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Toxicity of microplastics and associated chemicals: A comprehensive review of the current state of knowledge

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ABSTRACT

Microplastics (MPs) have rapidly emerged as a global environmental and public health concern, infiltrating ecosystems ranging from the deepest oceans to the most remote terrestrial and atmospheric regions. Their small size, chemical complexity, and remarkable persistence enable them to interact intimately with biological systems, creating a multifaceted toxicological challenge. In addition to the inherent properties of polymer particles, MPs serve as carriers for a diverse array of chemical additives and environmental contaminants including plasticizers, flame retardants, pesticides, metals, and persistent organic pollutants, amplifying their potential toxicity. As a result, MPs can induce oxidative stress, inflammation, endocrine disruption, metabolic disorders, and microbiome alterations across a wide range of organisms, with growing evidence suggesting implications for human health through ingestion, inhalation, and trophic transfer. Despite the escalating body of research, critical uncertainties persist. Variability in particle characteristics, inconsistent analytical methods, and limited understanding of chronic and low-dose exposures continue to hinder accurate risk assessment. Moreover, the increasing detection of nanoplastics raises additional concerns due to their enhanced reactivity and capacity to cross biological barriers. This review synthesizes current knowledge on the toxicity of microplastics and associated chemicals, integrating findings from environmental distribution, mechanistic toxicology, ecotoxicological effects, and human health implications. Key methodological challenges are highlighted, alongside emerging tools and policy efforts aimed at mitigating risks. By providing a comprehensive and forward-looking analysis, this review underscores the urgent need for standardized monitoring, interdisciplinary research, and regulatory action to address one of the most pervasive contaminants of the modern era.

Keywords: *Microplastics, Environmental Toxicity, Chemical Additives, Human Health, Ecotoxicology, and Nanoplastics.*

Introduction

Plastic production and use have surged worldwide over the last half-century, creating enormous convenience but also leaving a legacy of persistent waste. Large plastic items discarded into the environment gradually fragment into smaller particles, commonly defined as microplastics (MPs), typically plastic fragments less than 5 millimeters in size [1, 2]. These MPs are now detected across virtually all environmental compartments: marine and freshwater bodies, sediments, soils, and increasingly in atmospheric dust and aerosols [3, 4, 5]. This ubiquity raises urgent concern because MPs are not inert debris: their small size, varied polymer types, and surface properties enable them to interact intimately with biotic and abiotic environmental components, acting as persistent pollutants and potential vectors for further contamination [4].

The heterogeneity of microplastics in polymer composition (e.g., polyethylene, polypropylene, polystyrene), shape (fibers, fragments, pellets), size, density, and surface texture strongly influences their environmental behavior and impacts [1, 5]. For instance, low-density MPs may float and be transported long distances via water currents or wind, whereas higher-density or biofilm-coated particles may sink or aggregate with sediments [6]. Such diversity complicates attempts to standardize sampling, quantification, and risk assessment across ecosystems [2]. Recent reviews have noted that even remote or previously pristine environments e.g., polar ice, deep-sea sediments, high-altitude soils now show detectable levels of micro- and nanoplastics, underscoring the extensive reach of plastic pollution [1, 4].

Importantly, microplastics do not represent a physical burden solely. Many plastic materials incorporate chemical additives plasticizers, flame retardants, stabilizers, and colorants, introduced during manufacturing to modulate flexibility, durability, or appearance. These intrinsic chemicals may leach from MPs, especially under environmental stress (UV radiation, temperature fluctuations, mechanical abrasion) [2].

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In addition, MPs can sorb environmental pollutants present in water, soil or air such as heavy metals, persistent organic pollutants (POPs), pesticides, and other hydrophobic contaminants [4]. As such, MPs act as "Trojan horses," delivering a complex mixture of physical particles and chemical burdens to organisms, possibly amplifying their toxicity compared to "clean" plastic debris [5].

Toxicological and ecological studies provide growing evidence that MPs alone or combined with associated chemicals can have adverse effects on living organisms. Among aquatic and terrestrial fauna, exposure has been linked to oxidative stress, inflammation, growth and developmental delays, impaired reproduction, and behavioral changes [4, 7]. Moreover, a recent meta-analysis revealed that rising temperatures, a facet of global climate change, can exacerbate toxicity of microplastics in freshwater invertebrates, suggesting that environmental stressors may amplify MP impacts under global warming scenarios [8]. Human health concerns are also mounting: MPs have been detected in drinking water and other consumables, and the potential for ingestion, inhalation, or dermal exposure is increasingly recognized [9]. Experimental evidence from cell cultures, animal models, and early detection studies points to possible oxidative damage, cellular dysfunction, immune disruption, and systemic effects following MP exposure [1, 4, 7]. Yet, real-world risk assessment remains highly uncertain, due in part to variation in exposure levels, lack of standardized detection methods, and limited long-term or epidemiological studies.

