 PACs that have been identified have potentially detrimental properties, including endocrine disruption, carcinogenicity, developmental toxicity and reproductive toxicity, according to currently available data [87,88,89]. Exposure to MPs composed of PP, PE, PS and PVC has frequently been associated with increased oxidative stress and inflammatory responses, characterized by elevated concentrations of pro inflammatory cytokines such as IL-6, IL-8, and IL-1 β [90,91]. Oxidative stress is believed to be one of the primary mechanisms underlying MP toxicity because excessive production of reactive oxygen species (ROS) can damage proteins, lipids, DNA and mitochondria, ultimately leading to apoptosis and tissue damage. Experimental studies have demonstrated that MP exposure impairs male reproductive function by reducing sperm count, motility, viability and DNA integrity through ROS-mediated oxidative stress, pyroptosis and autophagy [92]. Furthermore, MPs may disrupt sertoli cell activity and impair the blood testis barrier, increasing germ cell susceptibility to toxic chemicals [93]. MP exposure in females has been associated with ovarian dysfunction, reduced follicle counts, altered sex hormone concentrations, fibrosis, apoptosis, endocrine disturbance and decreased fertility [94,95,96]. The detection of MPs in human placental tissue has raised concerns about prenatal exposure because it suggests that MPs may cross the placental barrier and potentially reach the developing foetus through the amniotic fluid [12]. Inhaled MPs can accumulate in lung tissues and contribute to pulmonary fibrosis, oxidative stress, chronic inflammation and impaired breathing.

Although causal relationships have not yet been established, emerging evidence also points to a potential link between long term MP exposure and lung cancer [97]. The neurotoxicity associated with MPs is significantly influenced by particle size and surface characteristics. Experimental studies suggest that MPs may disrupt normal brain communication by inhibiting acetylcholinesterase (AChE), an enzyme involved in regulating neurotransmission [98]. The adsorption of heavy metals, dyes and other environmental contaminants onto MP surfaces may further contribute to oxidative stress, inflammation, mitochondrial dysfunction and cell death in the liver, kidneys, heart and other tissues following systemic distribution. However, data on the long term consequences of MP exposure in humans remain limited. Long term epidemiological and mechanistic studies are therefore crucial because definitive evidence of MP toxicity in humans is still lacking. The major mechanisms and potential health consequences associated with microplastic exposure are summarised in Figure 3.

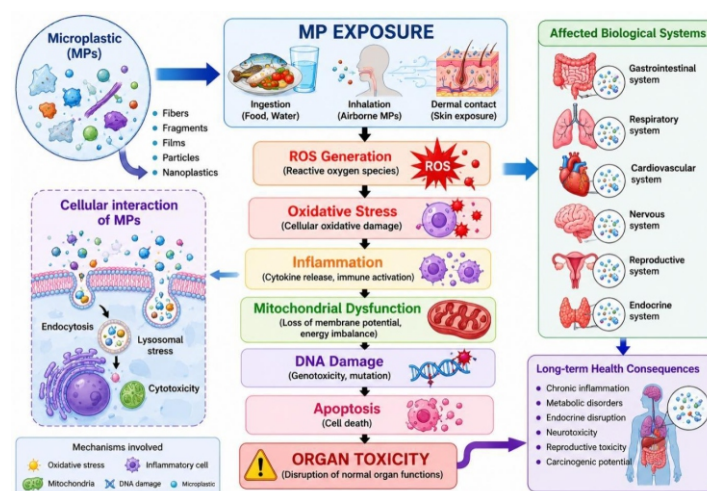


Fig. 3. Health impacts of microplastics

6. Detection and Characterization Methods

Reliable detection and characterisation are necessary to accurately determine the presence, quantity, polymer composition, morphology and potential health risks of microplastics (MPs) in food, beverages, water, biological tissues and environmental samples [99,16,100]. Accurate identification is essential for toxicological research, exposure assessment and the development of standardised monitoring protocols. No single analytical technique can accurately identify all MPs because of their wide variation in size, shape, colour, weathering state and polymer composition. Most studies therefore combine spectroscopic and microscopic techniques to improve analytical reliability. In MP analysis, sampling is the first and one of the most important stages because poor sampling can result in particle loss or external contamination. However, the lack of standardised sampling procedures still makes it difficult to compare different studies [10]. To reduce contamination during collection and storage, glass or stainless steel sampling containers are generally recommended over plastic containers. Pre cleaned borosilicate glass vials are commonly recommended for water samples, especially when examining small MPs and nanoplastics [17]. To minimise deterioration and avoid secondary contamination, samples should be transported in sealed containers and stored at approximately 4 °C until analysis.

