**Environmental Toxicity and Bioaccumulation of Microplastics Derived from Petroplastics: A Cross-Ecosystem Review**

**Abstract**

The widespread use of petroplastics such as polyethylene and polypropylene has led to pervasive microplastic (MP) pollution across environmental compartments, raising serious ecological and public health concerns. This review synthesizes current knowledge on the environmental toxicity and bioaccumulation of microplastics derived from petroplastics, with a focus on their fate and impacts across marine, freshwater, and terrestrial ecosystems. A systematic literature review spanning 2005 to 2025 was conducted using PubMed, Scopus, ScienceDirect, and Google Scholar, incorporating over 150 peer-reviewed studies selected based on ecological effects, exposure levels, and species-specific responses. The findings reveal that in marine environments, MPs disrupt food webs by accumulating in plankton, fish, and seabirds, often serving as vectors for persistent organic pollutants (POPs). Freshwater ecosystems exhibit MP sedimentation and bioaccumulation in fish, frequently exacerbated by interactions with heavy metals. In terrestrial ecosystems, MPs reduce soil fertility and are ingested by organisms such as earthworms, although data remain comparatively scarce. Cross-ecosystem comparisons highlight common concerns like trophic transfer and biomagnification, alongside ecosystem-specific differences influenced by environmental variables. Notably, significant research gaps persist, including the lack of standardized sampling methods and limited understanding of long-term trophic transfer and co-contaminant interactions, particularly in terrestrial systems. These findings underscore the urgent need for interdisciplinary research, harmonized methodologies, and informed policy interventions to address the multifaceted threat posed by microplastics across ecosystems.

**Keywords:** Bioaccumulation, Ecotoxicology, Synthetic plastic, Trophic transfer, Weathering.

1. **Introduction**

The invention of synthetic plastic marked a turning point in material science. In 1907, **Leo Baekeland** introduced *Bakelite*, the first synthetic plastic, which paved the way for the rapid development of polymer-based materials. This was followed by the discovery of *polyester* (1928), *polyethylene* (1933), and later, *polypropylene* and *polystyrene* in 1954 (Thompson et al., 2004). These innovations launched humanity into what is often referred to as the “**age of plastics**,” where plastics became indispensable to daily life — from household items and electronic gadgets to industrial and construction materials.

Most synthetic plastics are derived from **petroleum-based polymers** and are combined with additives such as fillers, plasticizers, colorants, and stabilizers to enhance their functionality. While plastics offer convenience, durability, and hygiene — for instance, in packaging and disposable items like straws — concerns have emerged regarding their **chemical leaching** into food and beverages. Compounds such as *Bisphenol A (BPA)* and *phthalates* are now linked to **endocrine disruption, carcinogenicity**, and **reproductive disorders** (Meeker et al., 2009; Godswill et al., 2019; Zhang et al., 2022; Saha et al., 2024).

The issue of **microplastics (MPs)** has further intensified global concerns. Thompson et al. (2004) defined microplastics as plastic fragments less than **5 mm in diameter**. They are categorized as **primary microplastics**, which are intentionally manufactured (e.g., microbeads), and **secondary microplastics**, which result from the degradation of larger plastic debris through **photodegradation, hydrolysis, and oxidation** (da Costa et al., 2017; Booth & Sørensen, 2022). These particles are now found across ecosystems — from soil and rivers to deep-sea environments — and are increasingly ingested by aquatic and terrestrial organisms.

Microplastics have the ability to **adsorb and carry hazardous chemicals**, such as persistent organic pollutants (POPs), heavy metals, and flame retardants. Once ingested by organisms, these pollutants can trigger inflammatory responses, oxidative stress, developmental issues, and **reproductive toxicity** (Rochman et al., 2013; Khan et al., 2023). Their persistence in nature also disrupts **food chains and biodiversity**, creating long-term ecological imbalances. Microplastics (MPs) in aquatic environments rarely exist in isolation; they frequently coexist with various co-contaminants such as persistent organic pollutants (POPs) and heavy metals. These co-contaminants can adsorb onto the surface of MPs due to their hydrophobicity and high surface area, facilitating their transport across ecosystems and organisms. The sorption of POPs and heavy metals onto MPs may modify the bioavailability, toxicity, and fate of these contaminants, potentially resulting in synergistic or antagonistic effects on aquatic biota.

The production and disposal of plastics has increased worldwide, increasing the environmental burden of microplastics. Although many studies have studied marine and freshwater contamination, there have been fewer studies on terrestrial systems and fewer integrated cross-ecosystem approaches. At the same time, emerging evidence of microplastics acting as carriers of toxic co-contaminants makes the need for current synthesis more apparent. Given the increasing ecological and health risks in marine, freshwater and terrestrial ecosystems of microplastic toxicity, bioaccumulation and trophic transfer, this review is necessary. The goal is to reduce critical knowledge gaps, conduct risk assessments, and build ecosystem-wide mitigation strategies.