This review seeks to deliver a comprehensive, up-to-date synthesis of the scientific literature on the toxicity of microplastics and their associated chemicals integrating environmental, ecotoxicological, and human-health perspectives. Specifically, it examines the sources, classification, and environmental distribution of MPs across water, soil, air, and sediment. It also discussed the chemical additives and sorbed pollutants that MPs carry, and the factors influencing chemical release, as well as the exposure pathways for wildlife and humans (ingestion, inhalation, dermal contact). The review examines the mechanistic toxicology, physical, chemical, and biological, including oxidative stress, inflammation, endocrine disruption, and microbiome effects. It also elaborates on the documented ecological and human health effects across taxa and scales and also includes methodological challenges such as sampling, detection, quantification, and standardization that currently limit comparative risk assessment and existing mitigation strategies and policy frameworks. By critically evaluating strengths and gaps in the current evidence, this review aims to identify priority research needs, propose directions for methodological standardization, and inform risk-assessment and regulatory efforts. In doing so, we aim to provide a resource that fosters interdisciplinary understanding and supports evidence-based policymaking for environmental sustainability and public health in the face of escalating microplastic pollution.

Definitions, Classification, Sources, and Environmental Distribution of Microplastics

Microplastics (MPs) are increasingly recognized as ubiquitous environmental pollutants, arising from both the fragmentation of larger plastic items and direct industrial or consumer sources. Their small size, diverse polymer types, and varied shapes enable wide dispersal across ecosystems and facilitate interactions with organisms and chemical contaminants. Understanding the definitions, classifications, sources, and environmental behavior of MPs is essential to contextualize their ecological and human health impacts. This section provides a structured overview of MP characteristics, major sources, and their fate and transport across marine, freshwater, terrestrial, and atmospheric compartments. Figure 1, presents an overview of microplastics, including their definitions, classifications, sources, and environmental distribution.

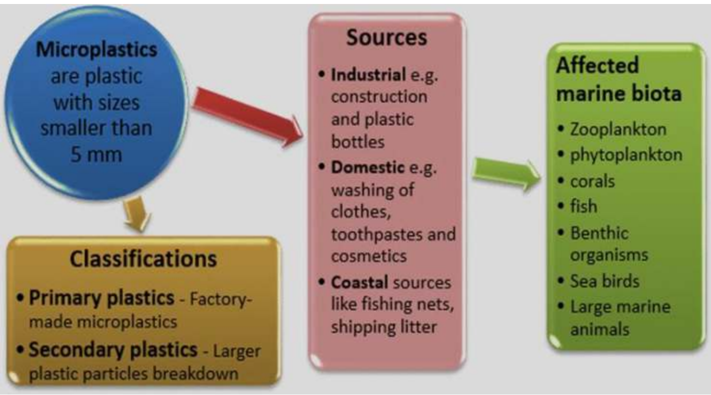

Figure 1. *Representative sources and classifications of microplastics on marine biota. This figure illustrates the main sources of microplastics and how they are classified, highlighting their presence and accumulation in marine organisms.*
Source: *Pereao et al. [10]*

Definition and Classification

Microplastics are broadly defined as synthetic polymer particles with at least one dimension smaller than 5 millimetres, though the exact threshold can vary depending on study and regulatory context. The classification into "primary" and "secondary" microplastics remains widely accepted: primary MPs are intentionally manufactured at microscopic size for uses such as pre-production pellets ("nurdles"), microbeads in personal care products, synthetic microfibres shed from textiles, and industrial abrasives; secondary MPs result from fragmentation and degradation of larger plastic objects (bottles, packaging, nets, etc.) under environmental processes such as UV radiation, mechanical abrasion, chemical weathering and biological breakdown [11]. Beyond origin, MPs vary substantially in polymer type (e.g., polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane), shape (fragments, fibres, films, pellets/beads, foams), density, color, and surface texture. This morphological and compositional heterogeneity strongly influences MPs' environmental behavior, buoyancy, chemical sorption capacity, and interactions with organisms making simple size-based classification insufficient for predictive risk assessment [12].

