**Advances in Bioresearch**
Adv. Biores., Vol 17 (5) May 2026: 129-151
©2026 Society of Education, India
Print ISSN 0976-4585; Online ISSN 2277-1573
Journal's URL:http://www.soeagra.com/abr.html
CODEN: ABRDC3
DOI: 10.15515/abr.0976-4585.17.5.129151

Advances in Bioresearch

## REVIEW ARTICLE

# Microplastic dynamics in aquatic and terrestrial settings: A comprehensive review on accumulation, toxicity, detection techniques, and mitigation strategies

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**ABSTRACT**
*Microplastics (<5 mm) have emerged as ubiquitous pollutants in both aquatic and terrestrial environments. Beyond their physical presence, these particles serve as carriers for a range of toxic contaminants, thereby intensifying ecological degradation and raising concerns for human and animal health. Although the distribution of microplastics is well established, their interactions with hazardous substances remain an evolving research frontier. This review synthesizes current insights into microplastic–contaminant dynamics and critically examines advanced analytical techniques for their detection and characterization. A systematic literature review was conducted using peer-reviewed studies published through 2025, sourced from Scopus, Web of Science, PubMed, and Google Scholar. Only studies with a clear methodological focus on microplastic–contaminant interactions and analytical procedures were included. The review classifies major contaminant groups such as heavy metals, synthetic dyes, and industrial chemicals alongside their environmental sources. It further compares analytical methods through tabular summaries and schematic representations. Mitigation strategies assessed include advanced oxidation processes (ozonation, Fenton's reagent, photocatalysis), nanofiltration technologies, and public outreach initiatives. Evidence indicates that microplastics significantly enhance the transport and environmental persistence of toxicants. Raman and FTIR spectroscopy are reliable for polymer identification, whereas GC-MS is optimal for analyzing organic pollutants. Persistent challenges include methodological inconsistencies, lack of standardization, and limited studies on terrestrial impacts. Photocatalytic oxidation appears most promising among remediation options, while public education supports long-term behavioral change. This review highlights critical knowledge gaps and proposes a multidisciplinary framework that integrates technological, regulatory, and community-based approaches to address microplastic pollution comprehensively.*
***Keywords:*** *Microplastic pollution, Source detection, Analytical techniques, Ecosystem health, Abatement strategies*

Received 24.11.2025 Revised 21.02.2026 Accepted 11.05.2026

**How to cite this article:**
Dusmant M, Shaktidhar N, Prashantkumar S, Pratyush D, Shreya P and Dinesh Kumar N. Microplastic dynamics in aquatic and terrestrial settings: A comprehensive review on accumulation, toxicity, detection techniques, and mitigation strategies. Adv. Biores. Vol 17 [5] May 2026. 129-151

## INTRODUCTION

Plastics have become indispensable in contemporary society, widely used in industrial, domestic, and personal care applications. The worldwide production of plastics reached 413.8 million metric tons in 2023, driven by the continued growth in demand due to the versatility of these materials [1]. A growing environmental concern arising from this trend is the widespread presence of microplastics, synthetic polymer particles smaller than 5 mm, originating from both primary sources (e.g., microbeads in cosmetics and cleaning agents) and secondary sources (fragmentation of larger plastic debris through physical, chemical, or biological degradation) [2]. Microplastics are now ubiquitous in aquatic environments, largely due to industrial effluents, wastewater discharge, and poor waste management practices [3]. Their small size enables ingestion by a wide range of aquatic organisms, resulting in adverse effects such as immune suppression, tissue damage, and bioaccumulation in food webs (Wong et al., 2020). Documented cases include ingestion by fish, crustaceans, mollusks, birds, and marine mammals [4]. Terrestrial ecosystems are similarly affected. MPs in soils can disrupt microbial balance, alter physicochemical properties, and impair the health and productivity of plants and animals [5,6]. Moreover, microplastics act as vectors for hazardous substances, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and toxic additives like plasticizers and flame retardants. Significantly, approximately 80% of marine plastic debris originates from land-based sources, highlighting the strong connectivity between terrestrial and aquatic pollution pathways. To better understand and manage these risks, various analytical techniques including Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, scanning electron microscopy (SEM), and gas chromatography–mass spectrometry (GC-MS) have been employed for microplastics detection and contaminant characterization [7]. However, inconsistencies in methodologies, data interpretation, and standardization present ongoing limitations in comparability and reliability. This review makes several significant contributions to the field of microplastic research. It synthesizes the latest findings on the interactions between microplastics and associated toxicants, such as heavy metals, dyes, and industrial chemicals, emphasizing their role in enhancing environmental toxicity. It critically evaluates the efficacy, limitations, and applicability of a range of analytical techniques including FTIR, Raman spectroscopy, SEM, and GC-MS for the detection and chemical characterization of microplastics and their adsorbed pollutants. Furthermore, the review compares the environmental behavior and biological impacts of microplastics in both aquatic and terrestrial ecosystems, with particular focus on processes such as bioaccumulation, ecotoxicity, and trophic transfer. In addition, it highlights emerging and established mitigation strategies, including advanced oxidation processes (AOPs), nano-filtration technologies, and the importance of public education and awareness campaigns. Finally, the review proposes a comprehensive, multidimensional framework that integrates scientific advancements, regulatory policies, and community engagement, offering a holistic approach to addressing the global challenge of microplastic pollution. Despite considerable advancements in microplastic research, several critical gaps remain unresolved. First, there is a significant lack of data on the occurrence, distribution, and ecological impact of microplastics in terrestrial ecosystems, particularly in agricultural soils, forested landscapes, and landfill environments. This gap limits our understanding of land-based microplastic dynamics and their potential to transfer into aquatic systems. Second, the absence of standardized methodologies for the sampling, extraction, and quantification of microplastics across various environmental matrices such as soil, sediment, and water hampers the generation of reliable and comparable datasets. Third, the interactions between microplastics and toxic contaminants remain poorly understood, especially in terms of sorption and desorption processes, their environmental persistence, and implications for long-term ecological and human health risks. Additionally, the current landscape of analytical approaches is fragmented, with inconsistencies in techniques and data interpretation, which hinders cross-study comparisons and the development of cohesive conclusions. Lastly, there is a weak integration between scientific advancements and policy implementation, with limited public awareness and community participation in mitigation efforts. These gaps collectively highlight the urgent need for a unified research framework that bridges scientific inquiry, policy development, and societal engagement. To address the identified research gaps, this review is guided by the following key questions: What are the primary sources and environmental pathways of microplastic contamination in both aquatic and terrestrial ecosystems? How do microplastics interact with toxic pollutants, and what are the resulting ecological and human health implications of these interactions? Which analytical techniques provide the most reliable and comprehensive results for detecting microplastics and characterizing their associated contaminants? What mitigation strategies have shown the greatest potential, and how can these approaches be effectively integrated into environmental policy frameworks and public education initiatives? .