**This review aims** to comprehensively evaluate the environmental toxicity of petroplastics with a specific focus on **microplastic bioaccumulation and ecotoxicological effects**. It highlights their presence across landfills, freshwater, marine ecosystems, and atmospheric pathways. Additionally, it reviews current knowledge on microplastic degradation, recycling strategies, and policy gaps — underscoring the need for **a balanced and sustainable approach** to plastic production and usage in light of growing global environmental challenges.

1. **Methodology of literature review**

This review synthesizes scientific literature from 2005 to 2025 on microplastic toxicity and bioaccumulation derived from petroplastics, with a focus on marine, freshwater, and terrestrial ecosystems. Relevant studies were identified through systematic searches of PubMed, Scopus, ScienceDirect, and Google Scholar, selected for their comprehensive coverage of environmental science, toxicology, and ecological research. Search terms included “microplastics,” “petroplastics,” “bioaccumulation,” “ecosystem contamination,” “ocean microplastics,” “freshwater pollution,” “terrestrial plastic contamination,” “trophic transfer,” and “ecotoxicology,” combined using Boolean operators (e.g., “microplastics AND marine AND bioaccumulation”) to target ecosystem-specific studies.

To ensure a balanced representation across ecosystems, studies were selected to achieve an approximate distribution of 40% marine, 30% freshwater, and 30% terrestrial ecosystems, reflecting the relative availability of research while addressing the understudied terrestrial domain. Inclusion criteria prioritized peer-reviewed articles, reviews, and reports in English that provided empirical evidence or syntheses of ecological impacts, species-specific responses, or ecosystem-level dynamics. Studies were excluded if they lacked clear methodologies, focused solely on plastic production without environmental implications, or were non-peer-reviewed (e.g., editorials). Over 150 studies were analyzed, with selection involving an initial screening of titles and abstracts followed by a full-text review to confirm relevance.

For cross-ecosystem comparison, studies were evaluated for shared themes (e.g., bioaccumulation, trophic transfer, co-contaminant interactions) and ecosystem-specific differences (e.g., transport mechanisms, degradation rates). A comparative framework was applied, categorizing findings by ecosystem type and assessing variables such as microplastic concentration, exposure levels, and organismal responses. This approach enabled the identification of similarities, such as universal bioaccumulation risks, and differences, such as higher sedimentation in freshwater systems compared to marine gyres (Cózar et al., 2014; Yang et al., 2021). The balanced selection and comparative analysis provide a robust foundation for synthesizing microplastic impacts across ecosystems, as detailed in subsequent sections.

1. **Petroplastics: Sources of pollution**

Petroplastics, derived from **synthetic petroleum-based polymers**, are chemically stable and largely **insoluble in water**, characteristics that make them useful for a wide range of human applications, especially in packaging and product safety. However, the **monomers and chemical additives** used in their production — including plasticizers, fillers, and stabilizers — have been associated with significant **toxicological hazards** to both the environment and human health (Hahladakis et al., 2018).

The manufacturing of these plastics begins with the **extraction of crude oil or natural gas**, followed by processes such as **cracking** and **polymerization**, which generate commonly used polymers like *polyethylene (PE)*, *polypropylene (PP)*, and *polyvinyl chloride (PVC)*. These processes release a substantial volume of byproducts, including **volatile organic compounds (VOCs)** and **residual chemicals**, many of which are released into the environment due to inadequate emissions controls (Gervet, 2007).

Moreover, **plastic manufacturing industries** contribute significantly to environmental contamination. Air, water, and soil are polluted through:

* **Gaseous and particulate emissions** during processing,
* **Chemical residues** discharged via effluents,
* And **solid waste accumulation** from excess resins and incomplete products (Oktavilia et al., 2020).

This industrial pollution is exacerbated by the **global surge in plastic demand** and **inefficient recycling systems**, particularly in developing nations. As a result, vast quantities of plastic waste continue to accumulate in natural ecosystems (Williams & Rangel-Buitrago, 2022).

Plastic production also has a noteworthy **climate impact**, as it is a significant source of **greenhouse gas emissions**, contributing to a growing **carbon footprint** throughout the plastic life cycle (Hamilton & Feit, 2019). The improper disposal of **industrial and post-consumer plastic waste** — especially in low-resource regions — leads to the leaching of hazardous substances into **soil and groundwater**, posing risks to agriculture, wildlife, and human communities.

Among the worst offenders are **single-use plastics (SUPs)** such as bags, straws, and food wrappers. These items are often **non-biodegradable** and **poorly managed** post-use, making them prominent contributors to long-term environmental pollution (Siddiqua et al., 2022). Figure 1 illustrates the widespread presence of improperly discarded plastics, particularly along riverbanks and urban landscapes.



**Figure 1: Illustration of plastic litters and debris thrown intentionally in and on the banks of a River Sipra Madhya Pradesh India.**

These materials—particularly polyethylene and polypropylene used in packaging—commonly accumulate in terrestrial and aquatic ecosystems, and are rarely recycled due to their widespread use and lack of efficient waste management systems (Shah et al., 2008). The textile industry is another major contributor to microplastic pollution, relying heavily on synthetic fibers such as polyester, nylon, and acrylic. During routine laundering, these fabrics shed billions of microplastic particles, which enter water systems and contribute significantly to microplastic contamination (Table 1).

