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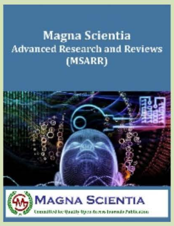

(Review Article)

Microplastics as Silent Invaders: A Multiscale Review of their Toxicological Effects and Contaminant Interactions in Terrestrial and Aquatic Environments

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Abstract

Microplastics (MPs), often termed “silent invaders,” have become ubiquitous pollutants across both terrestrial and aquatic environments, raising significant concerns in respect of their toxicological and ecological consequences. This review provides an in-depth multiscale evaluation of the toxic effects of microplastics, from molecular disruptions to ecosystem-level disturbances. Special priority is placed on the capacity of microplastics to act as vectors for a range of environmental contaminants, including heavy metals, persistent organic pollutants, and pharmaceuticals, thereby amplifying their toxic potential. This review also examines how microplastics interact with biological systems, triggering oxidative stress, inflammation, genotoxicity, endocrine disruption, and behavioural changes in organisms across various trophic levels. Comparative insights between terrestrial and aquatic systems divulge distinct exposure pathways and species-specific vulnerabilities, with remarkable research gaps persisting in soil ecosystems. Moreover, the review discusses current advances and limitations in detection methods and toxicological assays, while highlighting censorious needs for standardized protocols and long-term ecological studies. Ultimately, this synthesis underscores the urgent necessity for transdisciplinary research and regulatory frameworks to address the escalating risks posed by microplastics and their associated contaminants in global ecosystems.

Keywords: Microplastics; Silent Invaders; Toxicological Effects; Contaminant Interactions; Terrestrial Environments; Aquatic Environments

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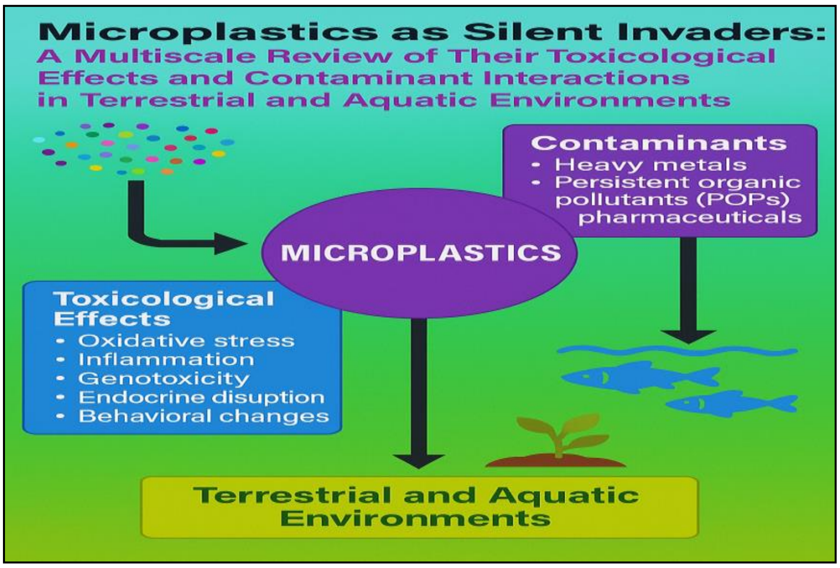
Graphical Abstract



1. Introduction

Microplastics (MPs) are minute synthetic polymer particles, typically defined as having diameters of less than 5 Millimeters, that have emerged as prevalent and persistent contaminants in the environment. These particles are broadly distributed due to their extensive use in commercial products and the long degradation timelines of plastics. Microplastics are generally classified into two categories based on their origin: primary microplastics, which are intentionally engineered at microscopic sizes for inclusion in products such as personal care items (e.g., exfoliating beads in cosmetics), industrial abrasives, and synthetic textiles; and secondary microplastics, which are generated through the breakdown of larger plastic debris due to physical weathering (abrasion, UV radiation), chemical degradation, or biological activity. The diversity in chemical composition (e.g., polyethylene, polypropylene, polystyrene), morphology (fibers, fragments, films, spheres), and density of MPs significantly influences their transport behavior, environmental fate, and potential for interaction with organisms and contaminants [1, 10].

The growing global concern surrounding microplastics is fueled by their omnipresence across virtually all environmental compartments. MPs have been identified in marine and fresh water ecosystems, terrestrial soils, atmospheric dust, and even in polar ice core sand remote mountainous regions, emphasizing their long-range transport capabilities. These particles have also been detected within a wide range of biota, including zooplankton, fish, birds, mammals, and humans, via inhalation, ingestion, and dermal exposure pathways. Their small size allows for easy entry into food webs, while their chemical resilience and hydrophobic nature enable them to persist for decade sand adsorb or concentrate hazardous pollutants such as persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and pharmaceutical residues on their surfaces. These interactions can enhance the bioavailability and toxicity of the sorbed pollutants, posing compounded risks to organisms and ecosystems [2]. In light of these complexities, there is a critical need for a comprehensive multiscale review of the toxicological implications of microplastics. Many current investigations remain compartmentalized, focusing narrowly on aspects such as detection, quantification, or uptake in specific species. However, the true threat posed by MPs spans multiple biological hierarchies and environmental contexts. At the molecular and cellular levels, MPs have been linked to oxidative stress, genotoxicity, inflammation, membrane disruption, and metabolic alterations. At the organismal level, exposure may lead to reproductive impairments, behavioral changes, neurotoxicity, and immune dysfunction. On a broader scale, MPs influence species interactions, biodiversity, and nutrient cycling, ultimately destabilizing entire ecosystem functions and services [3, 10]. Moreover, microplastics do not act alone. They often function as vector-like platforms, enhancing the mobility and toxicity of co-occurring contaminants. This vector effect introduces additional complexity to environmental risk assessments, as combined exposures to MPs and absorbed pollutants (e.g., cadmium, bisphenol A, antibiotics) may result in synergistic, additive, or antagonistic toxicological outcomes. These interactions are highly context-dependent, influenced by factors such as particle size, surface area, aging, environmental pH, salinity, and biofilm formation [4, 10]. Given this background, the present review aims to deliver a thorough, multiscale evaluation of microplastic toxicity, with an emphasis on mechanistic pathways and contaminant interactions in both terrestrial and aquatic systems. By bridging data from molecular biology, toxicology, environmental chemistry, and ecology, this review aspires to offer a holistic understanding of microplastics as complex environmental stressors. Such insights are vital for guiding scientific research, policymaking, pollution mitigation strategies, and the development of sustainable plastic alternatives and waste management solutions [5, 10].

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2. Properties and Environmental Behaviour of Microplastics

2.1. Physicochemical Properties

Microplastics (MPs) possess diverse physicochemical characteristics that critically influence their environmental fate, behavior, and potential toxicity. Understanding these properties is essential for assessing their interactions with biological systems and co-contaminants in both terrestrial and aquatic ecosystems [6].

2.1.1. Polymer Types

Microplastics are derived from a wide range of polymeric materials, each with distinct chemical and physical characteristics. The most common types include: Polyethylene (PE) is one of the most commonly encountered polymers in the environment, widely used in the production of plastic bags, bottles, and various packaging materials. It is known for its low density and high flexibility, which make it buoyant and easily transported in aquatic systems. Polypropylene (PP), another frequently used plastic, is commonly found in items such as bottle caps, food containers, and automotive components [7]. It has a moderate density and demonstrates good thermal stability, contributing to its durability in diverse environmental conditions. Polystyrene (PS) is a lightweight and brittle plastic typically used in disposable cutlery, foam food containers, and packaging materials. Due to its fragile structure, it readily breaks into smaller fragments, increasing its prevalence as microplastic particles. Polyvinyl chloride (PVC) is characterized by its rigidity and strong resistance to degradation. It is widely utilized in applications like plumbing pipes, medical devices, and construction materials. Unlike lighter plastics, PVC tends to settle in sediments due to its higher density. Polyethylene terephthalate (PET), known for its superior chemical resistance and density, is commonly used in beverage bottles, food packaging, and textiles. It is particularly prominent in synthetic fabrics, contributing to microfiber pollution through wear and laundering. These polymer types differ significantly in their physical and chemical properties, which influence how they behave, persist, and interact within various environmental compartments [7].

2.1.2. Particle Size, Shape, and Surface Chemistry

Microplastics exhibit a broad range of sizes, spanning from nanoplastics smaller than 100 nanometers to particles nearing the upper threshold of 5 millimeters. The size of these particles plays a vital role in influencing their bioavailability, capacity for mobility across environmental media, and the degree to which they can be taken up by cells and tissues [8]. In addition to size, the shape of microplastics significantly affects their environmental behavior and potential toxicity. These particles can occur as irregular fragments, often resulting from the mechanical or chemical breakdown of larger plastic items. Fibers, which are thin and thread-like, typically originate from the shedding of synthetic textiles. Spherical beads are commonly manufactured for use in personal care products and industrial abrasives. Films appear as thin, flat pieces derived from the degradation of plastic packaging materials [8]. Another notable form is foam, a porous and lightweight structure frequently associated with expanded polystyrene products. Each of these shapes interacts differently with environmental systems and organisms, affecting how microplastics are transported, degraded, and ingested across various ecosystems. The surface chemistry of MPs, including functional groups, surface area, charge, and roughness, dictates their ability to adsorb pollutants, bind to organic matter, and form biofilms. Surface properties may evolve over time due to environmental aging, altering their reactivity and toxicity profiles [8].