## MATERIAL AND METHODS

To ensure a comprehensive and systematic synthesis of existing literature, this review adopted a structured methodological approach involving database selection, keyword formulation, temporal scoping, and well-defined inclusion and exclusion criteria. Conceptual parameters were also established to guide data analysis and interpretation. Relevant literature was sourced from four major scientific databases such as Scopus, Web of Science, PubMed, and Google Scholar, chosen for their broad coverage of peer-reviewed publications in environmental science, toxicology, and analytical chemistry. Both broad and specific search terms were used to capture a diverse range of studies. The review focused on publications from 2010 to 2025, a period characterized by significant progress in microplastics research, particularly in the development of analytical techniques and the study of contaminant interactions. Included studies were those that examined the interactions between microplastics and toxic substances such as heavy metals, dyes, and industrial chemicals; employed detection or characterization methods like FTIR, Raman spectroscopy, SEM, or GC-MS; assessed ecological or human health impacts in both aquatic and terrestrial environments; or proposed mitigation strategies, risk assessments, or regulatory frameworks. Excluded from the review were studies focusing exclusively on macroplastics or nanoplastics, publications lacking methodological detail or experimental data, non-peer-reviewed sources such as opinion pieces and editorials, and research limited to plastic manufacturing or recycling without addressing environmental implications. Conceptual parameters guiding synthesis included source identification, transport pathways, contaminant sorption/desorption dynamics, analytical efficacy, bioaccumulation impacts, ecosystem-specific effects, and the evaluation of mitigation and policy frameworks. This methodology supports a critical, multidimensional analysis of microplastics as complex environmental vectors for toxic pollutants.

## RESULT AND DISCUSSIONS

### Common sources of microplastics and associated chemical pollutants

Microplastics primarily originate from the breakdown of larger plastic items such as bottles, bags, and packaging due to physical wear, UV radiation, and environmental exposure. Synthetic fabrics like polyester and nylon shed microfibers during washing, which enter wastewater systems and contaminate aquatic environments [8]. Despite regulations, microbeads in personal care products continue to contribute to pollution. Additionally, plastic pellets used in manufacturing can spill during production and transport, while tire wear produces rubber particles that wash into waterways [9]. Marine debris, including fishing gear and packaging, degrades into microplastics, and agricultural practices, such as using plastic mulch and contaminated fertilizers, exacerbate the problem [10, 11]. Wastewater treatment plants often fail to fully remove microplastics, allowing them to enter rivers and oceans. Moreover, airborne microplastics from urban dust and industrial activities can settle in terrestrial and aquatic ecosystems. Single-use plastics, like packaging and straws, fragment over time, intensifying the microplastic pollution crisis [12]. Organic pollutants primarily arise from human activities, such as industrial processes, agriculture, transportation, and domestic waste [13]. These pollutants include pesticides, herbicides, solvents, sewage, stormwater runoff, and vehicle exhaust, which releases volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). Oil spills, marine dumping, landfills, and incineration further introduce persistent organic pollutants (POPs) into ecosystems [14]. Once in the environment, these substances persist, accumulate, and often bind to microplastics, heightening ecological and health risks. A summary of microplastic sources and their associated pollutants is presented in Table 1. Household plastic waste may contain heavy metals, POPs, and flame retardants [10]. Synthetic textiles, such as clothing, release dyes, phthalates, microfibers, and plasticizers [15]. Industrial processes contribute bisphenol A, plasticizers, and solvents [16]. Vehicle tires release PAHs, antioxidants, and chemical additives [17]. Discarded fishing gear introduces pesticides, heavy metals, and hydrocarbons into marine environments [10]. Personal care products often contain microbeads, surfactants, parabens, and endocrine-disrupting chemicals [18]. Additionally, landfills and incineration emit PAHs, heavy metals, and dioxins [6,19], while agricultural runoff introduces herbicides, pesticides, and plastic additives into surrounding ecosystems. Stormwater runoff carries pharmaceuticals, heavy metals, and industrial chemicals into water bodies, further exacerbating pollution [10]. Understanding these sources is critical for developing effective strategies to mitigate microplastic pollution and its environmental consequences.

**Table 1: Microplastics, their associated chemical pollutants, and potential sources**

| Source of Microplastics | Associated Chemical Pollutants | References |
|---|---|---|
| Plastic waste from households | Heavy metals, persistent organic pollutants (POPs), flame retardants | [21] |
| Synthetic textiles (e.g., clothing) | Dyes, phthalates, microfibers, plasticizers | [15, 19] |
| Industrial waste and plastic production | Bisphenol A, plasticizers, solvents | [16] |
| Vehicle tires | PAHs (Polycyclic aromatic hydrocarbons), antioxidants, additives | [17] |
| Fishing nets and gear | Pesticides, heavy metals, hydrocarbons | [17, 21] |
| Personal care products | Microbeads, surfactants, parabens, endocrine-disrupting chemicals | [18] |
| Landfills and garbage incineration | Polycyclic aromatic hydrocarbons, heavy metals, dioxins | [19, 20] |
| Agricultural runoff (fertilizers, plastics) | Herbicides, pesticides, plastic additives | [90] |
| Stormwater runoff | Pharmaceuticals, heavy metals, organic dyes, industrial chemicals | [21] |

**Table 2: Aquatic microplastics identified by different countries including global studies, their size distribution, and major contributors**

| Location | Water Body | Microplastic Size (mm) | Key Findings | References |
|---|---|---|---|---|
| Lahore, Pakistan | River and drain | 0.5-5.0 | High concentration of polyethylene microplastics, bioaccumulation in wading birds | [29] |
| South China | River and mining area | 0.2-6.2 | Microplastics carry heavy metals from mining waste, impact on biodiversity | [30] |
| Tamil Nadu, India | Urban lake | 0.5-1.0 | Polyethylene and polypropylene microplastics detected, pollution from recreational activities | [31] |
| Jakarta, Indonesia | Urban rivers and estuary | <5.0 | High PET and PP contamination, major sources include beverage bottles and textiles | [32] |
| Haryana, India | Surface water | 0.61-4.87 | Dominant microplastics i.e., polyethylene and polystyrene, industrial waste as main source | [33] |
| Global | Freshwater and marine water | <5.0 | Sources include wastewater, textiles, and industrial discharge, trophic transfer impacts | [34] |
| India | Freshwater | <5.0 | Polyethylene and polystyrene microplastics identified, impact on aquatic biodiversity | [35] |
| Global | Freshwater and marine water | <5.0 | High presence of polyethylene and polystyrene, oxidative stress in aquatic organisms | [36] |
| USA | Rivers and lakes | <5.0 | Trophic transfer of microplastics through food webs, contamination from urban runoff | [37] |
| Europe | Coastal waters | <5.0 | Bioaccumulation in shellfish, impact on fisheries and human consumption | [37] |
| China | Yangtze river | <5.0 | High levels of microplastic contamination from industrial sources | [37] |
| Africa | Freshwater lakes | <5.0 | Pollution from improper waste disposal, impact on fish species | [37] |