Strict contamination control is essential because airborne fibres, laboratory plastics, chemicals and unfiltered water may introduce false positive particles during analysis [8]. Sample preparation in laminar flow cabinets, the use of cotton lab coats and nitrile gloves, filtration of all reagents, the use of pre cleaned glassware and analysis of procedural blanks throughout the analytical workflow are common contamination control measures [18].

6.1 Sampling and Contamination Control

Sample collection is the first essential stage; however, the lack of a standardised sampling quantity limits study comparability [10]. Glass or stainless steel sampling containers are preferred over plastic containers to minimise secondary contamination during sample collection and storage. Pre cleaned borosilicate glass vials are often recommended for water samples, particularly when analysing small MPs and nanoplastics [17]. Raw and treated drinking water samples should be collected in pre cleaned borosilicate glass bottles and stored at 4 °C before analysis to reduce contamination and degradation. Contamination control is critical because airborne fibres, laboratory plastics, reagents and water used during analysis can create false positives. Contamination can be reduced by working on a laminar flow clean bench, wearing cotton laboratory coats and nitrile gloves, using filtered water and pre cleaned gold-coated filters and including procedural blanks. Laboratory air may contain fibres and fragments, emphasising the importance of blank corrections in honey and sugar experiments [8,18]. Therefore, procedural blanks, field blanks, reagent blanks, recovery tests and plastic-free laboratory materials should be used whenever possible [1].

6.2 Sample Preparation and Extraction

Sample preparation aims to eliminate organic and inorganic matrix components while preserving plastic particles. Food matrices such as seafood, milk, honey, sugar, fruits, vegetables, cheese and beverages require different extraction procedures because of substantial differences in fat, protein, carbohydrate, fibre and mineral content [101,102]. Packaged beverage analysis is often performed using direct filtration or pretreatment followed by filtration. Direct filtration is suitable for low viscosity samples such as bottled water, beer, wine and soft beverages because these liquids pass readily through membranes [10]. Complex matrices, such as milk, honey, cheese, shellfish and plant tissues, require digestion before filtration to prevent matrix interference [103,16]. Chemical digestion is commonly used to remove biological material, but the reagent must be selected carefully to prevent polymer degradation [99]. Hydrogen peroxide, nitric acid, potassium hydroxide, sodium hydroxide and Fenton's reagent are often used, although strong oxidising or acidic conditions may alter polymers such as polyamide, polyethylene, low-density polyethylene or polyurethane [104]. Microwave-assisted wet digestion using 1 mol/L nitric acid at 200 °C for 10 minutes has been reported to rapidly break down shellfish tissue while preserving several polymers, including PET, PS, EPS, PP, HDPE, LDPE, PC and PVC. This method reduced digestion time from several hours or days to approximately 20 minutes, making it suitable for seafood monitoring [103]. However, pH-sensitive polymers may deteriorate under highly acidic or alkaline conditions, potentially leading to underestimated MP concentrations. Enzymatic digestion is regarded as a greener option because enzymes such as proteases, lipases and cellulases may remove organic materials under milder conditions.

Enzymatic digestion can preserve MP integrity while generating less hazardous waste than vigorous chemical digestion. However, in dense or highly complex food matrices, enzymatic digestion can be costly, time-consuming and less effective. Therefore, a combined approach involving mild digestion, density separation and filtration is often more reliable for complex food matrices [99].

6.3 Density Separation, Filtration and Particle Isolation

Density separation exploits the lower density of many polymers relative to mineral particles and organic debris, allowing efficient particle recovery before microscopic analysis. Many common plastics can be separated using low-density solutions such as NaCl, CaCl₂, and KHCO₃. However, dense polymers such as PET and PVC require high-density salts such as ZnCl₂, NaI, or sodium polytungstate, which are relatively expensive and corrosive. NaCl, CaCl₂ and KHCO₃ can therefore serve as safer alternatives to ZnCl₂ and NaI, depending on the target polymers and matrix [105,106].