2.1.3. Aging and Weathering Effects

Once microplastics are introduced into the environment, they are subjected to a variety of weathering and aging processes, including ultraviolet (UV) irradiation, mechanical abrasion, hydrolysis, oxidation, and, in some cases, biodegradation. These processes progressively alter the physical and chemical characteristics of the particles. As a result, microplastics may exhibit surface cracking and pitting, which compromise their structural integrity. The chemical composition of their functional groups can also be modified, often increasing their reactivity. Simultaneously, the surface area and porosity of the particles tend to increase, further influencing their interaction with surrounding substances. Visual and structural changes, such as discoloration and increased brittleness, are also common. These transformations not only promote the fragmentation of microplastics into even smaller particles, including nanoplastics, but also significantly enhance their capacity to adsorb and concentrate environmental contaminants. Such alterations heighten the complexity of their environmental behavior and amplify their potential ecological risks [9, 10].

Table 1 Summary of the Properties and Environmental Behaviour of Microplastics

Property	Description	Environmental Behaviour	Source
Polymer Types	*Polyethylene (PE): Low density, high flexibility. *Polypropylene (PP): Moderate density, thermally stable. *Polystyrene (PS): Brittle, lightweight. *Polyvinyl chloride (PVC): Rigid, dense, resistant to degradation. *Polyethylene terephthalate (PET): Dense, chemically resistant.	*PE and PP float, increasing aquatic transport. *PS fragments easily, raising abundance of MPs. *PVC and PET sink and accumulate in sediments. *Polymer type determines degradation rate, bioavailability, and interaction with contaminants.	[7]
Particle Size	Ranges from nanoplastics (<100 nm) to 5 mm.	Smaller particles are more mobile, bioavailable, and likely to penetrate biological membranes.	[8]
Shape	Includes fragments, fibers, beads, films, and foams. *Fragments: From breakdown of larger plastics. *Fibers: From textiles. *Beads: From cosmetics/abrasives. *Films/Foams: From packaging and foamed plastics.	Shape affects ingestion, transport, and accumulation in organisms. Fibers persist in water and air; fragments can be easily transported; foams are lightweight and mobile.	[8]
Surface Chemistry	Defined by surface area, charge, roughness, and functional groups. Can adsorb pollutants and form biofilms.	Surface aging alters adsorption capacity and reactivity. MPs can become vectors for heavy metals, persistent organic pollutants (POPs), and microbes.	[8]
Aging and Weathering Effects	Caused by UV radiation, abrasion, oxidation, and hydrolysis. Results in surface cracks, pitting, increased porosity, and discoloration.	Enhances pollutant adsorption and fragmentation into nanoplastics. Increases ecological risk and environmental persistence.	[9]

2.2. Environmental Fate and Transport

Microplastics are highly mobile pollutants that disperse across air, terrestrial soils, freshwater bodies, and marine environments. Their distribution and persistence depend on physical, chemical, and biological factors that govern transport, degradation, and transformation [11].

2.2.1. Transport Dynamics in Air, Soil, Freshwater, and Marine Systems

Microplastics exhibit complex transport dynamics across various environmental compartments, including the atmosphere, soil, freshwater bodies, and marine ecosystems. In the atmosphere, microplastics can become airborne through mechanisms such as wind erosion of contaminated soils, sea spray, and emissions from urban and industrial activities. Lightweight polymers like polyethylene and polypropylene, along with synthetic fibers, are particularly prone to long-distance atmospheric dispersal. This enables their deposition in remote and pristine regions, including high-altitude mountains and polar zones [10,11]. Within terrestrial systems, microplastics accumulate primarily through agricultural practices such as the application of biosolids, the degradation of plastic mulch, and improper disposal or littering. Their mobility in soil is strongly influenced by characteristics like porosity, moisture content, and biological activity, such as earthworm movement. These factors determine whether microplastics remain in the upper soil layers, migrate vertically, or are carried laterally by surface runoff. In some cases, particles may infiltrate deeper layers and reach groundwater systems, potentially contributing to subterranean pollution [12]. Freshwater environments such as rivers, lakes, and streams function as transitional pathways, channeling microplastics from terrestrial sources toward marine ecosystems. The transport and eventual fate of these particles are governed by hydrodynamic variables including water flow velocity, turbulence, and sediment interactions. Particles may remain suspended in the water column, settle into sediments, or be re-suspended depending on these conditions and their physical properties. In marine systems, which serve as the ultimate sink for much of the world's plastic pollution, the fate of microplastics is dictated largely by their density and surface characteristics. Less dense particles may float on the surface or drift within the upper water column, while denser polymers tend to sink, becoming embedded in the seabed. Oceanic currents, wave action, and wind patterns facilitate the long-range movement of floating particles, leading to accumulation in convergence zones such as subtropical gyres. One of the most well-known examples is the Great Pacific Garbage Patch, where massive quantities of microplastics persist, posing significant ecological threats [13].

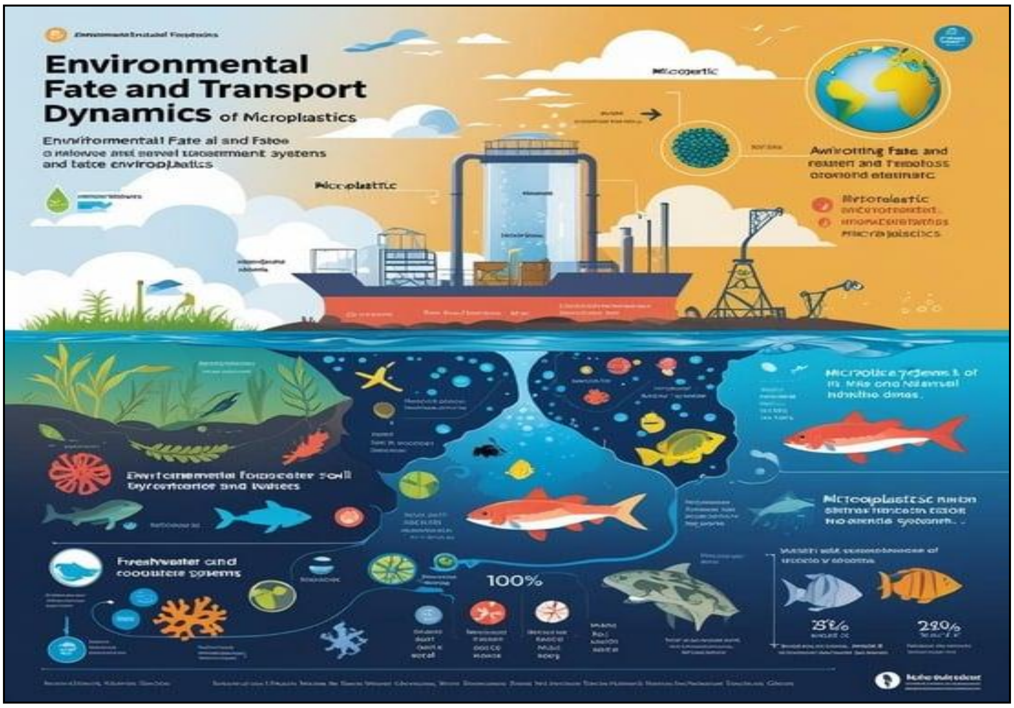

Figure 1 Environmental Fate and Transport Dynamics of Microplastics in Air, Soil, Freshwater, and Marine Systems [10 modified]

2.3. Fragmentation and Degradation

Once released into the environment, microplastics are subjected to various transformation processes that result in both physical fragmentation and chemical degradation. Mechanical forces such as wave action, abrasion from sediments, and collisions with other particles contribute significantly to their breakdown into smaller pieces. Exposure to sunlight, particularly ultraviolet-B (UV-B) radiation, initiates photo-oxidative reactions that further weaken the polymer structure. In addition, fluctuating environmental temperatures can cause thermal degradation, accelerating the deterioration of certain plastic materials. Under specific conditions, microbial communities may also contribute to the degradation of some polymer types, although this process is typically limited and highly variable depending on the environmental context and plastic composition. These combined processes gradually reduce microplastics into even smaller fragments, including nanoplastics, which can penetrate biological membranes more easily and pose distinct toxicological challenges to both aquatic and terrestrial organisms. However, the degradation of plastics in natural settings is generally slow and often incomplete, resulting in the long-term persistence and cumulative accumulation of microplastic particles within ecosystems [14, 10].

2.4. Interaction with Natural Organic Matter and Biofilms

Microplastics readily interact with natural organic matter (NOM), including humic substances, algae, and dissolved organic compounds, which can coat particle surfaces and modify their surface charge, hydrophobicity, and reactivity. These interactions influence particle aggregation, sedimentation, and bioavailability. In aquatic environments, MPs are rapidly colonized by microbial communities forming biofilms, creating what is known as the “plastisphere.” Biofilm formation alters the particle’s density, increasing its likelihood of sinking, and can harbourpathogens, antibiotic resistance genes, or decomposing pollutants, turning MPs into mobile vectors of biological and chemical agents [15].