## Global distribution and occurrence of microplastics in aquatic environments

The distribution and concentration of microplastics in aquatic ecosystems are influenced by both anthropogenic activities and environmental factors, with variations depending on hydrodynamic conditions, environmental pressures, and exposure duration [20]. Marine debris, primarily from improper waste disposal in rivers, lakes, ponds, and canals, is transported to marine, freshwater, brackish, and estuarine environments [21]. Coral reefs are key accumulators of microplastics [22], and wastewater treatment plants and nearby plastic disposal sites significantly contribute to microplastic pollution [23, 24]. Microplastic concentrations typically increase in surface waters as rivers flow from rural to urban areas, highlighting the growing impact of human activities. While microplastic pollution is a global concern, there is a notable research gap regarding freshwater ecosystems compared to marine environments. Extensive studies on marine ecosystems have documented widespread contamination [25]. In the Bay of Bengal, seasonal variations influence microplastic distribution, with anticyclonic rotation promoting the movement and accumulation of microplastics [26]. In Asia, secondary microplastics dominate aquatic plastic particles [20]. In Europe, microplastics are not only found in marine waters but also in various organisms. Urbanization, tourism, and environmental stressors have been linked to elevated microplastic concentrations in European water bodies [27]. Additionally, larger water bodies with longer residence times tend to accumulate more microplastics, likely due to extended exposure periods [28].

Table 2 compares the prevalence of microplastics across regions, showing size distributions and major pollution sources. For example, in Lahore, Pakistan, rivers and drains have polyethylene microplastic concentrations of 0.5-5.0 μg/L, leading to bioaccumulation in wading birds [29]. In South China, microplastic levels in rivers and mining areas range from 0.2 to 6.2 μg/L, with microplastics transporting heavy metals from mining waste, impacting local biodiversity [30]. In Tamil Nadu, India, urban lakes show 0.5-1.0 μg/L concentrations, mainly polyethylene and polypropylene, originating from recreational activities [31]. Jakarta, Indonesia's urban rivers and estuaries contain less than 5.0 μg/L, with PET and PP contamination from beverage bottles and textiles [32].

In Haryana, India, surface water shows microplastic concentrations of 0.61-4.87 μg/L, predominantly polyethylene and polystyrene from industrial waste [33]. Globally, freshwater and marine waters contain concentrations below 5.0 μg/L, with sources such as wastewater, textiles, and industrial discharge, leading to trophic transfer impacts [34]. In India, freshwater microplastics primarily consist of polyethylene and polystyrene, affecting biodiversity [35]. Globally, microplastics in aquatic ecosystems cause oxidative stress in organisms [36]. In the USA, rivers and lakes show less than 5.0 μg/L concentrations, with trophic transfer through food webs and urban runoff contamination [37]. In Europe, coastal waters, with concentrations under 5.0 μg/L, lead to bioaccumulation in shellfish, affecting fisheries and human consumption [37]. The Yangtze River in China shows contamination from industrial sources [37], while African freshwater lakes suffer pollution from improper waste disposal, impacting fish species [37]. To address microplastic pollution, comprehensive monitoring, advanced filtration technologies, and enhanced waste management are critical to reduce plastic waste release into aquatic ecosystems.

## MULTIPLE PATHWAYS OF MICROPLASTICS INTO AQUATIC ENVIRONMENTS

Urban areas contribute significantly to microplastic pollution due to high population density and increased human activity [38]. Microplastics enter aquatic ecosystems through various pathways, such as river runoff, plastic waste, recreational activities, atmospheric deposition, and wastewater effluent [39]. In the environment, plastics degrade through physical abrasion, UV exposure, and microbial activity, eventually finding their way into the aquatic ecosystem [40]. In open ocean waters, plastic debris is notably prevalent (88%), as plastics are less dense than saltwater [41]. Land-based sources significantly impact surface water quality, while cargo ship coatings also contribute to sea-based microplastics. Table 2 and Fig. 1 provide a comprehensive overview of microplastic sources and their interaction between aquatic and terrestrial environments.

 

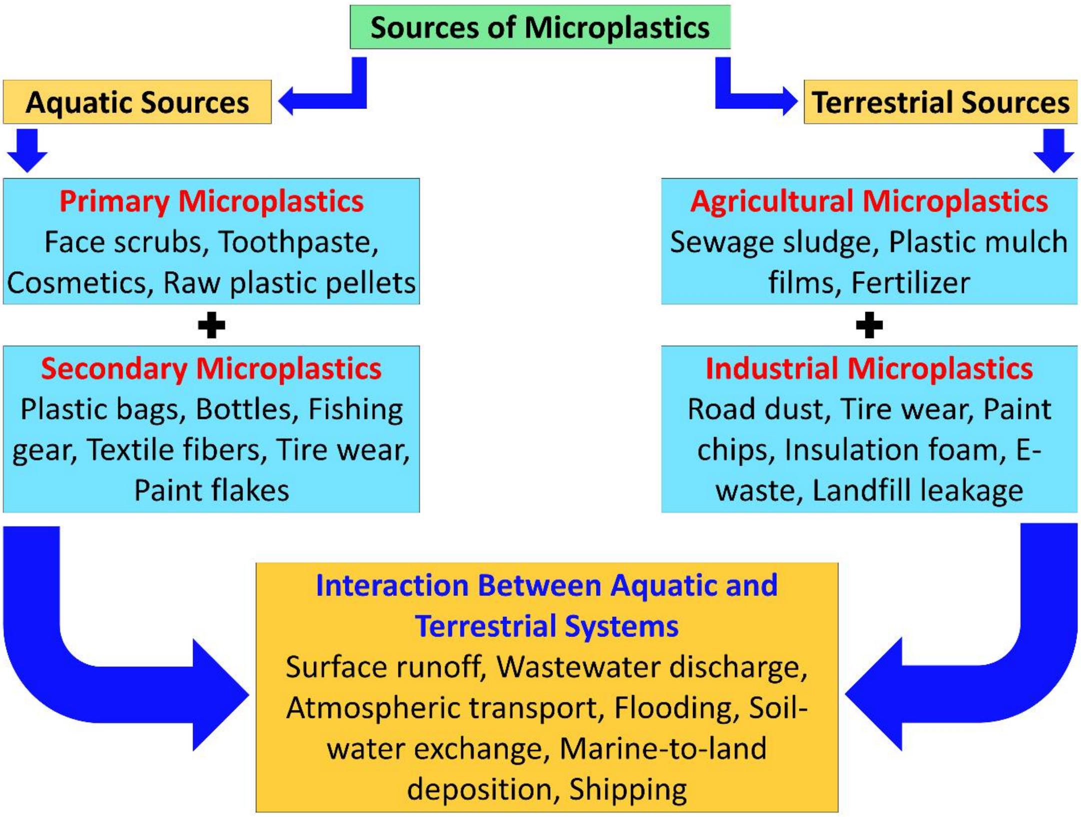


Fig. 1. Major sources of microplastics and their interactions across aquatic and terrestrial environments