Major Sources of Microplastics

The sources of MPs are diverse, reflecting both deliberate production and unintended release. Primary microplastics arise from direct manufacturing and use: microbeads in cosmetics and personal care products, pre-production plastic pellets used in plastic manufacturing, microfibres from synthetic textiles during washing, and industrial abrasives or blasting materials [11]. Among these, synthetic fibres from textiles are recognized as a major contributor: washing of garments composed of polymers such as polyester, nylon, or acrylic releases thousands of microfibres per laundry cycle, many of which evade wastewater treatment and enter aquatic systems [11]. Secondary MPs dominate in environmental samples worldwide, since almost any plastic waste, such as bottles, bags, packaging, fishing nets, fishing gear, plastic film, disposable items, can fragment over time under the influence of physical, chemical, and biological processes [1]. Additionally, abrasion of road surfaces during vehicle use (tyre and brake wear) is increasingly recognized as a significant and perhaps under-appreciated source of micro- and nano-sized plastic particles; such particles enter the environment via runoff, stormwater, and atmospheric transport, especially in urban and peri-urban settings [11].

Environmental Fate and Transport of Microplastics

Once released, microplastics (MPs) rapidly disperse across marine, freshwater, sedimentary, soil, and atmospheric compartments due to their small size, low mass, and persistence. A systematic review of 91 studies confirms the global ubiquity of both primary and secondary MPs, identifying rivers as key pathways from land to oceans and highlighting atmospheric circulation as an increasingly important vector for long-range transport [1]. Although buoyancy is often assumed to limit sinking, it is strongly influenced by particle density, biofilm formation, aggregation, and interactions with suspended sediments. Recent mechanistic evidence shows that eco-corona/biofilm-mediated heteroaggregation enables even low-density MPs to cross the "buoyancy barrier," with biofilm-coated MPs settling at more than twice the rate of bare particles in laboratory experiments, thereby enhancing sediment retention [6]. Particle shape further governs transport behavior: non-spherical MPs, particularly fibres, exhibit reduced settling velocities, remain airborne longer, and can be transported and deposited in remote regions [6, 13]. Beyond transport, MPs are highly persistent, as many polymers resist biodegradation and chemical breakdown, allowing them to remain in soils, sediments, waters, and atmospheric dust for decades to centuries [1, 14].

Table 1: Types, properties and sources of common microplastic waste constituents

Plastic Class	Abbreviation	Density (g cm−1)	Products and Typical Origin
High-density polyethylene	HDPE	0.96	Toys, solution containers, tubing
Low-density polyethylene	LDPE	0.92	Bags, plastic wrap, containers
Polypropylene	PP	0.90	Food packaging, pipes, microwavable
Polyvinyl chloride	PVC	1.40	Floor panels, piping, cable enclosures
Polystyrene	PS	1.02–1.05	Foamed foam, insulation material
Polyethylene terephthalate	PET	1.55	Water bottles, fabric
Polyamides	PA	1.02–1.14	Adhesive, fabric
Polymethylmethacrylate	PMMA	1.18	Plates, plexiglas
Polycarbonate	PC	1.36	Insulators, medical tubes, instrument casings
Polyurethane	PU	1.01~1.03	Artificial leather, foam, adhesive

Adapted from Li et al. [1]

Chemical Composition and Contaminant Interactions

Microplastics (MPs) present a combined chemical and physical hazard: their polymer composition and embedded additives define intrinsic risks, while their surfaces interact with environmental contaminants to form complex exposure mixtures. This section summarizes commonly encountered polymers and additives, the sorption behavior that makes MPs vectors for pollutants, and how aging/weathering modifies surface chemistry and toxicity potential.

Polymer Types and Additives

Common polymers found in environmental MP samples include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), among others; polymer prevalence varies by source and matrix (e.g., fibres from textiles vs. fragments from packaging) [15]. Commercial plastics routinely contain additives; plasticizers (phthalates, adipates), flame retardants (PBDEs, organophosphorus esters), stabilizers, pigments, and antioxidants, many of which are not covalently bound and can leach over time, adding chemical toxicity beyond the polymer itself [15, 16]. The identity and concentration of additives influence both the hazard profile and the propensity of MPs to interact with other contaminants [17].

Table 2: Types of polymer additives and associated applications.