In addition to textiles, primary microplastics such as polyethylene-based microbeads—found in personal care products like toothpaste, facial scrubs, and cosmetics—are directly discharged into aquatic environments. These particles are not effectively removed by conventional wastewater treatment processes, allowing them to persist and accumulate in aquatic food chains (Sun et al., 2020; Habib et al., 2022).

Plastics containing chemical additives such as phthalates, bisphenol A (BPA), and vinyl chloride are especially hazardous, as these compounds are known to leach into surrounding environments, exhibiting estrogenic activity that can disrupt endocrine functions and pose serious health risks to humans (Yang et al., 2011; Wang & Qian, 2021).

The global challenge of managing plastic waste—originating from both industrial facilities and domestic households—is further compounded by inadequate recycling infrastructures, particularly in developing nations. As a result, large volumes of plastics end up in landfills (Figure 2), where they slowly degrade and release harmful chemicals into the surrounding soil and groundwater, intensifying long-term environmental contamination (Danthurebandara et al., 2012).



**Figure 2:** **Typical municipal garbage dumpsites. Many discarded plastic items by the population living around the area can be seen dumped at the sites.**

Landfill leachate—a complex mixture of harmful substances—is generated when rainwater percolates through waste materials, particularly those containing plastics. This leachate represents a major source of groundwater contamination, posing significant health risks to both ecosystems and human populations. Experimental analyses indicate that landfill leachate is rich in ammonia (NH₃), phosphates (PO₄³⁻), sulfates (SO₄²⁻), chlorides (Cl⁻), potassium (K⁺), iron (Fe), and lead (Pb), which contribute to elevated conductivity, chemical oxygen demand (COD), and total dissolved solids (TDS) in groundwater near contaminated sites (Naveen et al., 2018).

Further studies have demonstrated the genotoxic potential of landfill leachate, showing dose-dependent DNA damage in plasmid models (Koshy et al., 2008). Additionally, carcinogenic and non-carcinogenic plasticizers leaching from plastic waste infiltrate groundwater systems, threatening human, animal, and plant health via the food chain.

The open burning of plastic waste—whether accidental or intentional—releases a range of toxic gases, including dioxins, furans, chlorinated biphenyls, mercury, and lead particulates, all of which are detrimental to environmental and public health. Among these, dioxins, particularly 2,3,7,8-tetrachlorodibenzo-p-dioxin (often referred to as Agent Orange), have been linked to cancer, reproductive disorders, respiratory ailments, and neurological damage (Nkwachukwu et al., 2019). Inhalation of plastic smoke increases the risk of heart disease, neurodegeneration, and lung dysfunction.

The persistence of petroplastics, combined with the global rise in plastic production and ineffective waste disposal practices, continues to escalate environmental degradation—causing irreversible damage to natural ecosystems and biodiversity.

**Table 1: Common Petroplastic Types, Their Environmental Persistence, and Degradation Timeframes in Natural Ecosystems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Petroplastic Type** | **Common Uses** | **Persistence in Environment** | **Degradation Time** | **Microplastic Formation** |
| Polyethylene (PE) | Packaging, plastic bags | High (non-biodegradable) | 100–1000 years | Breaks down into small particles |
| Polypropylene (PP) | Containers, straws | High (non-biodegradable) | 20–30 years | Breaks into small fibers |
| Polyvinyl Chloride (PVC) | Pipes, flooring | High (non-biodegradable) | 100–400 years | Shreds into small pieces |
| Polystyrene (PS) | Foam, containers | High (non-biodegradable) | 50–100 years | Degrades into small fragments |
| Polyethylene Terephthalate (PET) | Bottles, textiles | Moderate (slow degradation) | 100–200 years | Breaks down into fibers and particles |

Petroplastic pollution, primarily driven by improper plastic waste disposal, agricultural runoff, and landfilling, adversely affects both terrestrial and aquatic ecosystems. As large plastic debris breaks down, it forms microplastics, which accumulate in soil pores, disrupting soil structure, fertility, and the retention of water. This not only alters physical soil properties but also reduces the activity of essential microorganisms and soil fauna such as earthworms, which are critical for nutrient cycling and soil health (Joos & De Tender, 2022).

Moreover, the degradation of plastics in soil contributes to the leaching of harmful substances, including pesticides, heavy metals, and persistent organic pollutants (POPs). These toxicants pose a substantial threat to ecosystems and contribute to groundwater contamination (Chakraborty et al., 2022).

In marine environments, plastic waste accumulates in major oceanic gyres—such as the Great Pacific Garbage Patch—where it is often mistaken for food by marine organisms. The ingestion of microplastics can lead to gastrointestinal blockage, inflammation, and malnutrition, impairing survival and reproduction in species like fish, turtles, and seabirds. Larger plastic items also pose a physical hazard, causing entanglement injuries that can inhibit mobility, hinder predation and reproduction, or even result in mortality (Thompson et al., 2009; Gray et al., 2012). Recent studies have demonstrated that MPs can act as vectors, concentrating co-contaminants and enhancing their uptake by aquatic organisms. For instance, MPs loaded with heavy metals have shown increased toxicity compared to MPs or metals alone. Additionally, the combined presence of MPs and POPs can influence the metabolism and detoxification pathways in exposed organisms, altering physiological responses and bioaccumulation patterns.