Microplastics, typically averaging 250 µm, are commonly found in beauty products, particularly microbeads (0.5–5%) [42]. For example, a single use of an exfoliating wash can release between 4,500 and 94,500 microbeads, and toothpaste can contribute around 4,000 microbeads [43]. Wastewater is a significant pathway for microplastics entering aquatic ecosystems, with products like glitter, small buttons, cleaning agents, facial cleansers, and shaving foam being major contributors [44]. In South Korea, polypropylene polymers dominate microplastic contamination in cities like Seoul and Busan, primarily due to consumer products [45]. Industrial wastewater also contributes microplastics from plastic particles used in air blasting, Styrofoam, pre-production pellets, and synthetic textile materials [46]. Common polymers found in wastewater and stormwater runoff include polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), and polyethylene (PE) [47]. These polymers, often generated by coastal waste and fisheries, are frequently found in coral reefs [22]. The expansion of nautical operations, fishing practices, and aquafarming has significantly increased microplastic pollution in aquatic ecosystems. Fishing gear, including ropes, lines, floats, and buoys, often degrades into microplastics, causing toxicity for marine life, including fish, mammals, and benthic organisms [48]. Additionally, wastewater treatment plants play a significant role in microplastic contamination, as personal care products and synthetic fibres released during laundry contribute to microplastic loads [48]. Despite treatment processes reducing microplastic levels, smaller particles often escape into the environment, making complete elimination difficult [49]. Studies show high concentrations of microplastics in water and sediment downstream of treatment facilities [50]. Addressing microplastic pollution requires a comprehensive approach, starting with source reduction policies that limit single-use plastics, promote biodegradable alternatives, and support eco-friendly product designs.

**Aquatic toxicity of microplastics: polymer-specific risks and consequences**

Microplastics present a significant and diverse threat to marine and freshwater ecosystems. They cause physical harm by entangling organisms, hindering movement, blocking feeding, and leading to injuries [51]. When ingested, either directly or via contaminated prey, microplastics can result in intestinal blockages, poor nutrient absorption, and even death. Additionally, microplastics act as vectors for toxic chemicals, absorbing pollutants and releasing them into the tissues of aquatic organisms [52]. Microplastic pollution also poses risks to human health. Microplastics have been detected in seafood, entering the human food chain and potentially accumulating in the body [53]. Though the long-term health effects are still largely unknown, microplastics have been linked to inflammation, genotoxicity, and endocrine disruption [54]. Their presence in aquatic species impacts organisms across all trophic levels, from phytoplankton to mammals, causing both physical and chemical risks [55]. Beyond environmental effects, microplastic pollution has notable socioeconomic consequences, particularly for coastal communities that rely on marine resources. Key industries such as fishing, tourism, and marine-related sectors are disrupted, leading to long-term economic challenges [51]. Consumption of microplastics by aquatic animals can result in various harmful effects, including DNA damage [56], reduced phagocytic activity [57], increased contaminant levels in tissues [58], and altered behaviour [59], all of which pose significant risks to aquatic biodiversity [60]. While the rapid egestion of ingested microplastics may mitigate some of these adverse effects [61,62], prolonged retention within organisms exacerbates health risks and survival chances [63]. Microplastics and nanoplastics can cross the blood-brain barrier, leading to brain damage and behavioural changes in aquatic species such as crucian carp [64]. In red tilapia (*Oreochromis niloticus*), polystyrene microplastics accumulate mainly in the gut, gills, liver, and brain, where they inhibit acetylcholinesterase activity and disrupt liver metabolism [65]. While some studies have reported minimal toxicological effects of microplastics on aquatic biomarkers [66], their retention in fish appears to be low, suggesting a limited impact on top predators [67]. However, further research is necessary to understand the full extent of the effects of microplastics at environmentally relevant concentrations. The toxic mechanisms of microplastics remain under investigation, with potential effects including energy depletion, intestinal damage, metabolic disturbances, immunotoxicity, neurotoxicity, reproductive toxicity, and oxidative stress. Table 3 highlights the various microplastic polymer types and their detrimental effects on both human health and ecosystems. Polyethylene (PE), detected at concentrations ranging from 0.1 to 5.0 μg/L, has been shown to bioaccumulate in the organs of aquatic organisms, inducing oxidative stress and potential neurotoxic effects, while its ingestion by fish and mollusks further facilitates trophic transfer to higher organisms [68]. Polystyrene (PS) concentrations between 0.05-5.0 μg/L are known to cause endocrine disruption, inflammation, and impacts on gut microbiota, which alters the feeding behavior of aquatic organisms and leads to bioaccumulation [69]. Polyvinyl Chloride (PVC) releases toxic additives like phthalates at concentrations of 0.1-5.0 μg/L, which contribute to liver toxicity, carcinogenic effects, and contamination of sediments, ultimately harming fish survival [70]. Polypropylene (PP), with concentrations ranging from 0.1-4.5 μg/L, can alter immune responses, potentially carry pathogenic bacteria, and disrupt aquatic food chains when ingested by plankton, negatively affecting ecosystem health [71]. Lastly, Polyester (PES), with concentrations from 0.05-3.0 μg/L, can lead to lung inflammation from airborne fibers and respiratory toxicity, while microfibers accumulate in sediments, affecting filter feeders in aquatic ecosystems [72]. Recent studies emphasize the importance of understanding the aquatic toxicity of microplastics, particularly with respect to the specific risks posed by different polymers. Further identification of polymer types and their effects on both aquatic and terrestrial life, using advanced instruments integrated with AI technology, is essential for mitigating their harmful impacts.