3. Adsorption and Vector Potential for Environmental Contaminants

Microplastics (MPs) are not merely inert physical pollutants; they act as dynamic carriers or vectors of a wide array of environmental contaminants. Due to their physicochemical characteristics, including high surface area-to-volume ratios, hydrophobic surfaces, and chemical stability, MPs have a pronounced tendency to adsorb persistent and toxic substances from their surrounding environment. These include heavy metals, persistent organic pollutants (POPs), pharmaceutical residues, and antibiotics, all of which may significantly increase the ecological and toxicological burden associated with microplastic pollution [16]. This chapter explores the mechanisms of sorption, the conditions influencing desorption and bioavailability, and the combined toxic effects arising from the interactions between microplastics and adsorbed contaminants [16].

3.1. Sorption Mechanisms

The sorption of environmental contaminants onto microplastic surfaces is governed by a combination of physical adsorption, chemical bonding, and electrostatic interactions. These mechanisms allow microplastics to act as "pollutant sponges" in the environment, sequestering toxicants from surrounding media and concentrating them on their surfaces at levels significantly higher than those found in the ambient environment [17].

Heavy metals such as lead, cadmium, mercury, and arsenic readily adsorb to microplastic surfaces through mechanisms including ionic exchange, electrostatic attraction, and complexation with functional groups on aged plastic surfaces. The affinity for metal adsorption is often enhanced by the oxidative weathering of microplastics, which introduces oxygen-containing functional groups like carboxyl, hydroxyl, and carbonyl moieties [18].

Persistent organic pollutants (POPs) including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dioxins tend to accumulate on microplastics due to their hydrophobic nature. The non-polar surfaces of polymers like polyethylene (PE) and polypropylene (PP) favour van der Waals interactions and partitioning with similarly hydrophobic POPs [19].

Pharmaceuticals and antibiotics, especially those with aromatic and non-polar groups, also display significant sorption onto microplastics, driven by π–π interactions, hydrogen bonding, and other molecular affinities [20].

The extent and efficiency of contaminant sorption are heavily influenced by polymer type, surface area, and aging. Polymers differ in crystallinity, polarity, and hydrophobicity, all of which affect their sorption capacity. For instance, PE and PP, due to their low polarity and high surface hydrophobicity, typically show higher sorption of non-polar organic pollutants. Aged microplastics, having undergone weathering and oxidation, often exhibit increased surface roughness, porosity, and functional group diversity, which significantly enhances their sorption affinity [21].

Table 2 Summary of Microplastics Adsorption and Vector Potential for Environmental Contaminants [sources:16, 17, 18, 19, 20, 21]

Contaminant	Type of Microplastic	Adsorption Mechanism	Environmental Medium	Vector Behaviour	Ecological/Health Risk
Heavy Metals (e.g., Pb, Cd, Zn)	PE, PVC, PET, PS	Electrostatic attraction, surface complexation with oxidized functional groups	Soil, freshwater, sediment	MPs carry adsorbed metals into aquatic food chains, plant roots, and soil microbes	Toxicity to plants, bioaccumulation in fish, neurological effects in humans
Persistent Organic Pollutants (POPs) (e.g., DDT, PCBs, PAHs)	PE, PP, PS	Hydrophobic interactions, Van der Waals forces	Water bodies, sediments	MPs adsorb and transport hydrophobic compounds, enhancing their mobility in aquatic environments	Carcinogenicity, endocrine disruption, biomagnification
Antibiotics (e.g., Tetracycline, Sulfamethoxazole)	PET, PS, PE	Hydrogen bonding, π–π interactions	Wastewater, freshwater systems	MPs serve as mobile carriers of antibiotics, contributing to	Disruption of microbial ecology, antibiotic resistance

				the spread of antibiotic resistance genes	
Pesticides (e.g., Glyphosate, Atrazine)	PE, PVC, PP	Surface sorption, electrostatic and hydrophobic interactions	Agricultural runoff, soil, rivers	MPs adsorb pesticide residues and release them downstream or into terrestrial ecosystems	Soil degradation, aquatic toxicity, residue intake by crops
Pharmaceuticals & Personal Care Products (PPCPs) (e.g., Ibuprofen, Triclosan)	PET, PE, PS	Hydrogen bonding, hydrophobic and electrostatic interactions	Wastewater, sludge, rivers	MPs act as long-distance vectors through effluents and sludge applications in agriculture	Hormonal disruption, aquatic life toxicity
Pathogenic Microorganisms (e.g., *E. coli*, *Vibrio spp.*)	PE, PP, PS (biofilm-forming MPs)	Surface colonization, biofilm formation on aged or roughened MP surfaces	Rivers, lakes, estuaries	MPs serve as platforms for microbial attachment, aiding their dispersal across water bodies	Spread of disease, waterborne infections
Industrial Dyes & Chemicals (e.g., Benzidine dyes, BPA)	PET, PS, PE	π–π interactions, hydrogen bonding	Industrial discharges, urban runoff	MPs can bind colored chemicals and bisphenols, transporting them into food chains and aquatic systems	Mutagenicity, toxicity to aquatic organisms

PE: Polyethylene; PP: Polypropylene; PVC: Polyvinyl chloride; PET: Polyethylene terephthalate; PS: Polystyrene; PAHs: Polycyclic aromatic hydrocarbons; PCBs: Polychlorinated biphenyls; PPCPs: Pharmaceuticals and Personal Care Products

3.2. Desorption and Bioavailability

While adsorption concentrates contaminants on microplastic surfaces, desorption governs their potential release into biological or environmental compartments. The process of desorption determines whether the sorbed contaminants become bioavailable, that is, accessible for uptake by organisms and capable of exerting toxic effects [22]. Several environmental factors modulate the desorption of contaminants from microplastics. Changes in pH can alter the ionization state of both the microplastic surface and the contaminant, facilitating or hindering release. Temperature plays a critical role by increasing molecular motion, which can disrupt weak bonds and enhance desorption rates. Salinity can impact ionic strength and competition between contaminants and surrounding ions, especially in estuarine and marine environments. Once ingested, the bioaccessibility of sorbed contaminants within an organism's digestive tract becomes critical. The gastrointestinal environment, characterized by low pH, enzymatic activity, and the presence of bile salts, can induce the release of adsorbed pollutants, making them available for absorption into tissues. Several studies have shown that microplastics can act as a "Trojan horse," transporting otherwise less-mobile contaminants into the bodies of organisms, where desorption occurs internally, amplifying exposure and risk [23]. The desorption dynamics are not uniform across all contaminant classes or polymer types. Hydrophobic pollutants tend to desorb more slowly, maintaining prolonged association with plastic particles, whereas ionic compounds like certain heavy metals may desorb more readily under variable environmental or physiological conditions.

3.3. Combined Toxicity

The co-occurrence of microplastics and environmental contaminants leads to complex toxicological interactions, which can manifest as synergistic, additive, or antagonistic effects. These interactions often produce a toxic burden that is greater or occasionally less than the sum of the individual components. In synergistic toxicity, the combined presence of microplastics and adsorbed pollutants amplifies harmful effects on exposed organisms. For instance, microplastics loaded with endocrine-disrupting chemicals such as bisphenol A (BPA) or nonylphenols may enhance hormonal disruption in aquatic species beyond the effect of either stressor alone. Similarly, the ingestion of microplastics carrying PAHs or heavy metals has been shown to induce oxidative stress, immune dysfunction, and histopathological damage more severely than exposure to free pollutants [24]. Antagonistic interactions, though less common, can also occur. In some cases, the adsorption of a toxicant onto a microplastic surface may reduce its immediate bioavailability, temporarily mitigating its toxic impact. However, such effects are often transient and context-dependent, particularly when desorption is triggered by internal physiological conditions post-ingestion. The complexity of combined toxicity underscores the need for multidimensional risk assessments, which consider not only the individual hazards posed by microplastics and environmental contaminants but also their interactions, transformations, and cumulative effects across different levels of biological organization [10, 24]. Laboratory experiments, in situ monitoring, and ecotoxicological modeling are essential tools for unraveling these interactions and predicting long-term ecological consequences. Microplastics function as highly effective vectors for environmental contaminants, significantly altering the transport, bioavailability, and toxicity of a wide range of pollutants. Their sorption capabilities depend on polymer characteristics and environmental aging, while desorption is driven by dynamic environmental and physiological conditions. The resultant combined toxicity poses substantial risks to ecosystems and human health, far beyond what either component would induce in isolation. Understanding these interactions is pivotal for developing holistic environmental policies, risk assessment frameworks, and effective mitigation strategies in the face of escalating microplastic pollution [24].

4. Multiscale Toxicological Effects of Microplastics

Microplastics (MPs) have emerged as pervasive environmental stressors capable of inducing harmful effects at multiple biological scales. Their small size allows them to interact directly with cells and tissues, while their chemical properties and contaminant-loading potential amplify their toxicological footprint. This chapter provides a comprehensive analysis of microplastic-induced toxicity, beginning at the cellular and molecular level, extending to organismal-level responses, and culminating in population and community-level consequences across both terrestrial and aquatic ecosystems [25].

4.1. Cellular and Molecular Toxicity

At the cellular and molecular scale, microplastics can interfere with essential biochemical and physiological processes, often initiating the earliest signs of toxicity.