Despite growing evidence, the complexity of these interactions remains insufficiently understood due to varying environmental conditions, MP characteristics, and contaminant types. Further research is critical to elucidate the mechanistic pathways and ecological risks posed by these co-contaminant interactions in both freshwater and marine ecosystems.

Plastic debris further disrupts aquatic habitats, particularly in coral reef ecosystems, where it impairs coral regeneration and blocks sunlight needed for photosynthetic processes (Baulch & Perry, 2014). The consumption of plastics across trophic levels alters trophic interactions, reduces species reproductive success, and destabilizes ecosystem biodiversity and abundance (Au et al., 2017; de Souza Machado et al., 2018).

Although plastics in marine environments may degrade faster due to increased microbial and photolytic activity, the sheer volume of waste significantly slows overall decomposition. Certain plastic materials can persist for centuries in deep marine habitats (Schmidt et al., 2017).

The continued increase in plastic pollution threatens to cause irreversible damage to marine ecosystems within the next two to three decades, with cascading effects likely to impact terrestrial systems as well. To prevent such outcomes, experts advocate for the ban on single-use plastics (SUPs), the enforcement of zero toxic discharge policies, and the promotion of sustainable and pollution-free recycling practices (Murray et al., 2018).

1. **Microplastics: Formation, Characteristics, Fate and Persistence in the Environment**

Microplastics (MPs) are defined as plastic particles or fragments smaller than 5 mm, and they play a significant role in global environmental pollution. These particles are categorized into two types based on their origin:

Primary microplastics are intentionally manufactured at microscopic sizes and are commonly found in products such as cosmetics, personal care items, and synthetic textiles.

Secondary microplastics are formed through the fragmentation of larger plastic items due to environmental processes such as photoxidation, mechanical abrasion, and microbial degradation (Crawford & Quinn, 2016).

Microplastics enter ecosystems through multiple pathways, including industrial discharge, agricultural runoff, and ineffective waste management practices. On land, discarded plastic waste undergoes weathering, which is accelerated by rainfall, aiding the movement of microplastic particles into soil ecosystems.

Moreover, microplastics are not confined to local environments. They can become airborne, travel long distances through the atmosphere, and are eventually deposited in remote regions like the Arctic via precipitation or dry settling (Dris et al., 2016; Liu et al., 2019).

In aquatic environments, river systems act as major conduits for microplastic transport from terrestrial to marine ecosystems. These particles are carried by currents and often accumulate in ocean gyres, such as the Great Pacific Garbage Patch (Lebreton et al., 2018). Importantly, microplastics are found not only at the surface of oceans but also at depths of up to 1000 meters, particularly in regions with strong underwater currents (Cózar et al., 2014).

Rivers like the Yangtze and Ganges are known to release significant amounts of microplastics into the ocean, contributing further to their presence in freshwater systems, where they impact aquatic biodiversity (Yang et al., 2021; Atugoda et al., 2022). Additionally, MPs have been detected in the Arctic, where they accumulate in snow and ice and can enter food chains during melting events (Obbard et al., 2014; Kanhai et al., 2020).

The durability and chemically stable structure of microplastics enable them to persist for decades to centuries, posing long-lasting ecological risks. This is particularly concerning in sensitive environments such as deep-sea habitats, where their accumulation can interfere with benthic species, trophic interactions, and overall biodiversity (Woodall et al., 2014)

Microplastic toxicity is significantly associated with their size, especially in relation to their ability to cause physical damage to organisms. As soon as microplastic breaks into the environment, sea animals consume them, resulting in gastrointestinal blockage, inflammation with metabolic and physiological disturbances (Duis & Coorse, 2016) Large microplastic can damage internal tissues and causes ulcers and scars due to their sharp edges and rough surfaces. In addition, microplastics continuously have the ability to adsorb toxic pollutants such as pollutants like persistent organic pollutants (POPs), heavy metals, and pesticides, which can bioaccumulate in various tissues of affected organisms and consequently enhance the transfer of these toxic materials in the entire food web (Khan et al., 2023). By generating reactive oxygen species (ROS), these particles also cause oxidative stress, which can harm organs, impair the immune system, and alter metabolism in aquatic species. (Prinz and Korez, 2020).

In addition, the exposure to microplastic can cause worst impact of heavy metals to increase immune responses and inflammation (Wei et al., 2023) Microplastic has significant negative physical effects on aquatic life, which affects their development, reproduction, digestion and general health (Table: 2). Fish and invertebrates, among other organisms, usually confuse microplastic for food, resulting in low food intake, starvation and even death due to gastrointestinal tract choking (Wang et al., 2020; Zolotova et al., 2022).

The mechanical damage from sharp microplastics can disrupt the intestine lining and gills which can hinders the essential biological functions including such as respiration, movement and feeding (Hodkovicova et al., 2022). Furthermore, eating microplastics harms the reproductive systems of many fish and invertebrate species, lowering the quantity of eggs and the survivability of the progeny (Lusher et al., 2013).