**Table 3: Microplastic polymer types, their effects on human health and ecosystems**

| **Plastic Polymer Type** | **Size Range (mm)** | **Effect on Human Health** | **Effect on Ecosystem** | **References** |
|---|---|---|---|---|
| Polyethylene (PE) | 0.1-5.0 | Bioaccumulates in organs, induces oxidative stress, potential neurotoxicity | Ingestion by fish and molluscs, trophic transfer to higher organisms | [36] |
| Polystyrene (PS) | 0.05-5.0 | Endocrine disruption, inflammation, impacts on gut microbiota | Alters feeding behaviour of aquatic organisms, bioaccumulation | [68] |
| Polyvinyl Chloride (PVC) | 0.1-5.0 | Releases toxic additives (phthalates), liver toxicity, carcinogenic potential | Leaches harmful chemicals, contaminates sediments, affects fish survival | [69] |
| Polypropylene (PP) | 0.1-4.5 | Alters immune responses, may carry pathogenic bacteria | Ingestion by plankton, disrupts aquatic food chains | [70] |
| Polyester (PES) | 0.05-3.0 | Lung inflammation from airborne fibres, potential respiratory toxicity | Microfibers accumulate in sediments, impact filter feeders | [71] |

## Occurrence and distribution of microplastics in terrestrial ecosystems

Microplastics, once regarded as a predominantly aquatic issue, have now become a growing concern for terrestrial ecosystems. Their presence in soils is largely driven by human activities such as agriculture, industrial operations, and improper plastic waste disposal. Farmlands are particularly vulnerable, with microplastics entering the soil through sources like plastic mulching, irrigation, sewage sludge, compost, and fertilizers. While agriculture plays a critical role in feeding the global population, it also inadvertently contributes to microplastic pollution. For example, plastic mulch, commonly used to boost crop yields, can become a major contaminant if not properly managed [73]. Research shows that the more mulch is used, the higher the microplastic concentration in agricultural soils [74]. Even compost, often promoted as an eco-friendly soil enhancer, can be a hidden source of pollution. Studies have found that compost from household and supermarket waste contains up to 20–24 microplastic particles per kilogram [75]. Sewage sludge is another significant contributor. In Germany, microplastic levels in farmland treated with sludge reached up to 1.34 kg/ha, with additional contributions from sewage itself at 0.32 kg/ha [76]. Moreover, it shows that soils treated with nitrogen fertilizers can contain nearly double the number of microplastics compared to untreated soils [77]. The distribution and concentration of these particles vary depending on factors like soil type, farming techniques, and sampling depth. Tire wear particles (TWP), though often overlooked, also represent a substantial source of terrestrial microplastic contamination. As global vehicle usage rises, so does the release of TWP, with an estimated 66–76% settling in soils, while the remainder can enter nearby water bodies through runoff [78]. For example, Denmark contributes between 4,200 and 6,600 tons of TWP annually, while Austria and Germany release approximately 10,835 and 101,989 tons, respectively [79]. Given the diverse sources and widespread presence of microplastics in terrestrial environments, there is a pressing need for global-scale monitoring and intervention. Future research, supported by AI-enabled remote sensing and advanced detection technologies, could provide deeper insights into their distribution patterns and inform strategies for mitigation and sustainable land management.

## Significant sources of microplastics in terrestrial environments

Microplastics in terrestrial ecosystems are primarily introduced through human activities such as agriculture, waste disposal, industrial operations, urban runoff, and household products. Urban soils, which play essential roles in carbon storage and climate regulation, are increasingly contaminated with microplastics, entering through sewage sludge, sediment amendments, and airborne particles [80]. For instance, residential soils in Turkey contain 3,378 microplastic items per kilogram, while concentrations in European urban soils range from 593 to 158,000 items per kilogram [81,82]. In North America, microplastic levels in a home garden in Mexico and a playground in the USA are 870 and 72,000 items per kilogram, respectively, with playgrounds typically showing higher concentrations due to foot traffic and plastic use [83]. A significant contributor to global microplastic pollution is post-consumer plastic waste, exacerbated by poor waste management practices. Approximately 21-42% of plastic waste ends up in landfills, where it leaches into the environment as microplastics, particularly in leachate [84]. Microplastic concentrations in landfill soils are notably high, ranging from 544 to 150,000 items per kilogram in regions such as the UK, Pakistan, India, and Iran [86,85]. Factors such as plastic consumption, waste management practices, and population density further contribute to variations in microplastic concentrations across countries. Microplastics in soils pose significant risks to biodiversity, disrupting microorganisms, plants, and animals crucial for nutrient cycling and ecosystem functions [87]. These pollutants alter soil microenvironments, affect microbial activity, and interact with other contaminants like heavy metals and organic matter, increasing environmental risks [88]. Early detection and proactive strategies are essential to combat microplastic pollution at its sources. Globally, significant sources of microplastics have been identified through various regional studies (Table 4). In the USA, clothing fibres, wastewater effluents, and tire wear are major contributors, with advanced filtration methods like nanofiltration and reverse osmosis improving their removal [89]. In China, e-waste, industrial discharge, and urban waste are key sources, with e-waste recycling emerging as a significant contributor to microplastic pollution [90]. In India, domestic plastic waste, sewage, and the textile industry led to high levels of contamination, affecting both urban and rural areas. Europe faces persistent microplastic pollution from cosmetics, food packaging, and household waste, especially in densely populated urban regions [91]. In Africa, industrial effluents, river sediments, and landfill leachates contribute to microplastic pollution in freshwater systems [89]. On a global scale, mismanaged waste, urban runoff, and industrial activities are primary contributors to marine microplastic pollution, which poses a significant threat to aquatic ecosystems [92]. Plastic debris, road dust, and agricultural plastics are also major sources of environmental pollution, complicating efforts to meet Sustainable Development Goal 14 [93].

 

To effectively address these challenges, the identification of microplastic sources using fingerprinting markers and advanced detection techniques is recommended.