Filtration is simple, affordable, and applicable to water and beverage matrices. Research has utilised cellulose nitrate, mixed cellulose ester, polycarbonate, glass-fibre, gold coated polycarbonate and aluminium coated polycarbonate filters [10]. Gold coated polycarbonate filters have a low Raman background and facilitate particle identification using micro-Raman spectroscopy [18]. PTFE membrane filtration using 5 µm and 0.2 µm pore sizes has been used to remove particles from both raw and treated drinking water [33]. Filtration and centrifugation have been reported as practical separation processes, with removal efficiencies of approximately 74% and 98% respectively [17].

6.4 Microscopic Techniques

Microscopic techniques are useful for initial screening, particle counting, size measurement, and morphological classification [10,17]. Stereomicroscopy enables rapid visual detection of suspected MPs based on colour, shape and surface characteristics, but it cannot confirm polymer composition. Optical microscopy is affordable, non-destructive and suitable for screening relatively large particles however, its resolution limit of approximately 200 nm restricts nanoplastic detection. Visual and microscopic identification may also result in false positives because natural fibres, chemical residues and mineral particles can resemble MPs [107]. When dyes such as Nile Red or Rose Bengal are used to distinguish hydrophobic particles from organic materials, fluorescence microscopy can improve detection. Nile Red staining is useful for rapid screening of MPs in salt, seafood, beverages and other food matrices, although it may also stain other hydrophobic compounds and produce false positives [108]. Fluorescent staining has also been used to distinguish cellulose fibres from synthetically coloured fibres in honey and sugar [8]. Fluorescence based detection of MPs in non-alcoholic beverages demonstrates that staining-based techniques can facilitate rapid screening when combined with filtration and microscopy [46].

Scanning Electron Microscopy (SEM) produces high-resolution images of MP surface morphology, cracks, degradation patterns and particle form. SEM is useful for examining microscopic particles, but it cannot reliably determine polymer identity without complementary techniques or elemental analysis such as SEM-EDS. SEM has been used to characterise MPs in raw and treated drinking water and has detected particles in the 1-10 µm size range.

However, SEM is expensive and time-consuming and may require drying or coating, which can limit subsequent analyses [109]. Microscopy alone cannot reliably identify polymer composition and is therefore generally combined with spectroscopic confirmation.

6.5 Spectroscopic Techniques

Fourier-transform infrared spectroscopy (FTIR) is one of the most commonly used techniques for polymer identification because each polymer has distinct infrared absorption bands. FTIR is non-destructive and applicable to common polymers such as PE, PP, PET, PS, PVC and PA, and it can be used with microscopy for particle-level examination [100]. Micro-FTIR has difficulty detecting particles smaller than 20 μm [18]. Water can strongly interfere with FTIR spectra, making analysis of wet or high-moisture samples difficult without drying. Micro-FTIR, which combines microscopy and FTIR spectroscopy, is useful for chemical mapping and polymer identification of particles larger than 20 μm , whereas micro-Raman spectroscopy is useful for smaller particles. No single approach performs equally well across the entire MP size spectrum [16].

Raman spectroscopy provides polymer specific molecular fingerprints and is particularly beneficial for small particles because it has fewer size limitations than FTIR [16,18]. Micro-Raman spectroscopy can identify particles as small as 1 μm in mineral water. Approximately 80% of MPs observed in bottled water were between 5 and 20 μm , suggesting that FTIR-based investigations may have missed numerous particles. Raman spectroscopy is less sensitive to water than FTIR, making it suitable for beverages and biological materials. However, Raman analysis may be affected by fluorescence interference, low signal intensity, long acquisition times and complex data processing. Raman spectroscopy and FTIR-ATR have been used to confirm the migration of LDPE and PP from packaging onto cheese surfaces. As a result, Raman-based techniques are particularly useful for studying small MPs, packaging migration and food-contact materials [110,14].