Type of Additive	Example	Purpose
Fillers and minerals reinforcement	CaCO3, Mica, talcC	To increase bulk, stiffness, surface hardness
Fiber props	Carbon, aramid, glass	Improve mechanical strength
Colourants	Pigment, liquid colour, dyestuff	Add colours, replacement of heavy metals
Heat resistance	Anti-oxidant-octylphenol, nonylphenol, Bis-phenol A (BPA)	Delay/avoid oxidation of polymer when heated
UV resistanceC	Oxanilides, benzophenones, benzotriazoles	Slow down/stop oxidation of plastics under prolong sunlight exposure
Flame retardants	Polybrominated diphenylethers (PBDEs), BPA	Prevention ignition of polymer
Anti statics, conductive	Glycerol monostearates, carbon black, conductive fibers and nano materials	Enhance electrical conductivity and avoid electrostatic discharge
Cross linking, coupling	Styrene, peroxide, ZnOC	Improve bonding between polymers and additives
PlasticizerC	Phthalates	Improve ease of processing and flexibility

Adapted from [18]

Sorption of Environmental Contaminants

MP surfaces readily adsorb hydrophobic organic contaminants (e.g., PAHs, PCBs, pesticides), pharmaceuticals, and trace metals due to large surface-area-to-volume ratios and hydrophobic interactions; adsorption mechanisms can also include electrostatic forces, hydrogen bonding and π–π interactions depending on polymer surface chemistry [15]. Sorption strength and capacity depend on polymer type, particle size, surface area, crystallinity, and the presence of surface functional groups, all of which change with weathering [16, 17]. Desorption of sorbed contaminants is governed by environmental conditions (pH, salinity, dissolved organic matter) and biological conditions (gastrointestinal fluids, gut surfactants), meaning that MPs may act as Trojan horses, delivering sorbed pollutants to organisms upon ingestion and altering bioavailability compared with free dissolved contaminants [15, 16].

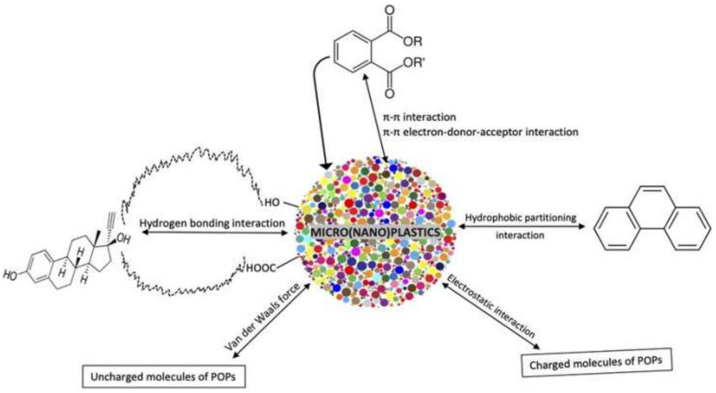

Figure 2: *The sorption mechanisms of organic contaminants to microplastics. This figure illustrates how organic contaminants attach to microplastics through different sorption mechanisms.*
Source: *[19]*

Aging and Weathering

Environmental aging processes photooxidation (UV), thermal oxidation, mechanical abrasion, and biodegradation, transform MP surfaces by introducing oxygenated functional groups, increasing surface roughness, producing cracks/fragments, and promoting biofilm (eco-corona) formation [2, 17, 20]. These changes typically increase sorption capacity for many contaminants (due to higher surface area and new binding sites) but may also enhance leaching of additives and low-molecular-weight degradation products [17, 20]. Aged MPs can generate reactive species and secondary oxidation products that themselves have toxicological relevance, and laboratory studies show that photo- and chemo-aged MPs often produce stronger biological responses (oxidative stress, inflammatory markers) than pristine particles, although responses vary by polymer and aging regime [17, 20]. Therefore, toxicity assessments that rely solely on pristine polymers likely underestimate real-world hazard, because environmental weathering alters both particle chemistry and contaminant interactions [7, 16].