**Table 4. Sources of microplastics identified by various researchers from different countries and global studies, and their key findings**

| Country | Sources of Microplastics | Key Findings | References |
|---|---|---|---|
| USA | Clothing fibres, wastewater treatment, tire wear | Nanofiltration and reverse osmosis improve removal | [89] |
| China | E-waste, industrial discharge, urban waste | E-waste recycling identified as a new microplastic source | [90] |
| India | Domestic plastic waste, sewage, textile industry | High levels of plastic pollution in urban and rural areas | [91] |
| Europe | Cosmetics, food packaging, household waste | Persistent sources of microplastics in urban areas | [92] |
| USA | Marine litter, synthetic textiles, stormwater | Primary pathways of microplastic pollution identified | [24] |
| Africa | Industrial effluents, river sediments, landfill leachates | Microplastics found in major freshwater systems | [88] |
| Global | Mismanaged waste, urban runoff, industrial activities | Major contributors to marine microplastic pollution | [91] |
| Global | Plastic debris, road dust, agricultural plastics | Links to Sustainable Development Goals (SDG 14) | [92] |

### Adverse effects of microplastics on terrestrial ecosystems

Microplastics pose significant risks to terrestrial ecosystems, although most research has focused on their impacts in aquatic environments. Studies in aquatic systems have highlighted issues like bioaccumulation, oxidative stress, metabolic damage, and pathobiological impairments [94,26]. However, the effects on terrestrial species, particularly earthworms, which are vital for soil health, are less understood. Microplastic exposure in earthworms has been shown to disrupt spermatogenesis, decrease body cavity cell viability, and negatively impact their digestive systems. For instance, earthworms exposed to 100 and 1000 mg/kg of polystyrene microplastics exhibited higher concentrations of microplastics in their intestines compared to those exposed to smaller particles [95]. Soil microorganisms, which are essential for nutrient cycling and maintaining ecosystem functions, also face significant disruption due to microplastics. These particles can alter the structure of soil microbial communities and interfere with the symbiotic relationships between microorganisms and plants. Microplastics can create unique habitats for microorganisms, including plastic-degrading and pathogenic bacteria like *Aspergillus niger* [96]. The size and concentration of microplastics have a profound impact on microbial activity. For example, polypropylene (PP) microplastics with a particle size of 200-630 μm have been shown to reduce soil microbial biomass [97]. Conversely, smaller microplastics (<150 μm) initially increase bacterial abundance but later inhibit it and reduce fungal diversity [98]. Monitoring microplastic levels in soils and understanding their long-term effects are crucial for effective mitigation strategies. Sustainable agricultural practices, such as reducing plastic use in farming, promoting natural pest control, and implementing soil restoration techniques, can help curb microplastic pollution. Furthermore, stronger policies, including bans on microbeads and restrictions on plastic use in agriculture and packaging, are essential to reduce the widespread presence of microplastics in terrestrial ecosystems. Table 3 summarizes the various types of microplastic polymers, their effects on human health and ecosystems, and their impact on both aquatic and terrestrial environments. Polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), and polyester (PES) have been shown to cause a range of harmful effects, including bioaccumulation, immune disruption, endocrine disruption, and respiratory toxicity. Addressing these issues requires concerted efforts at local, national, and global levels.

## MICROPLASTICS IN THE HUMAN BODY: OCCURRENCE, SOURCES, AND HEALTH IMPACTS

Microplastics enter the human body through various sources, including food packaging, pharmaceuticals, and the food web. Plastics are ubiquitous in daily life, found in items such as toothbrushes, water bottles, and food containers, which contribute to increased human exposure. Food packaging is a major contributor, and seafood serves as a primary entry point via the food chain. Microplastics also originate from larger plastic items, clothing, and personal care products such as toothpaste and shower gels. Due to their extremely slow degradation, often taking thousands of years, microplastics accumulate in living organisms, including humans. While microplastics have been detected in human blood, the full extent of their health effects remains unclear. However, continuous buildup in the human body is believed to impair respiratory and digestive functions, potentially leading to significant health issues [99]. Accumulated microplastics in the human body have been linked to several adverse health effects, including cytotoxicity, neurotoxicity, oxidative stress, and immune system disruption. Cytotoxicity refers to cell damage caused by toxic substances, while neurotoxicity involves the impairment of the nervous system. Oxidative stress arises from an imbalance in reactive oxygen species, which can cause cellular and tissue damage. Immune system disruption can lead to improper immune responses and increased susceptibility to disease. Humans are primarily exposed to microplastics through oral, inhalation, and dermal routes [26], with food and drinking water serving as the primary pathways [17]. The detection of microplastics in human feces confirms ingestion, and everyday products such as salt, toothpaste, and other personal care items contribute to exposure, potentially causing long-term health effects [100]. Microplastics have recently been detected in human veins, with food packaging and paint identified as major sources; although the precise health effects are still being investigated, evidence from cell culture studies indicates that microplastics can provoke inflammatory and cellular stress responses [101]. In a pilot study conducted by researchers from Hull University Teaching Hospitals NHS Trust and the Universities of Hull and York, microplastics were found in saphenous vein tissue from patients undergoing cardiac bypass surgery. Five types of polymers and 15 microplastic particles per gram of venous tissue were detected [102]. This discovery raises concerns about the potential for microplastics to damage vascular tissue and impair normal function, highlighting the need for further research to establish a causal link and identify effective mitigation strategies [103]. In a related study using FTIR spectroscopy, 20 microplastic particles were detected in human saphenous vein tissue, with 90% of them having irregular shapes. Dominant polymers included alkyd resin (45%) and poly (vinyl propionate/acetate), with an average concentration of 29.28 ± 34.88 microplastics/g of tissue. These results significantly differed from control samples, confirming contamination. Microplastics enter the human body through multiple pathways, including the food chain. Aquatic organisms often mistake microplastics for food, leading to their accumulation in digestive systems. As these organisms are consumed by predators, microplastics move up the food web and ultimately enter humans through seafood consumption. This bioaccumulation process has been linked to various health issues, some of which may be life-threatening [104]. In addition to aquatic sources, microplastics are widespread in soil, water, and air, where they bind with dust and suspended particulate matter (SPM). These particles can be inhaled and accumulate in the lungs, potentially leading to respiratory complications [105]. In aquatic environments, larger plastic debris breaks down under UV radiation and wave action into microplastics, which are ingested by fish, causing digestive blockages or shock. During heavy rainfall, fragmented plastics can mix with soil and be absorbed by crops, entering the human food supply through agricultural produce [106]. Microplastics can also degrade into microscopic fibers finer than a human hair, which become airborne and enter the human body. These airborne particles may trigger inflammation, disrupt cellular processes, and contribute to a variety of diseases [6]. When inhaled, they affect the respiratory system and accumulate in internal organs. Table 3 presents various microplastic polymer types and their effects on human health and ecosystems, while Fig. 2 illustrates the exposure routes of microplastics in the human body, including ingestion, inhalation, and associated health risks. Ongoing research is crucial to fully understand the airborne transmission of microplastic particles and their long-term impact on human health.