Microplastics can harm plankton and other primary producers as they build up in aquatic environments. This can disrupt food webs, have an effect on higher trophic levels, and jeopardize biodiversity and ecosystem services (Wright et al., 2013). Marine ecosystems and species diversity are seriously threatened by the persistent presence of microplastics in the marine environment (Auta et al., 2017).

**Table 2: Major Sources of Microplastic Pollution in Aquatic Ecosystems: Pathways, Concentrations, and Potential Ecotoxicological Risks**

|  |  |  |  |
| --- | --- | --- | --- |
| **Source of Microplastic** | **Pathways to Aquatic Ecosystem** | **Concentration in Water** | **Potential Toxicity Effects** |
| Primary Microplastics (e.g., microbeads in cosmetics) | Direct discharge from products into waterways | High in urban and industrial areas | Skin irritation, endocrine disruption |
| Secondary Microplastics (e.g., degraded plastic waste) | Breakdown of larger plastics via UV, weathering | Varies by location (often widespread) | Ingestion by marine life, bioaccumulation |
| Synthetic Fibers (e.g., from clothing) | Washing of synthetic textiles | Moderate to high in freshwater and oceans | Digestive problems, transfer up the food chain |
| Tires and Vehicle Wear (e.g., tire dust) | Road runoff into water bodies | Moderate, with hotspots near roads | Bioaccumulation in fish, toxic buildup |
| Industrial Waste (e.g., plastic pellets) | Direct spillage from factories or transportation | High near industrial zones | Toxicity to marine organisms, reproductive effects |

Microplastics (MPS) that are made up of polymers such as polyethylene, polypropylene, polystyrene, and polyethylene terephthalate have the ability to absorb heavy metals, persistent organic pollutants (pops), and other chemicals such as flames retardants, antioxidants and plasticizers that are added during the manufacture of plastics(Rochman et al., 2013).These harmful compounds, which can disrupt the physiological and reproductive processes of aquatic life, include phthalates, bisphenol A (BPA), and polybrominated diphenyl ethers (PBDES) (Gallo et al., 2018; Mathieu-Denoncourt et al., 2020).

Furthermore, MPSs serve as carriers of toxic compounds, allowing hydrophobic contaminants like DDT, PCBs, and pesticides to pass down the food chain (Amelia et al., 2021; Cverenkárová et al., 2021). The health and ability to reproduce of fish and marine mammals are impacted by these contaminants, which build up in their important organs (Nelms et al., 2019; Walkinshaw et al., 2020). For a range of aquatic animals, ingestion of microplastics (MPS), particularly those contaminated with hazardous compounds, has shown impressive physiological and toxic effects. For instance, creatures like zebrafish and medaka are vulnerable to oxidative stress, genetic harm, developmental abnormalities, and reproductive problems when they come into touch with microplastics (Cormier et al., 2021; Rainie et al., 2018).

Furthermore, MPs have been linked to immunological responses and behavioral changes in fish and amphibians, with some species experiencing increased mortality and decreased eating efficiency (Araujo et al., 2021; Pannetier et al., 2020). By influencing microbial populations, these plastics not only damage individual species but also interfere with ecological processes like nitrogen cycle. Additionally, the transfer of microplastics and their associated contaminants through the food web worsens the distribution of pollution, posing a major threat to biodiversity and ecosystem stability (Kasamesiri and Thaimuangphol, 2020).

For instance, Wang et al. (2020) reported ingestion rates of up to 1,800 particles per individual in anchovy fish from coastal China, with exposure leading to reduced digestive efficiency and reproductive output. In freshwater systems, concentrations of MPs have been documented at 0.01 to 1.5 items per liter, with chronic exposure in zebrafish (Danio rerio) resulting in significant oxidative stress and liver pathology at doses as low as 20 µg/L (Cormier et al., 2021). In terrestrial environments, earthworms (Eisenia fetida) exposed to 1% w/w microplastic-contaminated soil exhibited a 35% decrease in reproduction and altered enzymatic activity (Rodrigues et al., 2019). Such quantitative findings highlight the severity of MP toxicity even at environmentally relevant concentrations.

Therefore, microplastic pollution is a major environmental issue with wide-ranging implications for ecology and human health. Table:3 is representing the toxicological consequences of microplastic ingestion in marine organism specially focused on physiological, biochemical, and behavioral disruptions.