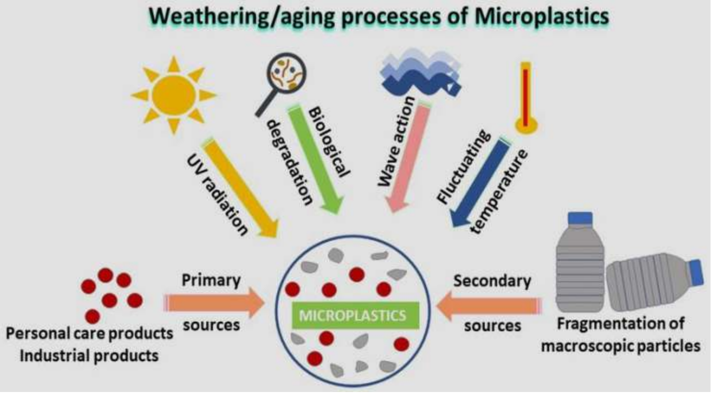

Figure 3: *Weathering or ageing processes of microplastics. This figure shows the weathering and ageing processes of microplastics in the environment. These processes alter the physical and chemical properties of MPs, influencing their environmental behavior and interactions with contaminants.*
Source: *[21]*

Ecotoxicological Effects on Aquatic and Terrestrial Organisms

Microplastics pose complex ecotoxicological risks to organisms across freshwater, marine, and terrestrial environments. Their impacts arise not only from physical interactions such as ingestion or entanglement but also from chemical pathways involving additive release and the transfer of sorbed pollutants. These stressors can disrupt physiological processes, impair reproduction, and alter food-web dynamics, ultimately threatening ecosystem stability. Recent research highlights that the severity of effects depends on particle characteristics, species traits, and environmental conditions, underscoring the need for integrated, mechanism-based assessments [7, 14, 22**]**. Figure 4 illustrates the ecotoxicological effects of microplastic exposure on aquatic and terrestrial ecosystems, showing their how they affect organism health, reproduction, and food-web dynamics.

Physical Effects

Physical interactions with microplastics are among the most widely documented ecotoxicological impacts. Ingestion occurs across diverse taxa, including zooplankton, fish, seabirds, and soil invertebrates, often because particles resemble natural food items [23]. Once ingested, microplastics may accumulate in the digestive tract, leading to reduced feeding, false satiation, impaired nutrient absorption, and gut blockage. In aquatic species such as fish and bivalves, these disruptions have been linked to decreased growth rates and altered energy allocation [24]. Entanglement, though more commonly associated with larger plastic debris, also occurs with microfibers and filamentous particles, which can impair mobility and foraging efficiency in small organisms. Soil fauna, such as earthworms, exhibit reduced burrowing activity and altered gut function when exposed to microplastics, demonstrating that physical stressors extend beyond aquatic environments [25].

Chemical Effects

Microplastics also act as vectors for chemical toxicity. Many polymers contain manufacturing additives including plasticizers, flame retardants, and stabilizers, that can leach into biological tissues upon ingestion [2, 7]. Additionally, microplastics sorb environmental contaminants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and metals, increasing the chemical burden on exposed organisms [2, 14]. Chemical exposure via microplastics has been linked to oxidative stress, inflammation, altered enzyme activity, and endocrine disruption in both aquatic and terrestrial species [2, 7, 26]. In fish, contaminant-loaded microplastics exacerbate liver damage and induce metabolic disturbances. Soil invertebrates similarly exhibit genotoxicity and reduced detoxification capacity following exposure to chemically active microplastic particles [2, 27].

Species and Ecosystem-Level Impacts

At broader biological scales, microplastic exposure can impair reproduction, growth, and survival, with potential consequences for population dynamics. Studies show reduced fecundity in copepods, decreased egg quality in fish, and developmental abnormalities in bivalves following chronic exposure [28]. In soil ecosystems, microplastics alter microbial community structure, nutrient cycling, and plant–soil interactions, thereby influencing primary productivity and soil health [2, 29]. Food-web impacts arise when microplastics and associated chemicals trophically transfer from prey to predators, amplifying exposure along the chain [2, 7]. Such bio-transfer may reduce predator performance, disrupt energy flow, and increase ecosystem vulnerability to additional stressors. While ecosystem-level consequences remain an emerging field, current evidence suggests that persistent microplastic inputs may contribute to long-term ecological degradation, biodiversity loss, and compromised ecosystem services [2, 14].