4.1.1. Oxidative stress and ROS production

When microplastics enter biological systems, they frequently stimulate the excessive generation of reactive oxygen species (ROS), chemically reactive molecules containing oxygen. This leads to oxidative stress, a condition where the antioxidant defense mechanisms of the cell are overwhelmed, resulting in damage to proteins, lipids, and DNA. This ROS imbalance is a common pathway through which microplastics initiate cellular injury, especially in sensitive tissues such as gills, intestines, and hepatocytes of aquatic organisms [26].

4.1.2. Inflammatory responses

The recognition of microplastics as foreign particles often triggers inflammatory reactions, particularly in immune-competent tissues. This is mediated by the activation of signaling molecules like cytokines and chemokines, which recruit immune cells to the site of exposure. Chronic inflammation can lead to tissue damage, fibrosis, and impaired organ function, especially when microplastics are persistent or repeatedly introduced into the system [27].

4.1.3. Apoptosis and necrosis

As oxidative and inflammatory stress escalate, cells may undergo apoptosis (programmed cell death) or necrosis (uncontrolled cell death). Apoptosis is often a protective mechanism to eliminate damaged cells; however, widespread apoptosis may compromise tissue integrity and function. Necrosis, in contrast, can provoke further inflammation and tissue disruption. Both outcomes have been observed in lab studies involving fish, earthworms, and mammalian cell lines exposed to microplastics [28].

4.1.4. Genotoxicity and epigenetic changes

Microplastics can directly or indirectly cause DNA damage, leading to genotoxicity, a precursor to mutations and potentially cancerous transformations. Additionally, exposure to microplastics and their associated contaminants may induce epigenetic modifications, such as DNA methylation and histone modification, which alter gene expression without changing the genetic code [29]. These changes can disrupt normal cellular function and may even be heritable across generations, raising concerns about long-term and trans-generational effects.

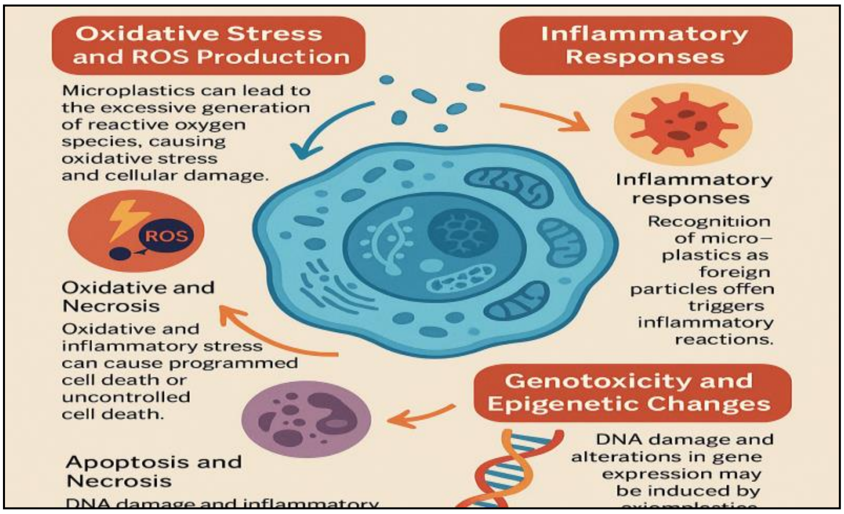

Figure 2 Toxicological Effects of Microplastics at the Cellular and Molecular Scale [10, 26, Modified]

4.2. Organismal-Level Effects

Moving beyond the cellular level, microplastics have been shown to impair fundamental physiological, behavioral, and immunological processes in a wide range of terrestrial and aquatic species.

4.2.1. Physiological disruptions: reproduction, growth, metabolism

Microplastic exposure can interfere with key physiological processes such as reproductive output, developmental growth, and metabolic efficiency. For instance, marine organisms like oysters and fish exhibit reduced egg production and impaired sperm motility following ingestion of microplastics. Growth retardation has been reported in earthworms and aquatic invertebrates, likely due to energy reallocation towards stress responses. Moreover, disrupted lipid and carbohydrate metabolism has been observed, indicating systemic metabolic dysfunction [30].

4.2.2. Behavioural alterations: feeding, mobility, predator avoidance

Behavior is often the first observable indicator of sub-lethal stress. Ingestion of microplastics has been associated with reduced feeding efficiency, possibly due to gut blockage or altered appetite-regulating hormones. Changes in mobility and swimming patterns have been documented in zooplankton and fish, potentially impairing their ability to forage or migrate. More alarmingly, predator avoidance behaviour can be disrupted, making prey species more vulnerable and altering predator-prey dynamics [31].

4.2.3. Immune suppression and endocrine disruption

Microplastics and their chemical additives, such as phthalates and bisphenol A, are known endocrine-disrupting compounds (EDCs). These can mimic or block hormonal signals, affecting reproduction, development, and stress regulation. Furthermore, prolonged exposure to MPs can suppress immune function, reducing the organism's ability to fight infections [32]. This has been observed in fish and amphibians, where reduced immune cell counts and altered cytokine levels were reported.

4.3. Population and Community-Level Impacts

At larger ecological scales, the cumulative effects of microplastic toxicity manifest in disruptions to population structure, species interactions, and ecosystem processes.

4.3.1. Bioaccumulation and biomagnification

Microplastics and the contaminants they carry can bioaccumulate within organisms and biomagnify through trophic levels. Small organisms such as plankton or earthworms ingest microplastics and are subsequently consumed by larger predators, leading to increasing concentrations of plastic-associated toxins in higher trophic organisms, including birds, fish, and potentially humans [33]. This poses a serious risk to food safety and biodiversity.

4.3.2. Altered species composition and biodiversity loss

Chronic microplastic contamination can shift species composition within ecosystems. Sensitive species may decline due to reproductive failure, behavioral impairment, or reduced survival, while more tolerant or opportunistic species may proliferate. Such imbalances reduce biodiversity, which undermines ecosystem resilience and functionality [34]. For example, benthic communities exposed to sediment-laden microplastics show reduced species richness and abundance.

4.3.3. Ecological imbalance: nutrient cycling, food web dynamics

Microplastics can influence ecosystem services such as nutrient cycling, primary productivity, and food web stability. Soil-dwelling organisms like nematodes and earthworms, which play crucial roles in organic matter decomposition and soil aeration, exhibit altered activity when exposed to microplastics, thereby disrupting soil fertility [35]. In aquatic ecosystems, changes in plankton behavior or abundance can ripple through the food web, affecting energy flow and trophic interactions. The toxicological effects of microplastics are multifaceted and cascade across biological scales, from molecular disturbances to ecosystem-wide consequences. These effects are not isolated; they often intersect, amplify, and manifest in complex, context-dependent ways. Understanding these multiscale impacts is essential for assessing ecological risk, formulating environmental regulations, and developing comprehensive mitigation strategies to protect both biodiversity and human health from the pervasive threat of microplastic pollution [35].

5. Comparative Analysis of Terrestrial versus Aquatic Ecosystems

Microplastic (MP) pollution has garnered significant attention for its profound impacts on aquatic ecosystems. However, emerging research reveals that terrestrial environments are also experiencing a rising burden of microplastic contamination, with potentially comparable ecological consequences. Understanding the similarities and differences in microplastic behaviour, exposure, biological sensitivity, and knowledge coverage across terrestrial and aquatic ecosystems is vital for developing comprehensive environmental risk assessments. This chapter presents a comparative analysis of these two ecosystems, highlighting variations in distribution, species vulnerabilities, and research disparities [36].

5.1. Environmental Distribution and Exposure Routes

The environmental distribution of microplastics and their routes of exposure differ substantially between terrestrial and aquatic systems, primarily due to variations in environmental matrices (soil vs. water), particle transport dynamics, and biological interfaces [37].

In terrestrial ecosystems, microplastics are predominantly introduced through agricultural and urban practices. The use of plastic mulch films, composts containing plastic residues, wastewater irrigation, atmospheric fallout, tire wear particles, and biosolid application from wastewater treatment plants contributes to widespread soil contamination [38]. Once in the soil, microplastics may become embedded within the upper layers or migrate vertically due to soil fauna movement, water infiltration, and root growth.

In aquatic ecosystems, microplastics enter water bodies through surface runoff, wastewater discharge, stormwater overflows, littering, and industrial effluents. Their distribution is influenced by particle density, hydrodynamics, and salinity. Buoyant microplastics tend to remain in the surface waters, while denser polymers settle into sediments [39]. Suspended particles can be ingested by filter feeders and plankton or become trapped in biofilms.

The routes of exposure also vary between ecosystems. In terrestrial systems, microplastics are primarily ingested by soil fauna such as earthworms, springtails, and insect larvae during feeding or burrowing. These organisms play critical roles in nutrient cycling and soil structure, making their exposure particularly concerning [40]. In aquatic systems, ingestion occurs across a wide array of organisms including zooplankton, mollusks, crustaceans, fish, and even apex predators. Many aquatic species mistake microplastics for food due to their size, colour, and movement, leading to widespread ingestion across trophic levels [41].

5.2. Species-Specific Sensitivities

The toxicological effects of microplastics are not uniform across species; rather, they depend on physiological traits, ecological roles, and exposure pathways. Comparing sensitivities across terrestrial and aquatic organisms reveals both ecosystem-specific vulnerabilities and broader patterns of biological response [42].