**Table 3: Toxicological Consequences of Microplastic Ingestion in Marine Organisms: Physiological, Biochemical, and Behavioral Disruptions**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Effect Type** | **Toxicological Impact** | **Affected Organisms** | **Examples of Microplastic-Related Damage** | **Paper** |
| **Physical Harm** | Blockage of digestive system, injury | Fish, Invertebrates, Plankton | Physical injury to organs, feeding impairment | Jovanowic, 2017; Egbeocha et al., 2018; Subaramaniyam et al., 2023; Shahriar et al., 2024 |
| **Chemical Toxicity** | Release of toxic additives (e.g., BPA, phthalates) | Fish, Mollusks, Sea Turtles | Organ damage, hormonal disruption | Godswill et al., 2019; Di Renzo et al., 2021; Zhang et al., 2022; Saha et al., 2024 |
| **Endocrine Disruption** | Hormonal imbalances, reproductive issues | Fish, Crustaceans, Amphibians | Decreased reproduction, abnormal development | Sun et al., 2022; Kolas et al., 2024; Hasan et al., 2024 |
| **Immune Suppression** | Weakening of immune response | Crustaceans, Fish | Reduced ability to fight infections | Nan et al., 2022; Niemcharoen , (2022); Sun et al., 2023; Zhang et al., 2024; Hamed et al., 2025 |
| **Behavioral Changes** | Altered feeding, movement, or predator avoidance | Fish, Seabirds, Marine Mammals | Disruption of migration, feeding behavior | Fossi et al., 2013; Sovoka, (2017); Bos, (2019); Hamidian & Feizi, (2023); |

1. **Mechanism of microplastic bioaccumulation and biomagnification**

Microplastic pollution, due to its potential effects on the food web, species, and aquatic habitats, has become a significant environmental problem. For important processes such as bioaccumulation and biomagnification, microplastics are ingested by organisms, remain within their systems and ascend to trophic levels (Wang et al., 2016). The particles that influence microplastic accumulation are size, shape, type of polymer, and behavior against individual organisms. Fish, bivalves, and zooplankton eat smaller microplastics more readily (Botterell et al., 2020; Severnkorova et al., 2021). In addition, the ability of microplastics to adsorb toxins increases their toxicity when ingested, leading to bioaccumulation (Yu et al., 2019; Fu et al., 2021; Costigan et al., 2022).

Also the unregulated forms of microplastics, such as fibers and fragments, can cause physical damage to the digestive system, further increasing bioaccumulation by affecting absorption rates and retention periods in organisms (Pirsaheb et al., 2020; Hert and Body-Malapel, 2020). Important bioaccumulation polymer types, like polyethylene (PE) and polystyrene (PS), can accumulate in living things and interact with pollutants like pesticides and heavy metals because they are chemically stable and long-lived ((Besseling et al., 2013; Rodrigues et al., 2019; Arienzo et al., 2021; Menéndez-Pedriza & Jaumot, 2020). Table 4 depicting the toxicological impact on various aquatic organisms can consume microplastics through contaminated prey or by ingesting suspended particles.

Filter feeders like zooplankton and bivalves are particularly susceptible to this. Microplastics move from lower trophic levels to higher when they cross the food web and become biomagnified (Pantoja et al., 2020). The process of absorbing microplastics at different trophic levels and feeding habits of predators also influences biomagnification (Carbery et al., 2018). Small microplastics are more likely to be absorbed in the body because they can pass easily through the gills, digestive tract, and cell membrane (Tursi et al., 2022).

The chemical characteristics of microplastics are also helpful in biomagnification because they can transport toxins, which put the food chain at greater risk (Verla et al., 2019). Recent studies have shown large-scale biomagnification in marine species, putting humans at risk from seafood consumption (Elizalde-Velázquez et al., 2020).

This accumulation can disrupt ecosystems and food webs, as well as marine mammals and sea birds (Noventa et al., 2021). The growing body of evidence underscores the need for additional research into the log term effects, influence of environmental factors, and the implications for biodiversity in terrestrial, freshwater and marine ecosystems (Tatli et al., 2025; Zeng et al., 2025).

**Table 4: Bioaccumulation and Trophic Transfer of Microplastics in Marine Ecosystems**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Trophic Level** | **Organisms Involved** | **Microplastic Concentration** | **Bioaccumulation Effects** | **Paper** |
| **Primary Producers** | Phytoplankton, Algae | Low to moderate | Initial ingestion of microplastics | Zhang et al., 2017; Mao et al., 2018; Malinowski et al., 2023 |
| **Primary Consumers** | Zooplankton, Small Fish | Moderate | Microplastics enter the food web | Cole et al., 2013; Aytan et al., 2020; Alfonso et al., 2023; Kankılıç et al., 2023 |
| **Secondary Consumers** | Larger Fish, Invertebrates | Moderate to high | Increased concentration, health effects | Karlsson et al., 2017; Foley et al., 2018; Lusher et al., 2020; Doyle et al., 2022 |
| **Tertiary Consumers** | Marine Birds, Larger Fish, Seals | High | Toxic buildup, reproductive issues | Have et al., 2021; Sühring et al., 2022; Phillip et al., 2022; Singh & Upadhyay, 2025 |
| **Quaternary Consumers** | Humans (through seafood consumption) | High | Potential long-term health risks | Smith et al., 2018; Cox et al., 2019; Danopoulos et al., 2020; Pan et al., 2022 |

1. **Microplastic abundance at cross-trophic levels: A Cross ecosystem perspective**

Microplastic pollution has become a common problem in land, sea and freshwater systems, having a significant impact on biodiversity and ecosystem health। Although marine microplastics have received a lot of attention, most studies have concentrated on how they move, accumulate, and affect marine life like invertebrates, fish, and seabirds (Horton & Barnes, 2020; Marcharla et al., 2024), ecological long-term effects on marine populations are unclear (Lee et al., 2016; Law, 2017). The transport of microplastics through ocean currents and their role in food webs, particularly in relation to apex predators, have been ignored (Anthony et al., 2023; Aransiola et al., 2025).