6.6 Thermal and Mass-Based Techniques

Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) is an effective technique for thermally decomposing plastics into identifiable products for polymer identification and mass-based quantification [17,14]. Py-GC-MS is not dependent on particle size and can determine total polymer mass in complex matrices. However, it does not provide information on particle number, size, shape or morphology. Py-GC-MS can identify polymers using characteristic degradation products and is useful for complex samples containing common plastics. The technique offers good sensitivity and specificity but is less environmentally friendly because of its energy consumption, destructive nature and generation of pyrolysis products.

Thermogravimetric analysis (TGA) detects mass loss during controlled heating and can aid polymer characterisation through thermal degradation patterns. TGA combined with FTIR or MS can identify evolved gases and assist in the characterisation of MP-containing matrices. Thermal approaches, however, require precise calibration and may be affected by interference from lipids, proteins or other thermally degradable compounds in food matrices [17].

6.7 Emerging and Advanced Detection Technologies

Laser direct infrared imaging (LDIR) is an automated infrared technology that rapidly scans wide regions and provides particle counts, size, shape, and polymer spectra.

LDIR improves throughput compared with conventional FTIR and is effective for particles larger than 20 μm [111,14]. Near-infrared spectroscopy (NIR) is also being investigated for rapid screening because of its non-destructive nature and low sample-preparation requirements; however, its sensitivity is lower than that of FTIR and Raman spectroscopy. Hyperspectral imaging combines image and spectral information and shows promise for automated MP classification in food and environmental samples [17].

Surface-enhanced Raman spectroscopy (SERS) is a promising advanced technique in which nanostructured substrates strongly amplify Raman signals and improve trace-level detection. SERS enhances Raman intensity through electromagnetic and chemical enhancement mechanisms using nanostructures such as Au, Ag, metal alloys, metal-organic frameworks (MOFs), semiconductors and polymer-based substrates. SERS can identify 1 μm polystyrene nanoplastics, highlighting its potential for micro- and nanoplastic detection. However, SERS approaches still require validation for complex food matrices, reproducible substrates, standardised spectral libraries and quantitative calibration. Artificial intelligence and machine learning techniques are increasingly being used to automate particle recognition, reduce operator bias, classify spectra and enhance high-throughput analysis. Chemometric methods, including principal component analysis (PCA), support vector machines, partial least-squares discriminant analysis and artificial neural networks, can assist in analysing Raman and SERS data [112]. AI-driven categorisation algorithms remain underexplored but have the potential to improve detection accuracy and efficiency [17].

6.8 Quality Assurance, Reporting and Standardisation

A major limitation in MP research is the lack of harmonised protocols for sampling, pretreatment, detection, quantification, and reporting. The lack of standardised analytical methods prevents firm conclusions regarding the public health significance of MPs in foods [9]. Occurrence data are difficult to compare because studies use different matrices, digestion methods, filters, detection limits, particle-size ranges and reporting units [3]. Variability in MP concentration, pore size, pH sensitivity, matrix effects and analytical protocols further reduces detection reliability.

7. Challenges and Limitations

Despite significant progress in understanding the occurrence, detection, and health effects of microplastics (MPs), major challenges remain in analytical methodologies, exposure assessment, toxicological evaluation and regulatory frameworks. These limitations make it difficult to conduct accurate risk assessments and establish appropriate mitigation strategies [16].

7.1 Lack of Standardised Methods

Differences in sample pretreatment methods, particularly acid digestion, alkaline digestion, oxidation, and enzymatic digestion, may alter polymer integrity and affect recovery rates. Consequently, direct comparison among studies remains difficult, limiting the reliability of exposure assessments and global databases. Furthermore, there is currently no universally accepted reporting system for expressing microplastic abundance in food, beverages, environmental samples, and biological tissues, which complicates meta-analyses and regulatory evaluations [16].