5.2.1. In terrestrial ecosystems

Earthworms serve as key indicators of soil health and are particularly vulnerable to microplastic exposure. They ingest particles directly while consuming organic matter, leading to gut inflammation, reduced growth, and impaired reproduction. Insects, especially detritivores and pollinators, may ingest microplastics incidentally or through trophic transfer, with consequences ranging from developmental delays to behavioral impairments. Plants, while not direct consumers of microplastics, are affected through changes in soil properties and root interaction with contaminated particles. Studies suggest that MPs can reduce seed germination rates, alter root architecture, and impair nutrient uptake, thereby affecting plant health and productivity [43].

5.2.2. In aquatic ecosystems

Fish are among the most studied organisms regarding microplastic ingestion. Exposure can result in gastrointestinal blockage, oxidative stress, impaired swimming performance, and altered reproductive behavior. Mollusks such as mussels and oysters, which are filter feeders, readily accumulate microplastics from the water column and sediments, leading to cellular damage and reduced filtration efficiency. Crustaceans, including shrimp and crabs, can experience reduced feeding, molting disruption, and developmental abnormalities. Plankton, which form the base of aquatic food webs, are highly susceptible due to their small size and inability to distinguish microplastics from food, with implications for energy transfer and ecosystem stability [44]. These examples underscore the species-specific sensitivities that must be considered when assessing the ecological risks of microplastics. Terrestrial and aquatic organisms differ not only in their exposure pathways but also in their physiological capacity to detoxify, excrete, or accumulate these particles, leading to distinct patterns of vulnerability [45].

5.3. Knowledge Gaps in Terrestrial Toxicology

Despite growing recognition of microplastic pollution in terrestrial environments, significant knowledge gaps persist, particularly in comparison to the relatively advanced understanding of aquatic microplastic toxicology [46]. Most microplastic research to date has been focused on marine and freshwater systems, where standardized methodologies, long-standing ecological monitoring programs, and visible impacts such as the Great Pacific Garbage Patch have driven scientific inquiry. Numerous studies have characterized the effects of MPs on aquatic biodiversity, trophic transfer, and physiological responses in aquatic species. In contrast, terrestrial microplastic toxicology remains underrepresented, both in volume and scope [47]. The lack of consistent sampling protocols, limited field-based studies, and insufficient understanding of long-term ecological effects in soil systems hinder progress. For instance, while laboratory studies have shown that microplastics affect earthworm reproduction and plant development, field-based evidence of community-level impacts remains scarce. Moreover, the interactions between microplastics and other soil contaminants such as pesticides, heavy metals, or pharmaceuticals are poorly understood, leaving a critical gap in evaluating cumulative risks. Another important gap lies in the microbial ecology of soils. Microplastics may alter microbial diversity, enzyme activity, and nutrient cycling processes, yet this area is still emerging and largely speculative. Similarly, terrestrial food web dynamics, including trophic transfer of microplastics and their toxic effects across different levels, remain insufficiently explored. Addressing these gaps is essential for developing a holistic understanding of microplastic impacts across ecosystems. A more balanced research effort that includes both aquatic and terrestrial systems will ensure that environmental risk assessments and regulatory frameworks are grounded in a comprehensive scientific foundation. The environmental behavior and biological impacts of microplastics vary significantly between terrestrial and aquatic ecosystems due to differences in exposure routes, species-specific sensitivities, and ecosystem functions. While aquatic systems have received considerable attention, terrestrial systems remain underexplored, despite growing evidence of comparable ecological threats. Bridging this knowledge divide is critical for building effective environmental policies and advancing a truly global response to microplastic pollution [47].

Table 3 Summary of the Comparative Analysis of Microplastic Impacts in Terrestrial vs Aquatic Ecosystems [36, 47, 37, 38, 46, 39, 45, 40, 44, 41, 43, 42].

Parameter	**Terrestrial Ecosystems**	**Aquatic Ecosystems**
Main Sources of MPs	Plastic mulching, compost, tire wear, wastewater irrigation, biosolids, atmospheric deposition	Wastewater discharge, surface runoff, stormwater overflow, littering, industrial effluents
Environmental Matrix	Soil	Water and sediment

Main Exposure Pathways	Ingestion by earthworms, insects; root interaction	Ingestion by plankton, mollusks, crustaceans, fish
Key Affected Species	Earthworms, springtails, insect larvae, plants	Zooplankton, mollusks, crustaceans, fish, apex predators
Common Effects	Gut inflammation, growth inhibition (earthworms); altered germination, root structure (plants)	Oxidative stress, feeding reduction, developmental issues, reproductive impairment
Particle Transport Mechanisms	Vertical migration via roots, fauna movement, infiltration	Buoyancy-based sorting; suspension and sedimentation influenced by hydrodynamics and salinity
Microplastic Accumulation Tendency	Surface and subsurface soil layers	Surface water, water column, and sediment
Species Sensitivity Level	Moderate to High (esp. in earthworms, plants)	High (esp. filter feeders and fish)
Trophic Transfer Evidence	Emerging, limited field data	Well-documented through food chains
Research Volume (Relative)	Low	High
Standardization of Methods	Poor (non-uniform sampling, limited protocols)	Advanced (standard protocols, wide adoption)
Knowledge Gaps	Soil microbial impacts, trophic transfer, long-term community effects	Less pronounced; focus now shifting toward nanoplastics, cumulative toxicity

6. Human and Public Health Implications

As microplastics (MPs) have become pervasive in the environment, their intersection with human health is now a critical area of concern. Unlike traditional environmental pollutants that are often confined to specific regions or sources, microplastics are omnipresent in the air we breathe, the food we eat, and the water we drink. Their minute size and complex composition, often laced with toxic additives or adsorbed pollutants, make them biologically accessible and potentially harmful to human systems [48]. This chapter explores the major routes through which humans are exposed to microplastics, the risk of food chain contamination, and the possible long-term health effects stemming from chronic exposure.

6.1. Entry Routes (Inhalation, Ingestion, Dermal Contact)

Humans are exposed to microplastics through three primary routes: inhalation, ingestion, and dermal contact, each of which presents unique risks based on particle size, concentration, and duration of exposure [49].

Inhalation is now recognized as a significant pathway for microplastic entry, particularly in urban, industrial, or indoor environments. Synthetic textiles, degraded car tires, dust, and building materials release airborne microplastic fibers and fragments that can remain suspended for long periods. Particles small enough to be respirable (especially those below 10 micrometers) can penetrate deep into the lungs and potentially cross the alveolar-capillary barrier into the bloodstream. Chronic inhalation may cause respiratory irritation, pulmonary inflammation, or exacerbate preexisting conditions such as asthma or bronchitis [50].

Ingestion is perhaps the most well-documented exposure pathway. Microplastics have been found in a wide variety of consumables, including seafood, salt, honey, sugar, fruits, vegetables, drinking water (both bottled and tap), and even beer. Seafood, particularly filter feeders like mussels and oysters, accumulates significant amounts of microplastics, which are then transferred to humans upon consumption [51]. Additionally, microplastics may be inadvertently ingested through contaminated hands, utensils, or packaging materials. Once ingested, particles can interact with the gastrointestinal epithelium, potentially causing local inflammation or disrupting nutrient absorption.

Dermal contact, while considered a less efficient route, still poses potential risks, particularly through prolonged exposure to cosmetic products, clothing fibers, or contaminated water during activities such as swimming, bathing, or handling plastic-rich materials. Nanoplastics, plastic particles smaller than 100 nanometers, may penetrate skin layers or hair follicles, especially if the skin is damaged or exposed for extended durations. Furthermore, plastic-derived chemicals like bisphenol A (BPA) and phthalates can leach and be absorbed trans-dermally, raising concerns about endocrine disruption [52].

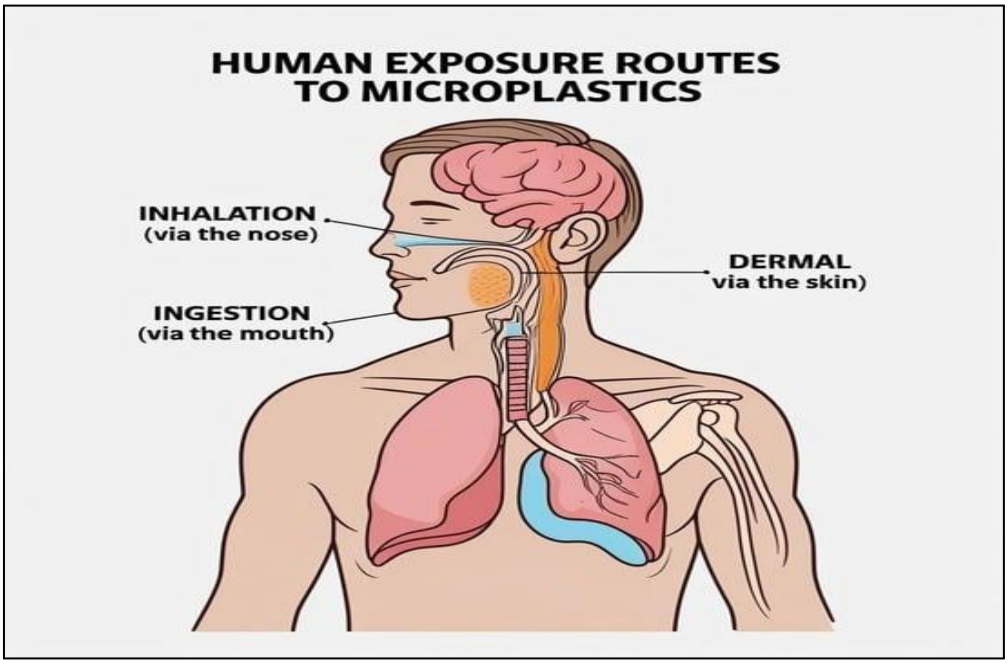

Figure 3 The three Primary Human Exposure Routes to Microplastics [10 modified]