## MICROPLASTIC-ADSORBED CHEMICAL POLLUTANTS: MECHANISM AND BIOMAGNIFICATION

Microplastics serve as carriers for a range of organic pollutants by adsorbing contaminants onto their surfaces through physical and chemical interactions [104]. This adsorption is influenced by the chemical properties of both the microplastics and pollutants, along with environmental factors. Hydrophobic microplastics such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are particularly effective at binding non-polar contaminants like pesticides, pharmaceuticals, and industrial chemicals through hydrophobic interactions. Van der Waals forces also contribute by stabilizing the accumulation of organic molecules on plastic surfaces. Pollutants with aromatic structures, such as polycyclic aromatic hydrocarbons (PAHs), can engage in π–π stacking interactions with electron-rich regions of microplastics, further enhancing adsorption. Additionally, electrostatic interactions may occur when oppositely charged surfaces attract, and polar compounds with functional groups (OH, NH, COOH) can form hydrogen bonds with microplastics. Surface characteristics such as roughness and overall surface area, play a critical role, as more textured microplastics provide additional binding sites for contaminants. Environmental conditions like pH, salinity, and the presence of dissolved substances can significantly alter the adsorption process. For example, low pH may increase the positive charge on microplastics, improving adsorption of negatively charged pollutants, while high pH may favor binding of positively charged compounds. Salts and natural organic matter can either compete for adsorption sites or modify the surface chemistry, enhancing or inhibiting pollutant uptake. Despite these insights, the full ecological consequences of microplastic-mediated pollutant transport remain insufficiently understood, emphasizing the need for further research.

Once ingested, microplastics can act as vectors for toxic substances, including heavy metals and persistent organic pollutants. These contaminants can bioaccumulate in organisms and biomagnify through food chains. For example, a predator consuming prey with contaminated microplastics may accumulate increasing levels of toxins over time. The extent of bioaccumulation depends on the toxicity of the substance, the organism's trophic level, and the size of the microplastic particles [107]. Although studies confirm microplastic bioaccumulation in marine organisms, conclusive evidence of biomagnification remains limited [108]. Nonetheless, health risks are apparent, ranging from tissue damage and oxidative stress to immune dysfunction and microbial infections from pathogens adhering to plastic surfaces [109]. In addition, microplastics often contain harmful additives such as plasticizers, flame retardants, and stabilizers. These compounds can leach into the environment and enter food webs. Biomagnification typically begins with primary producers like algae or crops, absorbing pollutants from contaminated water or soil. Herbivores that consume these producers accumulate toxins, which are amplified as they move up the food chain to predators, including humans. Many of these compounds are fat-soluble, allowing them to accumulate in fatty tissues and persist in organisms, posing long-term health risks [107]. Given the complexity of chemical interactions and trophic transfer, the mechanisms of microplastic-related biomagnification are still not fully understood. Emerging technologies, such as AI-based biomarkers, may enhance future research by identifying tissue-specific chemical impacts and improving strategies for environmental monitoring and health protection.

## ANALYTICAL APPROACHES FOR POLYMER IDENTIFICATION AND CHARACTERIZATION

**Physical characterization:** The physical characterization of microplastics is essential for determining attributes such as particle size, color, shape, morphology, and degree of degradation [9]. Common techniques include visual inspection [110], dynamic light scattering [111], and laser diffraction particle size analysis. Several comprehensive review articles have summarized analytical methods for microplastic detection, covering aspects such as sampling procedures, separation techniques, and measurement approaches in sediment matrices, while emphasizing the importance of robust quality assurance protocols [112]. These reviews also detail standard methods for detecting and quantifying microplastics [113], addressing challenges related to sampling, handling, identification, quantification, and quality control, and offering practical guidance to overcome existing methodological limitations [114]. Collectively, these resources serve as critical references for advancing the field of microplastic analysis." Visual analysis is a commonly used method for the physical characterization of microplastics [110]. This process involves observing pretreated samples with the naked eye or under a microscope, where microplastics are classified and counted based on color, shape, and size. The visual analysis method offers advantages such as simplicity, low cost, and minimal chemical hazard [115]. However, it has limitations, including the inability to determine the chemical composition of microplastics [116]. It is also time-consuming and labor-intensive, with accuracy and efficiency potentially affected by factors like environmental media, sample impurities, and subjective judgment [116]. For example, when microplastics are too small or samples contain other particles, visual analysis becomes ineffective [117]. Therefore, visual analysis is typically used as an auxiliary method, not as an independent analysis technique. It can be further categorized into naked-eye analysis and microscopic analysis.

**Laser diffraction particle size analysis:** Laser diffraction particle size analysis is a fast, reliable, and automated method used for analyzing soil and sediment particle size distribution. It provides detailed, high-resolution, and precise results while being essentially non-destructive, allowing for the recovery of critical samples, and can analyze particles ranging from 0.04 µm to 2000 µm [118]. However, impurities in environmental samples may interfere with results, and the technique requires the prior separation and extraction of microplastics. While not yet widely used for microplastic particle size distribution, it is expected to play an important role in microplastic detection as technology improves.

**Scanning electron microscopic characterization of microplastics**: Scanning electron microscopy (SEM), combined with energy-dispersive X-ray (EDX) analysis, is one of the key methods for analyzing the morphology of microplastics [119]. SEM provides high-resolution imaging of microplastic surfaces, while EDX is used to analyze the types and contents of elements at a micro-scale level [120] . This combination allows for simultaneous analysis of both the surface morphology and elemental composition of microplastics, making it a promising technique for detailed characterization [10]. Despite its advantages, scanning electron microscope-energy-dispersive X-ray (SEM-EDX) has some limitations. Since most microplastics are non-conductive, they require complex pretreatment, such as gold plating, before analysis [121]. Additionally, SEM-EDX cannot analyze the color of microplastics, and there are instances when it may fail to identify microplastics due to technical limitations [119]. Overall, the technique is costly, time-consuming, and inefficient for routine microplastic analysis.

**Fourier transform infrared spectroscopy in polymer identification and analysis**: Fourier transform infrared (FTIR) spectroscopy is a vibrational spectroscopy technique that provides information about the chemical bonds and functional groups of samples [9]. By analyzing changes in a material's dipole moment, FTIR produces infrared spectra that are compared with known polymer standard spectra to identify the chemical composition of microplastics [9]. FTIR operates in three modes: specular reflection, transmission, and attenuated total reflection. Specular reflection is often used for opaque or thicker materials but has limitations, such as weak signals and low accuracy [122]. Transmission mode offers higher quality results but requires specific sample conditions, such as thickness greater than 5 μm, and is best for transparent or light materials [48]. FTIR provides insights into a polymer's molecular structure, identifying monomer types, polymerization methods, and chain configuration. It can detect carbonyl groups or ester linkages in polyesters or polyurethanes and distinguish between crystalline and amorphous regions. FTIR also helps monitor polymer degradation from environmental factors or mechanical stress by identifying degradation by-products, such as carbonyl or hydroxyl groups, indicating the polymer's stability and lifespan.