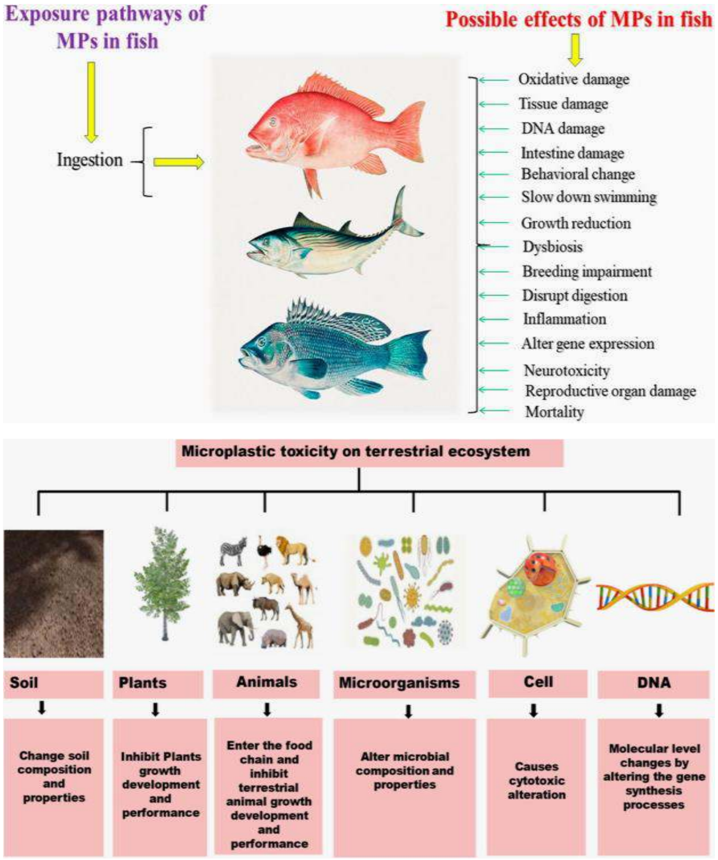

Figure 4: *Ecotoxicological effects of microplastic exposure on aquatic (e.g fish) and terrestrial ecosystems. This figure highlights how MPs can impact organism health, disrupt food webs, and affect ecosystem functioning.*
Source: *[30, 31]*

Human Exposure and Health Risks

Human exposure to microplastics (MPs) is now recognized as a global public health concern, as these particles are increasingly detected in drinking water, food, indoor air, and even human biological samples. Their small size, diverse chemical composition, and ability to transport environmental contaminants make them capable of interacting with human tissues and physiological systems [32]. Understanding exposure pathways, toxicological mechanisms, and available empirical evidence is critical for evaluating potential health risks and guiding future regulatory and scientific priorities.

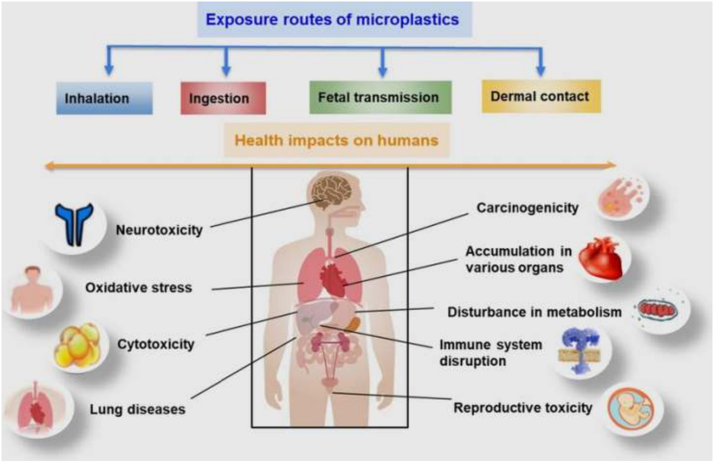

Figure 5: *Exposure routes and effects of microplastics on human health. This figure illustrates the main exposure routes of microplastics to humans such as ingestion, inhalation, and dermal contact and their potential health effects, including physiological stress, reproductive toxicity etc.*
Source: *Kataria et al. [33]*

Exposure Pathways

Humans are exposed to microplastics primarily through ingestion, inhalation, and dermal contact. Drinking water, both bottled and tap, contains measurable levels of MPs, with bottled water often demonstrating higher concentrations due to packaging and bottling processes [2, 34]. Food contamination occurs across seafood, salt, fruits, vegetables, and processed foods, reflecting widespread environmental distribution and agricultural uptake [2]. Inhalation is another significant route, particularly indoors where airborne microfibers from textiles, furnishings, and dust accumulate at higher concentrations than in outdoor environments. Dermal exposure is considered less significant but may occur through personal care products and contaminated water, although current evidence suggests limited skin penetration due to barrier properties [7, 22].