6.2. Food Chain Contamination

One of the most alarming aspects of microplastic pollution is its infiltration into the human food chain, a process that amplifies exposure and introduces additional risks due to biomagnification and trophic transfer [53]. Microplastics enter the base of the food chain via soil and aquatic organisms. Terrestrial plants can absorb plastic-associated chemicals from contaminated soils or water, which may then accumulate in edible parts. In aquatic systems, plankton, shellfish, and small fish readily ingest microplastics, which are subsequently consumed by larger predators and eventually humans. Studies have documented microplastics in commercially important seafood species, underscoring the reality of dietary exposure [54]. The food chain is further complicated by the vector potential of microplastics, as they frequently carry hazardous substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), dioxins, and pharmaceutical residues. These substances may desorb within the digestive tract, becoming bioavailable and exerting toxic effects. Over time, the accumulation of such contaminants through repeated dietary exposure may disrupt homeostatic processes and pose significant health threats [55]. Contamination is not limited to marine products. Microplastics have been detected in meat, dairy, grains, and bottled beverages, suggesting that contamination extends to terrestrial food webs through fodder, irrigation, and processing. As microplastics become embedded in agricultural systems through biosolid application and polluted water use, their presence in food products is likely to rise [10].

6.3. Potential Long-Term Effects: Inflammation, Metabolic Disorders, Carcinogenicity

Although the full extent of human health effects from microplastic exposure remains under investigation, mounting evidence suggests that chronic, low-dose exposure could have serious long-term consequences [56].

Inflammation is one of the most immediate biological responses to microplastic exposure. When microplastics interact with epithelial or immune cells, either in the lungs, gut, or skin, they can trigger the release of inflammatory mediators like cytokines and chemokines. Persistent inflammation may lead to tissue damage, fibrosis, or contribute to the progression of chronic diseases such as inflammatory bowel disease (IBD) or chronic obstructive pulmonary disease (COPD) [10].

Metabolic disorders may also be linked to microplastic exposure, particularly due to the endocrine-disrupting chemicals (EDCs) that are often either inherent to the plastic or adsorbed onto its surface. Compounds like BPA and phthalates have been shown to interfere with hormonal regulation of metabolism, potentially leading to obesity, insulin resistance, diabetes, and thyroid dysfunction. Disruption of gut microbiota due to microplastic exposure may also contribute to metabolic imbalance [57, 10].

Carcinogenicity, while less conclusively established, remains a critical area of concern. The capacity of microplastics to induce genotoxicity, oxidative DNA damage, and epigenetic alterations raises the possibility of cancer risk, particularly in organs involved in detoxification and filtration, such as the liver and kidneys. Furthermore, the chemicals associated with microplastics such as dioxins, styrene, and certain flame retardants, are already classified as probable human carcinogens. Chronic exposure via ingestion or inhalation may elevate the risk of developing malignancies over time, particularly in vulnerable populations [10].

The omnipresence of microplastics in our environment has translated into inevitable human exposure through inhalation, ingestion, and dermal contact. Their infiltration into the food chain and interaction with biological systems raises serious concerns about their potential to trigger inflammation, metabolic dysfunction, and possibly cancer. As research continues to unravel these effects, there is an urgent need for regulatory frameworks, public health strategies, and pollution mitigation efforts to safeguard human health from this emerging threat [57, 10].

7. Methodological Advances and Challenges of Microplastics

As the global crisis of microplastic (MP) pollution intensifies, the need for accurate, reliable, and standardized methodologies to detect, characterize, and assess their toxicological effects becomes more pressing [58]. Despite rapid technological advancements, significant methodological challenges persist, particularly due to the vast diversity of microplastic types, sizes, and environmental behaviours. This chapter discusses the current state of methodological approaches in microplastic research, highlighting both the analytical techniques used for detection and characterization, and the experimental models applied for toxicological evaluation. It also examines critical limitations and future directions in refining these methods.

7.1. Detection and Characterization of Microplastics (MPs)

The accurate detection and thorough characterization of microplastics are foundational to understanding their prevalence, environmental behaviour, and biological impact. However, due to the heterogeneity in size, shape, colour, polymer type, and chemical complexity, analyzing microplastics presents significant scientific challenges [59, 10].

Microscopy, especially optical and electron microscopy, is widely used as a preliminary tool for visual identification and size estimation of microplastics. Optical microscopy allows for observation of larger particles (usually >20 µm) and can provide insight into shape (e.g., fragments, fibers, beads). However, it lacks chemical specificity. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) offer higher resolution imaging and can reveal surface morphology and structural features, although they also do not directly confirm chemical identity [10, 60].

Spectroscopy-based techniques are crucial for chemical identification. Fourier-Transform Infrared Spectroscopy (FTIR) and Raman Spectroscopy are the most commonly used methods. FTIR identifies polymer types by measuring their unique infrared absorption spectra, particularly effective for particles >10 µm. Raman Spectroscopy offers higher spatial resolution and is particularly useful for smaller particles (<10 µm), but is more susceptible to fluorescence interference and sample degradation. Both techniques can be coupled with microscopy (e.g., µFTIR, µRaman) for more detailed analysis [61, 10].

Thermal analysis techniques, such as Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), provide highly sensitive and quantitative detection by thermally decomposing plastics and identifying their characteristic breakdown products. These methods are particularly effective for identifying mixed or degraded plastic samples and can detect nanoplastics and oligomers, though they are destructive and require intensive sample preparation [10, 62].

Despite these advancements, detection of nanoscale plastics (<1 µm) remains an enormous challenge. Nanoplastics are difficult to isolate and quantify due to their small size, tendency to agglomerate, and interactions with organic matter and natural colloids [63, 8]. Conventional filtration and imaging techniques lack the necessary resolution and sensitivity, while existing spectroscopic tools often fall short in clearly differentiating nanoparticles from environmental matrices. This detection gap leaves a critical blind spot in risk assessment, as nanoplastics may penetrate biological membranes and cause distinct toxicological effects. Additional challenges in detection and characterization include the lack of standardized sampling procedures, contamination control, and polymer-specific reference databases. This results in inconsistencies across studies, hindering comparative analysis and meta-research [64].

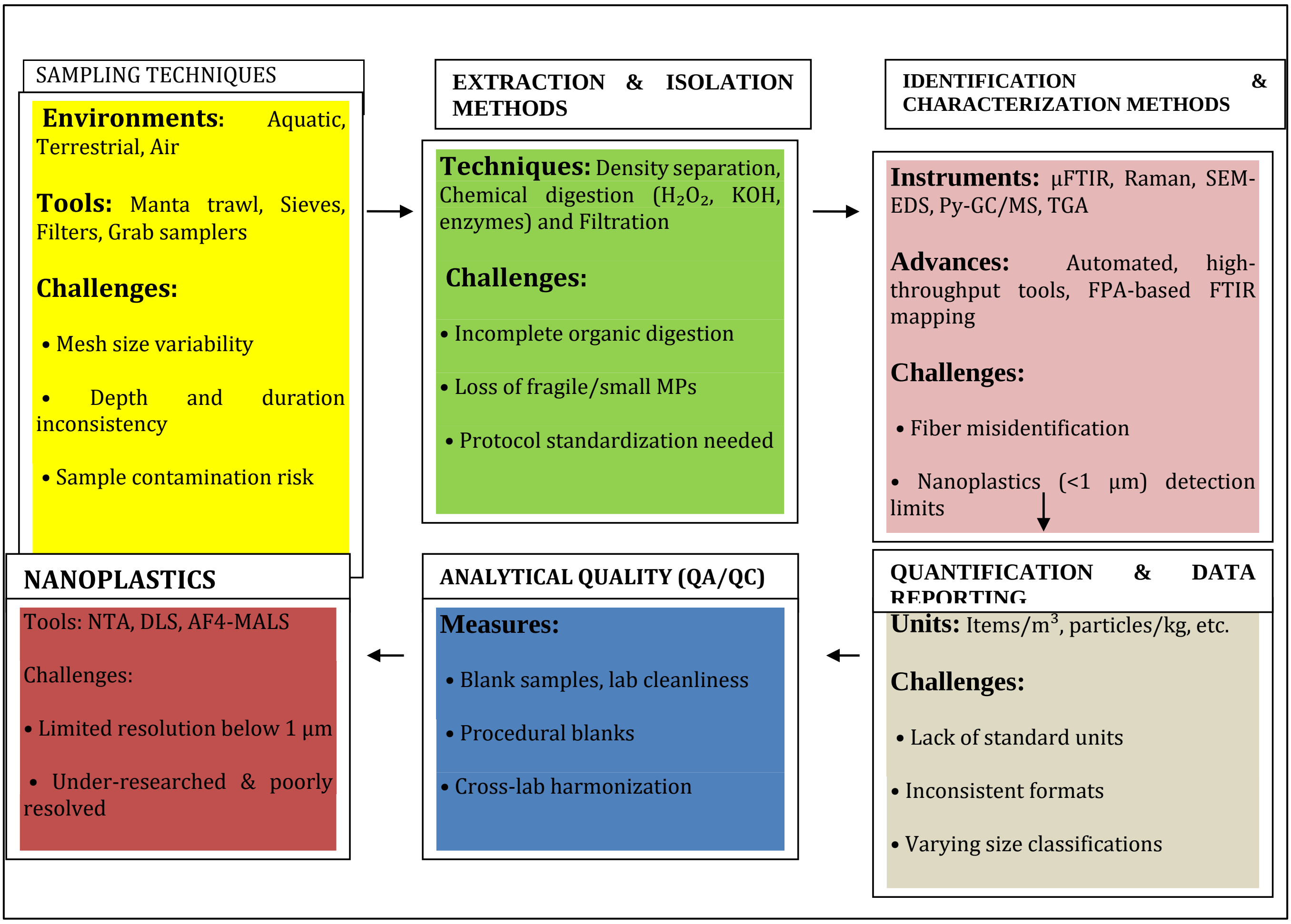

Figure 4 Schematic Sketch of the Methodological Workflow for Microplastic Analysis: Advances and Challenges [10 modified]