Conversely, research on freshwater systems is still in its infancy. Researchers currently concentrate on microplastics levels, their trajectory, and their impact on aquatic life, including fish, amphibians, and invertebrates (Neelavannan & Sen, 2023; Bexeitova et al., 2024). The variation in freshwater environments and the lack of standardized research methods impede the comparative and in-depth understanding of microplastic pollution (Murshed et al., 2025) highlighting the urgent need for further studies regarding the breakdown of microplastics and its harmful effects on freshwater species (Sharma et al., 2024). In terms of microplastic pollution, land ecosystems are among the least studied. However, new research indicates that microplastics enter the soil via waste disposal, agricultural runoff, and atmospheric deposition. According to research, microplastics can accumulate in the soil, which causes soil health and plant growth to be compromised.

In Nigerian water bodies, such as the Sombreiro and New Calabar Rivers, microplastics (MPs) are a significant pollutant, with fish tissues containing 0.5–5 particles per gram, primarily polyethylene and polypropylene fragments (Attah et al., 2023). This study found higher MP concentrations in river sediments near urban areas, suggesting that human activities like waste dumping exacerbate contamination. Ingestion of MPs by fish leads to oxidative stress and reduced immune function, disrupting freshwater food webs and threatening biodiversity. These findings highlight the urgent need to address MP pollution in African freshwater systems, where data remain limited compared to marine environments.

Additionally, terrestrial animals like earthworms, rodents, and insects can ingest microplastics, resulting in toxicity (Dissanayake et al., 2022; Rashid et al., 2025). The study of terrestrial microplastics often leads to discrepancies in sampling methods, analysis, and experimental design, which makes interpreting data difficult (Yang et al., 2021; Zhu et al., 2023). When it comes to terrestrial food webs, particularly those with high trophic levels, there is a lack of knowledge about the potential for bioaccumulation and biomagnification. This requires additional research to assess the long-term effects on soil health, plant growth, and the general ecosystem dynamics (Hassan & Tarannum, 2024). Understanding microplastics' transport mechanisms in terrestrial ecosystems is essential to study their distribution and effects on the environment.

Microplastic pollution has emerged as a widespread environmental concern across land, sea, and freshwater systems, greatly affecting biodiversity and the health of ecosystems. Although the examination of marine microplastics has been thorough, focusing mainly on their movement, accumulation, and impacts on marine life such as invertebrates, fish, and seabirds (Horton & Barnes, 2020; Marcharla et al., 2024), the long-term ecological repercussions for marine populations, especially at greater ocean depths, are not well understood (Li et al., 2016; Law, 2017). The transport of microplastics via ocean currents and their involvement in food webs, particularly concerning apex predators, has received inadequate attention (Anthony et al., 2023; Aransiola et al., 2025).

Conversely, research on freshwater systems, while growing, is still in its infancy, with investigations mainly focusing on microplastic levels, their fate, and their effects on aquatic life, including fish, amphibians, and invertebrates (Neelavannan & Sen, 2023; Bexeitova et al., 2024). The variation among freshwater environments and the lack of standardized research methods impede the comparison and thorough understanding of microplastic pollution (Murshed et al., 2025), highlighting the urgent need for further study into microplastic breakdown and its harmful effects on freshwater species (Sharma et al., 2024). Terrestrial ecosystems are among the least examined regarding microplastic pollution, although recent studies indicate that microplastics enter soils from waste disposal, agricultural runoff, and atmospheric deposition. Research reveals that microplastics can accumulate in soil, adversely affecting both plant growth and soil health, while terrestrial animals such as earthworms, rodents, and insects may ingest microplastics, which could lead to toxicity (Dissanayake et al., 2022; Rashid et al., 2025).

In spite of the growing interest, investigations into terrestrial microplastics often show inconsistencies in sampling methods, analysis, and experimental design, which hinders data interpretation (Yang et al., 2021; Zhu et al., 2023). The potential for bioaccumulation and biomagnification within terrestrial food webs, especially at higher trophic levels, is still not well understood, necessitating further research to evaluate the long-term impacts on soil health, plant growth, and overall ecosystem dynamics (Hasan & Tarannum, 2024). It is essential to comprehend the transport mechanisms of microplastics in terrestrial ecosystems to ascertain their environmental distribution and effects. Table 5 comprises the data of microplastic abundance across the ecosystems.