Toxicological Mechanisms

Microplastics may induce toxicity through inflammation, oxidative stress, endocrine disruption, and bioaccumulation of chemicals [2, 7]. Their small size allows interactions with epithelial cells in the gut and respiratory tract, triggering inflammatory responses and altering barrier integrity [14]. MPs can generate reactive oxygen species (ROS), resulting in oxidative stress that affects cellular homeostasis and DNA integrity [2, 7]. Chemical additives such as bisphenol A, phthalates, and flame retardants may leach from MPs, while sorbed pollutants including pesticides, PAHs, and metals, can transfer upon ingestion, contributing to endocrine disruption and metabolic effects [2, 7]. Nanoplastics, in particular, pose additional concern due to their potential to cross biological membranes and accumulate within tissues [35].

Evidence from Epidemiological and Experimental Studies

Empirical evidence on human health effects is emerging from both epidemiological observations and controlled experimental models. Recent findings report microplastics in human stool, placenta, lung tissue, and blood, demonstrating that exposure leads to internalization and systemic distribution [2, 36]. However, direct epidemiological links to disease outcomes remain limited due to challenges in exposure assessment and confounding factors. Experimental studies in human cell lines and animal models suggest that MPs can impair immune responses, alter metabolic processes, disrupt development, and cause inflammatory and oxidative stress mediated toxicity [2, 7, 35]. Despite these findings, significant uncertainties remain regarding dose response relationships, long-term effects, and population-level risks. Continued research integrating toxicology, exposure science, and epidemiology is needed to clarify health implications and inform risk management [2, 7].

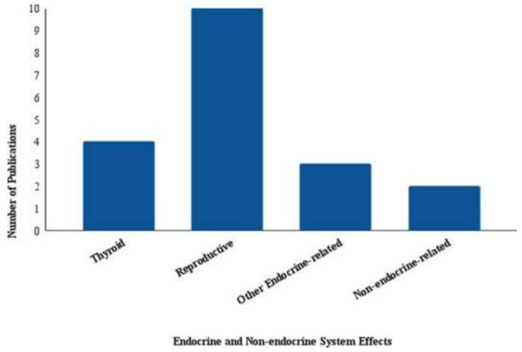

Figure 6: *Effects of microplastics and nanoplastics on endocrine and other related diseases by publications. This figure shows how microplastics and nanoplastics are linked to endocrine and related diseases, summarizing evidence reported across multiple publications.*
Source: *Thin et al. [37]*

Analytical Approaches for Microplastics and Associated Chemicals

Accurate analysis of microplastics (MPs) and their associated chemical contaminants depends on robust sampling, extraction, and instrumental identification. Because MPs occur in diverse matrices (water, soil, air, biota), analytical workflows must balance sensitivity, precision, and comparability. Despite advances in spectroscopic and chromatographic techniques, methodological limitations persist, especially for small particles and chemical characterization [38]. Figure 7, demonstrates these approaches, showcasing the methods and equipment involved in the analysis.

Sampling and Extraction Techniques

Sampling strategies depend on the matrix. Water samples commonly use filtration and density separation to isolate MPs efficiently [39]. Sediment and soil extraction typically combine density flotation and chemical/enzymatic digestion to remove organic matter while preserving polymers [40]. Airborne MPs are collected using high-volume air samplers or cascade impactors, enabling recovery of fibrous particles within $PM_{2.5}/PM_{10}$ fractions [41]. For biota, enzymatic digestion minimizes polymer degradation and improves recovery. Despite these tools, contamination control and matrix effects remain persistent obstacles [38].

Identification and Quantification Tools

FTIR and Raman spectroscopy remain the primary methods for polymer identification due to their molecular fingerprinting capacity; however, their size detection limits generally fall above 10–20 μm and 1–5 μm, respectively [42]. Py-GC-MS and TED-GC-MS provide sensitive, polymer-specific mass quantification and can detect smaller particles, though they do not provide particle counts or shapes [38]. Microscopy (optical, SEM) remains essential for assessing particle morphology and size but must be coupled with spectroscopic tools for polymer confirmation. Emerging methods such as hyperspectral imaging and LDIR aim to automate identification and expand detection of smaller MPs [42].