7.2. Toxicological Testing Approaches

To understand the biological effects of microplastics (MPs), a variety of toxicological testing approaches have been employed, ranging from simplified laboratory assays to complex ecotoxicological models. These studies typically aim to assess endpoints such as survival, reproduction, behaviour, immune response, and cellular integrity in organisms exposed to MPs [10].

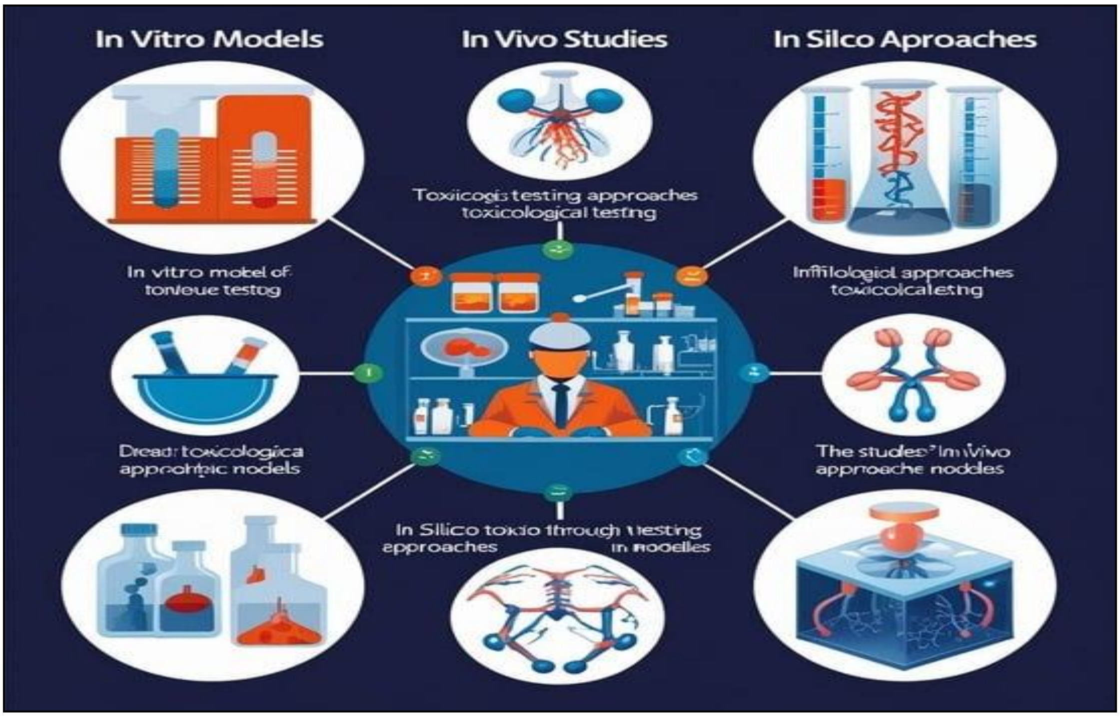

Figure 5 The basic Toxicological Testing Approaches (In Vitro Models, In Vivo Studies, and In Silico Approache) [10 modified]

In vitro models involve the use of isolated cells, tissues, or organoids under controlled laboratory conditions. These models allow for high-throughput testing, mechanistic insight, and precise dose control [65]. Human or animal cell lines can be exposed to microplastics to study effects like oxidative stress, inflammation, cytotoxicity, genotoxicity, and endocrine disruption [66]. In vitro systems are particularly valuable for initial screening of microplastic toxicity and for reducing reliance on animal testing. However, they lack the complexity of whole organisms and do not account for interactions between multiple physiological systems or ecological processes.

In vivo studies involve whole organisms, often ranging from model organisms such as Daphnia magna, Caenorhabditis elegans, and zebrafish, to higher vertebrates like rodents and birds. These studies provide a more integrated understanding of the systemic effects of microplastics on behaviour, reproduction, growth, and multi-generational impacts [67]. In vivo studies are crucial for capturing bioaccumulation, trophic transfer, and long-term health effects. However, they are more resource-intensive, time-consuming, and ethically constrained compared to in vitro methods.

A major limitation across both approaches is the lack of standardization. There is currently no universally accepted guideline for microplastic exposure studies, including test concentrations, particle sizes, polymer types, exposure duration, or endpoints [68]. As a result, the toxicological outcomes reported across different studies are often difficult to compare or replicate. Moreover, many laboratory studies employ microplastic concentrations far exceeding environmentally relevant levels to elicit observable effects within short testing periods. This raises concerns about the ecological validity of such findings [69]. Environmentally realistic exposure models that account for factors such as weathering, contaminant co-exposure, and species-specific behaviors are urgently needed to bridge the gap between experimental and real-world conditions. Another challenge lies in dose quantification—whether to report exposure in terms of particle number, mass, surface area, or volume. Each metric offers different insights, but the lack of consistency complicates inter-study comparison and risk assessment [70]. While significant methodological strides have been made in the detection, characterization, and toxicological testing of microplastics, substantial challenges remain. Advanced techniques such as spectroscopy, thermal analysis, and high-resolution microscopy have enhanced our capacity to identify MPs, but detection of nanoplastics and environmental relevance still lag behind. Similarly, both in vitro and in vivo toxicological models have contributed vital insights, yet the absence of standardized protocols and realistic exposure scenarios hampers global progress. Moving forward, interdisciplinary collaboration and the establishment of international guidelines are essential to refine methodologies, ensure comparability, and enable accurate risk assessment of microplastics to human and environmental health [71].

In Silico Approaches (Computational Models): In silico approaches involve the use of computer-based models and simulations to predict the toxicological effects of microplastics (MPs) without the need for laboratory or animal testing. These methods are valuable for risk assessment, hypothesis generation, and data integration, especially when experimental data is limited [10].

In silico approaches are computational models used to simulate the interactions of microplastics (MPs) with biological molecules and predict toxicological outcomes based on their physical and chemical properties, such as size, shape, and surface chemistry. These methods support extrapolation across species, exposure routes, and dose ranges [10]. Common tools include QSAR models for estimating toxicity, PBPK models for simulating distribution within organisms, and molecular docking for predicting binding to biological targets. They offer fast, cost-effective testing and reduce reliance on animal studies, but their accuracy depends on high-quality input data and they may not fully capture complex biological interactions, especially with novel or mixed MP types [10].

Table 4 Toxicological Testing Approaches for Microplastics: In Vitro vs. In Vivo (advantages and disadvantages)[10, 65, 71, 66, 70, 67, 69, 68].

Aspect	**In Vitro Models**	**In Vivo Studies**
Definition	Studies using isolated cells or tissues in a controlled lab environment	Studies using whole living organisms (e.g., rodents, fish, invertebrates)
Biological Complexity	Low – Simplified cellular systems	High – Full organism complexity with interacting systems
Systemic Effect Evaluation	Not possible – limited to cellular responses	Possible – evaluates systemic, organ-specific, and whole-body responses
Ethical Concerns	Minimal – no animal use	Significant – involves animal experimentation
Cost	Generally low	Generally high due to animal care, housing, and long duration
Time Requirement	Short-term – rapid results achievable	Long-term – may require weeks to months
Throughput Capability	High – suitable for screening many conditions or doses	Low – fewer samples can be processed simultaneously
Control Over Variables	High – precise manipulation of dose, size, exposure duration	Moderate – more variables and individual differences among test organisms
Realism of Exposure Scenarios	Limited – artificial exposure routes	High – mimics environmental exposure (ingestion, inhalation, dermal contact)
Mechanistic Insight	Strong – identifies molecular and cellular mechanisms (e.g., oxidative stress, inflammation)	Moderate – less resolution at the cellular/molecular level
Reproducibility	High – standardized protocols and controlled conditions	Variable – affected by genetic and environmental variability among organisms
Chronic Effect Detection	Limited – often restricted to acute toxicity studies	Strong – can assess long-term and reproductive effects
Model Relevance to Humans/Wildlife	Moderate – depends on cell type and species used	Higher – closer approximation to real-world biological effects
Examples of Models Used	Human or animal cell lines (e.g., HepG2, Caco-2), primary cell cultures	Zebrafish, mice, rats, crustaceans, marine invertebrates

8. Research Gaps and Future Perspectives

Despite the exponential growth in microplastic research over the past decade, significant knowledge gaps persist that impede a comprehensive understanding of their environmental and health impacts. Microplastics represent a complex and multifaceted pollutant that interacts with biological systems, ecosystems, and chemical contaminants in ways that are still poorly understood. This chapter outlines the most pressing research gaps and articulates future directions necessary for advancing the field and guiding policy-making and mitigation strategies. Key areas of concern include the lack of chronic exposure data, interactions with other global stressors, the underexplored domain of nanoplastics, and the absence of standardized risk assessment frameworks [72].