**Table 5: Comparison across ecosystems in terms of microplastic abundance**

|  |  |  |  |
| --- | --- | --- | --- |
| **Aspect** | **Marine** | **Freshwater** | **Terrestrial** |
| Dominant MP Types | Fibers, pellets, fragments | Fibers, tire wear particles | Films, fragments, fibers |
| Transport Mechanism | Ocean currents, wind | River flow, runoff | Wind, surface runoff, farming |
| Exposure Pathways | Ingestion by fish/seabirds | Ingestion by fish/invertebrates | Ingestion by soil fauna |
| Degradation Rate | Slower in deep ocean | Moderate (varies by flow/UV) | Often slower due to soil cover |
| Research Maturity | Advanced | Moderate | Emerging |

1. **Knowledge Gaps and Future Research Directions**

Despite significant progress in microplastic research, several critical gaps hinder a comprehensive understanding of their environmental toxicity and bioaccumulation across ecosystems. First, terrestrial ecosystems are significantly underexplored compared to marine and freshwater systems. Limited data exist on microplastic impacts on soil health, plant growth, and terrestrial food webs, with studies often restricted to small-scale experiments on soil fauna like earthworms (Dissanayake et al., 2022; Yang et al., 2021). This gap limits our ability to assess the broader ecological consequences of microplastics in terrestrial environments, particularly in agricultural and urban soils.

Second, the absence of standardized protocols for sampling, quantifying, and assessing microplastic risks poses a major challenge. Variations in sampling methods, particle size definitions, and analytical techniques across studies make it difficult to compare findings or establish baseline contamination levels (Sharma et al., 2024). For example, marine studies often use neuston nets with differing mesh sizes, while terrestrial studies lack consistent soil extraction methods, complicating cross-ecosystem comparisons.

Third, the long-term dynamics of microplastic trophic transfer, especially in freshwater and terrestrial food webs, remain poorly understood. While marine systems show evidence of biomagnification in apex predators (Sühring et al., 2022), comparable data for terrestrial species, such as mammals or birds, are scarce. Studies like Elizalde-Velázquez et al. (2020) highlight trophic transfer in freshwater organisms, but quantitative data on biomagnification rates and long-term ecological impacts are lacking.

Fourth, the synergistic interactions between microplastics and co-contaminants, such as persistent organic pollutants (POPs) and heavy metals, require deeper exploration. Although microplastics are known to adsorb contaminants like PCBs and cadmium (Rochman et al., 2013; Wei et al., 2023), the dose-response relationships and species-specific sensitivities, particularly in terrestrial organisms, are not well-characterized. This gap hinders accurate risk assessments for ecosystems and human health.

Finally, the ecological and health impacts of microplastic degradation products, such as nanoplastics, are underexplored. While microplastics persist for decades, their breakdown into smaller particles may enhance bioavailability and toxicity, yet few studies quantify these effects across ecosystems (Zhang et al., 2022). Future research should prioritize developing harmonized methodologies, quantifying exposure thresholds, investigating terrestrial trophic dynamics, and assessing nanoplastic risks to address these gaps and inform effective mitigation strategies.

1. **Conclusion**

This review synthesizes current knowledge on microplastic (MP) toxicity and bioaccumulation across marine, freshwater, and terrestrial ecosystems, revealing both established impacts and persistent uncertainties. What we know: MPs cause harm through physical, chemical, and biological mechanisms, including gastrointestinal blockages, pollutant adsorption (e.g., PCBs at 1–100 ng/g), and oxidative stress in organisms like zebrafish and earthworms (Rochman et al., 2013; Cormier et al., 2021; Joos & De Tender, 2022). In marine ecosystems, MPs disrupt food webs, with concentrations up to 1,000 particles/m³ in gyres, affecting plankton to seabirds (Cózar et al., 2014; Lusher et al., 2020). Freshwater systems face sedimentation (0.1–100 particles/L) and synergistic toxicity with heavy metals, impacting fish health (Yang et al., 2021; Attah et al., 2023). Terrestrial ecosystems suffer soil fertility loss and fauna ingestion, though data are limited (Dissanayake et al., 2022). Bioaccumulation is universal, with MPs detected from phytoplankton to human blood, amplifying risks through trophic transfer (Amelia et al., 2021; Leslie et al., 2022). Cross-ecosystem comparisons show shared bioaccumulation but distinct transport patterns, such as ocean currents versus soil retention.

What remains unknown: Significant gaps persist, particularly in terrestrial ecosystems, where only 30% of studies focus, leaving trophic transfer and long-term soil impacts unclear (Dissanayake et al., 2022). Standardized protocols for MP sampling and risk assessment are absent, hindering data comparison (Sharma et al., 2024). Long-term biomagnification dynamics, especially in freshwater and terrestrial food webs, lack quantitative data (Elizalde-Velázquez et al., 2020). The synergistic effects of MPs with co-contaminants (e.g., heavy metals) and the toxicity of nanoplastics (<1 µm) are underexplored, despite their potential for greater bioavailability (Wei et al., 2023; Zhang et al., 2022).

Future research priorities: Research should prioritize developing standardized MP sampling and analysis methods to enable cross-study comparisons. Terrestrial ecosystems demand urgent attention, particularly studies on trophic transfer in mammals and birds. Long-term experiments are needed to quantify biomagnification rates and ecosystem-level impacts over decades. Investigating nanoplastic toxicity and MP interactions with co-contaminants will improve risk assessments. These efforts are critical to inform evidence-based policies for mitigating MP pollution and protecting ecosystems.

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3. Grok to assist the manuscript writing more scientifically.

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