Challenges and Methodological Gaps

Analytical limitations are still significant. Lack of harmonized protocols results in inconsistent reporting and inter-laboratory variability [41]. Detection of nanoplastics remains extremely limited due to optical resolution barriers and sample complexity [42]. Chemical characterization is also constrained by overlapping organic signals and heterogeneous aging of plastics, which complicate polymer identification and additive detection [38]. Progress requires validated reference materials, cross-method integration, and standardized workflows.

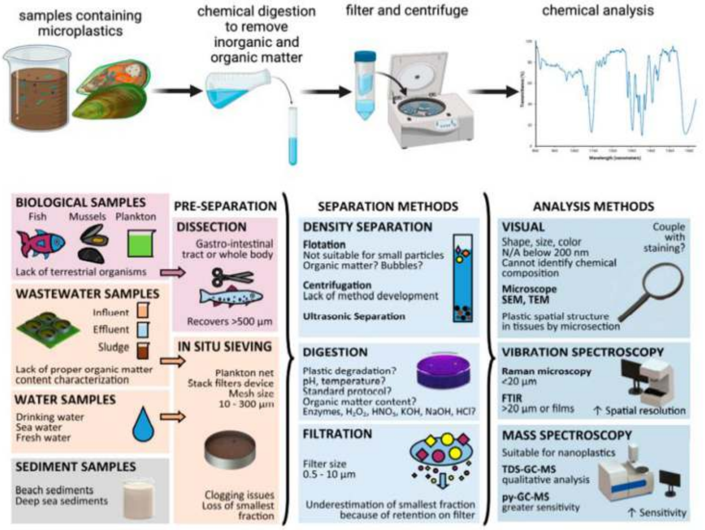

Figure 7: *Analytical approaches for microplastics. Top—Overall microplastics analysis workflow. Prior to separation using gravimetric or filtration techniques, samples are first digested to dissolve and eliminate organic and inorganic components. It is finally possible to analyze microplastics chemically. Bottom: Summary of methods for separating and analyzing microplastics and nanoplastics in both simple and complicated matrices.*
Source: *Sarkar et al. [43]*

Research Gaps and Future Directions

Despite rapid growth in microplastics (MPs) research, critical knowledge gaps remain that limit robust risk assessment and regulatory action. Most toxicological studies are short-term and laboratory-based, often using concentrations that exceed environmental relevance. There is a clear need for long-term, chronic exposure studies that reflect realistic doses, aging states, and organism life stages to better understand cumulative and delayed effects [38, 42]. A major analytical limitation concerns the poor detection and characterization of nanoplastics (<1 μm). Current spectroscopic tools struggle at this scale, leaving the most biologically reactive fraction of plastic pollution largely unquantified. Advancing high-resolution analytical techniques and integrating thermal, spectroscopic, and imaging approaches are essential for resolving nanoplastic abundance, chemistry, and toxicity [41, 42].

Another critical gap lies in understanding the combined and interactive effects of MPs and associated chemicals, including additives, metals, and sorbed organic pollutants. Most studies assess single stressors, yet environmental exposures occur as complex mixtures, potentially leading to synergistic or antagonistic toxicological outcomes that are not captured by isolated assessments [38, 40]. Finally, the absence of harmonized monitoring and reporting standards continues to hinder cross-study comparability and global risk evaluation. Differences in sampling methods, size thresholds, and reporting units introduce significant uncertainty. International alignment of protocols, validated reference materials, and quality assurance frameworks is therefore a priority for future research and policy development [41, 44].

Conclusion

This review highlights current understanding of microplastic toxicity and their interactions with associated chemicals, emphasizing their dual role as physical stressors and carriers of hazardous substances. Microplastics can disrupt biological functions through ingestion, tissue interaction, and chemical release, with effects shaped by particle size, polymer composition, aging, and environmental context. These characteristics contribute to complex toxicological responses across ecosystems. The environmental and human health implications are increasingly apparent. In ecological systems, microplastics affect organism health, reproduction, and food-web dynamics, while in humans, continuous exposure via water, food, and air raises concerns about chronic outcomes such as inflammation, oxidative stress, and endocrine interference. Although significant uncertainties remain—particularly regarding long-term, low-dose exposures, the persistence and ubiquity of microplastics justify precautionary concern. Mitigating microplastic risks requires coordinated global action. Progress depends on harmonized monitoring approaches, improved analytical tools, and integrated risk assessment frameworks, alongside preventive measures such as plastic reduction, safer material design, and improved waste management. Together, these efforts are essential for limiting the long-term environmental and health impacts of microplastics.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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