8.1. Lack of Chronic Exposure Data

One of the most critical limitations in current microplastic research is the lack of long-term, chronic exposure data. Most laboratory studies conducted to date focus on acute exposures with high concentrations over short time frames. While such studies provide valuable insights into potential toxicity, they fail to capture the subtle, cumulative, and long-term effects of environmentally relevant microplastic concentrations [73]. Chronic exposure is particularly important because microplastics are persistent in ecosystems and are continuously encountered by organisms through multiple pathways (e.g., ingestion, inhalation, dermal contact). Repeated low-dose exposure over weeks, months, or even generations may lead to physiological stress, metabolic dysregulation, immune suppression, endocrine disruption, and trans-generational effects, which are not detectable in short-term assays [74]. For instance, in terrestrial ecosystems, microplastics in agricultural soils may be in constant contact with soil organisms and plants across several crop cycles. Similarly, in aquatic systems, filter feeders like mussels may accumulate microplastics over their lifetime, with potential impacts on reproduction, filtration efficiency, and longevity. In humans, microplastic ingestion through food and water, or inhalation from indoor air, likely occurs daily, yet the long-term biological consequences remain poorly documented [75]. There is thus a pressing need for longitudinal in vivo studies, multi-generational assays, and epidemiological investigations to better understand chronic exposure risks across biological scales and environments [76].

8.2. Interactions with Other Global Stressors (Climate Change, Pathogens)

Microplastics do not exist in isolation within the environment. They co-occur and interact with a range of other global stressors, including climate change, emerging pathogens, habitat degradation, eutrophication, and chemical pollutants. However, the synergistic or antagonistic interactions between microplastics and these co-stressors remain largely unexplored [77]. Climate change, for example, may influence the behaviour and toxicity of microplastics through changes in temperature, ocean acidification, salinity shifts, and extreme weather events. Higher temperatures may accelerate plastic degradation, increasing the formation of nanoplastics or altering surface chemistry, which in turn affects their biological reactivity and contaminant-binding capacity [78]. Additionally, pathogens and microbes can colonize microplastic surfaces, forming biofilms, sometimes referred to as the "plastisphere." This micro-ecosystem may serve as a vehicle for antibiotic-resistant bacteria, viruses, or invasive species, potentially aiding in their dissemination across ecosystems and into host organisms. Microplastics may thus facilitate disease transmission or modulate host-pathogen dynamics, especially in aquatic species or immune compromised individuals [79].

Furthermore, chemical stressors such as pesticides, heavy metals, and pharmaceuticals often co-occur with microplastics and can adsorb to their surfaces. These mixtures may exert additive or multiplicative toxic effects when introduced into biological systems, leading to outcomes that are more severe or unpredictable than the effects of each pollutant alone. Future studies must adopt multi-stressor experimental designs and systems-based approaches to unravel these complex interactions and to simulate real-world environmental scenarios more accurately [80].

8.3. Better Understanding of Nanoplastics

While microplastics (typically defined as particles <5 mm) have been extensively studied, nanoplastics (particles <100 nanometers) remain a largely uncharted frontier. Nanoplastics can originate either as manufactured products (primary nanoplastics) or as secondary particles resulting from the environmental degradation of larger plastics. Their ultra-small size, large surface area-to-volume ratio, and enhanced reactivity make them particularly insidious and potentially more hazardous than microplastics [8, 81]. Nanoplastics can cross biological barriers that microplastics cannot, such as cellular membranes, the blood-brain barrier, and possibly even the placental barrier. This opens up concerns about their accumulation in critical tissues, including the brain, liver, kidneys, and reproductive organs. Moreover, nanoplastics may directly interact with DNA, proteins, or enzymes, potentially disrupting cellular function at the molecular level [8, 82]. From an analytical standpoint, detecting and characterizing nanoplastics poses significant technical challenges. Conventional methods like FTIR or Raman spectroscopy lack the resolution to identify nanoscale particles, and even electron microscopy has limitations in accurately quantifying them within complex environmental or biological samples. This leaves a major methodological void in the field [8, 83]. To move forward, there is a need to develop high-resolution, sensitive analytical techniques, such as nanoparticle tracking analysis (NTA), Field-Flow Fractionation (FFF), and advanced mass spectrometry methods. Equally important is the creation of well-characterized nanoplastic standards and reference materials for experimental consistency [8, 84].

8.4. Standardized Risk Assessment Frameworks

Despite the growing body of literature on microplastic toxicity, regulatory frameworks and risk assessment protocols remain fragmented and inconsistent across regions and scientific disciplines. Unlike traditional pollutants, microplastics vary widely in size, shape, polymer type, surface properties, and contaminant load, making their hazard classification and exposure assessment particularly complex [85]. Currently, there is no universally accepted method for quantifying microplastic exposure, defining safe threshold levels, or standardizing ecotoxicological testing. As a result, risk assessments often rely on assumptions, inconsistent metrics (e.g., particle number vs. mass), and non-representative experimental conditions. This hampers the ability of regulatory bodies to compare findings, establish environmental quality standards, or make informed policy decisions [86]. Moreover, many studies focus on single-species, laboratory-based models, which do not reflect the intricate interactions in natural ecosystems or account for vulnerable groups such as children, pregnant women, or populations with high seafood consumption. The precautionary principle, commonly applied in chemical risk regulation, has yet to be fully invoked for microplastic governance [87].

To address this, it is crucial to develop harmonized guidelines for sampling, detection, toxicity testing, and exposure modeling. Regulatory agencies, academic institutions, and international organizations must collaborate to establish standardized risk assessment frameworks that are adaptable, science-based, and globally implementable [88]. Addressing the global threat of microplastic pollution requires a concerted effort to bridge existing research gaps. The lack of chronic exposure data, insufficient understanding of interactions with climate stressors and pathogens, the methodological challenges of studying nanoplastics, and the absence of standardized risk assessment protocols all represent significant barriers to progress. Future research must embrace interdisciplinary collaboration, technological innovation, and regulatory harmonization to protect both ecosystems and human health from the pervasive and evolving threat posed by plastic particles [88].

Table 5 Summary of the Research Gaps and Future Perspectives in Microplastics Research [8, 72, 88, 73, 87, 75, 76, 85, 84, 77, 78, 83, 79, 80, 81,].

Research Gap	Description	Future Directions
Lack of Chronic Exposure Data	Most studies focus on acute, high-dose exposures, overlooking cumulative, long-term effects on organisms across different ecosystems.	Conduct longitudinal in vivo studies, multi-generational toxicological assays, and epidemiological surveys to evaluate real-world exposure impacts.
Interaction with Other Global Stressors	Limited understanding of how MPs interact synergistically or antagonistically with climate change, pathogens, and chemical pollutants.	Develop multi-stressor experiments simulating real environmental conditions; explore biofilm formation, pathogen colonization, and chemical mixtures.
Poor Understanding of Nanoplastics	Nanoplastics (<100 nm) can cross biological barriers and disrupt cellular functions, but are difficult to detect and poorly studied.	Innovate sensitive detection tools (e.g., NTA, FFF, AF4, mass spectrometry); create nanoplastic reference standards for reproducibility.
Lack of Standardized Risk Assessment Frameworks	No globally accepted methods for hazard classification, exposure modeling, or threshold limit setting due to microplastic heterogeneity.	Harmonize risk assessment protocols through interdisciplinary, regulatory-academic collaboration; develop unified metrics for exposure and hazard.
Methodological Inconsistency Across Studies	Variations in sampling, extraction, detection, and reporting hinder data comparison and meta-analysis.	Standardize methodologies and QA/QC protocols across laboratories and regions.

Limited Focus on Human Health Effects	Few human studies assess bioaccumulation, toxicity, or long-term effects of microplastics through ingestion, inhalation, or dermal exposure.	Advance human exposure modeling, biomonitoring, and epidemiological studies.
Underrepresentation of Terrestrial and Atmospheric Systems	Research is predominantly aquatic, neglecting terrestrial soil, agricultural systems, and airborne MPs.	Expand studies to soil-food chains, crop uptake, air deposition, and human indoor exposure.

9. Conclusion

This multiscale review underscores the pervasive and insidious nature of microplastics as "silent invaders," synthesizing key findings that highlight their widespread distribution, complex toxicological effects, and capacity to interact with environmental contaminants across both terrestrial and aquatic ecosystems. The evidence reveals that microplastics impact biological systems at molecular, cellular, organismal, and ecological levels, necessitating a shift toward integrative, cross-scale approaches in research and mitigation. Addressing these challenges requires robust transdisciplinary collaboration that bridges environmental science, toxicology, material science, and policy, paving the way for informed regulation, innovative remediation strategies, and a sustainable path forward.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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