7.2 Toxicological Uncertainties

Although adverse biological effects of MPs have been reported, major uncertainties remain regarding their actual effects on human health [13,14]. The majority of toxicological information comes from in vitro research or animal models exposed to quantities significantly greater than those commonly experienced by humans. As a result, extrapolating these findings to realistic human exposure scenarios remains challenging. Multiple factors influence the toxicity of MPs, including particle size, shape, polymer composition, surface chemistry, additives and adsorbed pollutants [16,2]. Furthermore, MPs can act as carriers for heavy metals, persistent organic pollutants, antibiotics, endocrine-disrupting compounds and pathogenic microorganisms, making it difficult to distinguish particle-specific effects from those caused by associated contaminants [12]. Additional uncertainty arises from limited knowledge regarding long-term accumulation, chronic exposure, biotransformation and clearance mechanisms in humans [14]. Therefore, current evidence remains insufficient to establish definitive dose-response relationships or safe exposure thresholds.

7.3 Regulatory Challenges

Global regulatory monitoring of microplastics remains fragmented and inconsistent. Although numerous countries have prohibited the intentional inclusion of microplastics in cosmetic and personal care products, comprehensive regulations addressing microplastic contamination in food, drinking water, and packaging materials are still lacking [1]. Existing risk-assessment frameworks are limited by insufficient occurrence data, inadequate toxicological evidence and a lack of standardized testing techniques. Furthermore, regulatory agencies face difficulties in setting size thresholds, implementing monitoring standards, and identifying acceptable exposure levels. Differences in analytical capabilities among countries, environmental conditions, industrial practices, and socioeconomic priorities impede international regulatory harmonisation. As a result, coordinated global efforts are required to develop science-based policies and effective monitoring programmes.

8. Future Perspectives

Growing scientific evidence regarding microplastic contamination necessitates the development of improved analytical tools, comprehensive monitoring systems, and sustainable mitigation strategies. Future research should focus on addressing current methodological limitations while enhancing our understanding of the long-term health implications of microplastic exposure.

8.1 Standardisation of Analytical Methods

Establishing internationally agreed techniques for sampling, sample preparation, detection, characterization and reporting should be a research priority [11,16]. Standardised analytical workflows would enhance data comparability, facilitate global monitoring, and strengthen risk assessments. Harmonisation of particle size classifications, reporting units, recovery calculations, contamination-control methods and quality-assurance procedures is also required.

Future analytical methodologies should combine microscopy, spectroscopy and thermal techniques to achieve comprehensive characterisation of microplastics and nanoplastics across a variety of matrices.

8.2 Long-term Human Studies and Risk Assessment

Future research should prioritise well-designed longitudinal and epidemiological studies to clarify the relationship between realistic microplastic exposure and human health outcomes. Greater emphasis is also needed on harmonised exposure assessment, biomonitoring, dose-response relationships and the identification of health-relevant exposure thresholds. Integrating occurrence data, toxicological evidence, and human exposure estimates will strengthen evidence based risk assessment and support the development of consistent regulatory approaches.

8.3 Sustainable Alternatives to Plastics

Reducing environmental plastic pollution remains the most effective long term strategy for mitigating microplastic contamination. The development and adoption of biodegradable polymers, bio-based materials, compostable packaging systems and circular-economy approaches should be prioritised [1]. Furthermore, improved waste-management systems, enhanced recycling technologies, public-awareness campaigns and sustainable consumption practices are essential for reducing future microplastic generation. Collaborative efforts among governments, industries, researchers and consumers will be critical for achieving meaningful reductions in plastic pollution.

9. Conclusion

Microplastics are widespread contaminants in food and environmental systems and represent an emerging concern for human health through dietary and inhalation exposure. The reviewed evidence shows their occurrence in a wide range of food products, including seafood, drinking water, fruits, vegetables, beverages, dairy products, salt, honey and processed foods and shows their possible biological effects, such as oxidative stress, inflammation, endocrine disruption, reproductive toxicity, neurotoxicity and alterations of gut microbiota. However, important uncertainties remain regarding realistic human exposure levels, long-term health impacts and detection of smaller particles, in particular, nano plastics. Differences in analytical methods and the lack of adequate standardisation also limit reliable comparison among studies and risk assessment. Future research should therefore focus on harmonised analytical procedures, better contamination control, realistic exposure assessment, long term human studies and effective regulatory strategies. Addressing these gaps will strengthen evidence-based risk assessment and support practical measures to reduce microplastic exposure and protect food safety and human health.

Conflict of Interest

The authors declare that they have no conflict of interest.

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