**Raman spectroscopy in microplastic analysis:** When excited light irradiates a sample, molecules vibrate, producing scattered light at different frequencies, leading to Raman shifts [10]. Raman spectra, which serve as a fingerprint of the substance, result from changes in the polarizability of molecular bonds [123]. Raman spectroscopy, based on inelastic light scattering, complements Fourier transform infrared spectroscopy (FTIR) because some substances show mutually exclusive infrared and Raman activity. It offers several advantages: minimal sample damage, small sample size, high-throughput potential, and environmental friendliness. Raman spectroscopy also has high spatial resolution (1 μm), wider spectral coverage, and lower noise compared to FTIR [124]. It can identify microplastics as small as 500 nm, and does not require sample drying, being more responsive to non-polar groups. Raman spectroscopy can be used semi-quantitatively or quantitatively to estimate microplastic concentration in samples. By analyzing the intensity of specific Raman peaks linked to plastic components, researchers can estimate microplastic amounts in water, sediment, or biological samples. This technique is powerful and versatile, offering high specificity, minimal sample preparation, and the ability to analyze small quantities in complex environmental samples.

**Mass spectrometry analysis:** Mass spectrometry plays a vital role in microplastic analysis, offering detailed insights into polymer structure, molecular weight, degree of polymerization, and functional groups [125]. It is often used alongside other analytical methods to accurately identify microplastic polymer types. Common techniques include pyrolysis gas chromatography–mass spectrometry (Py-GC-MS) [126], thermal extraction desorption-GC-MS (TED-GC-MS) [127], and matrix-assisted laser desorption ionization-time of flight MS (MALDI-TOF-MS) [128]. Py-GC-MS and TED-GC-MS are particularly effective in identifying polymers by analyzing their thermal degradation products. In these methods, samples are heated in an oxygen-free environment, breaking down polymers into smaller compounds, which are then separated and identified using mass spectrometry [48]. However, these methods do not provide information on the physical characteristics of microplastics and may damage samples during analysis. Furthermore, different polymers can produce similar pyrolysis products, increasing the risk of misidentification [114]. One of the ongoing challenges in microplastic detection is the development of effective aptamers or fluorescent dyes for selective identification. If successful, these markers could be integrated with advanced tools like flow cytometry to rapidly detect specific microplastics in complex environmental samples. However, interference from impurities remains a potential source of error. Accurate detection and characterization of microplastics and associated chemical pollutants require advanced analytical techniques capable of simultaneously identifying, quantifying, and characterizing these particles in diverse environmental matrices [107]. The integration of AI technologies with high-resolution instrumentation could significantly improve the precision and efficiency of microplastic detection, paving the way for more reliable environmental monitoring systems.

**Advanced remediation techniques and mitigation strategies for microplastics**

Addressing microplastic contamination requires a multifaceted approach that combines prevention, mitigation, and remediation efforts. Public awareness is crucial in reducing waste, promoting responsible consumption, and encouraging sustainable alternatives [26]. International cooperation is also key to establishing global standards for microplastic management, facilitating knowledge sharing, and advancing technological solutions. Filtration devices and enzymatic degradation have shown promise in effectively removing microplastics from aquatic ecosystems. Moreover, the adoption of sustainable materials, such as biodegradable plastics, can help reduce future plastic pollution [129]. A proactive approach is essential for protection marine ecosystems and preventing irreversible damage. Nanotechnology offers an innovative solution for combating microplastic contamination. Nanoparticles, nanotubes, and nanofibers, with their high surface area-to-volume ratios and enhanced reactivity, enable efficient microplastic adsorption, catalysis, and filtration [130]. Nano-enabled adsorption methods can effectively remove microplastics from air, water, and soil by selectively binding to microplastic particles and improving surface interactions. Additionally, filtration systems enhanced with nanoparticles increase the efficiency of microplastic capture.

Advanced oxidation processes (AOPs), including ozone treatment, Fenton's reagent, and photocatalytic oxidation, are effective for degrading microplastics in wastewater. These techniques utilize strong oxidants and light-activated catalysts to break down plastics into less harmful substances. However, further research is required to optimize these processes and assess their environmental impacts. Photocatalytic methods, such as those using titanium dioxide ($TiO_2$) activated by UV light, generate reactive oxygen species that degrade plastics efficiently at mild temperatures. Despite the promising potential of these methods, challenges remain, including optimizing catalyst efficiency, ensuring complete degradation, and understanding broader environmental impacts. Scaling up these technologies for practical use remains an important area of future research. Bioremediation, which involves using living organisms like bacteria, fungi, and plants, offers an eco-friendly approach to degrade plastics into less harmful substances. Certain bacteria and fungi produce enzymes capable of breaking down plastics such as polyethylene and polystyrene, while plants can absorb microplastics through their roots. This approach reduces reliance on harsh chemicals and energy-intensive processes. However, slow degradation rates and the influence of environmental conditions need to be addressed. Ongoing research is essential to optimize these systems for practical applications [131]. Bacterial remediation, involving bacteria that produce enzymes like PETase, targets microplastics such as PET and polystyrene, breaking them down into less harmful substances. While this eco-friendly approach is promising, challenges remain in optimizing growth conditions, accelerating degradation rates, and scaling the process for various environments. Further research is needed to enhance the efficiency and applicability of bacterial remediation [132]. Mitigation strategies in waste management are crucial to reducing the entry of plastics into the environment and minimizing their breakdown into harmful microplastics. Effective strategies include enhancing recycling systems to ensure proper processing and reuse of plastics, promoting biodegradable alternatives, and reducing plastic production through sustainable packaging practices. Public education campaigns are essential for raising awareness about proper disposal methods and minimizing single-use plastics. By integrating these strategies, communities can significantly reduce plastic waste generation, foster a circular economy, and empower individuals to take action against microplastic pollution [131]. Although some regions have begun regulating plastic waste, significant gaps remain in global policies and regulations regarding microplastics. More comprehensive, internationally coordinated efforts are needed to address the environmental risks posed by microplastics and their pollutants. A unified global strategy would strengthen regulatory enforcement, enhance cooperation among nations, and support the development of innovative solutions to combat microplastic pollution on a global scale. Microplastic pollution management strategies, including both the most and least favored approaches, are outlined in Fig. 3. Additionally, Table 5 presents comprehensive strategies that combine technical solutions and awareness-based initiatives to address microplastic pollution effectively. Public awareness plays a vital role in addressing plastic pollution by educating communities on waste reduction, sustainable consumption, and the adoption of alternatives to plastics [133, 134]. Effective waste management and recycling strategies such as enhancing recycling infrastructure, encouraging the use of biodegradable packaging, and reducing single-use plastics, are critical for mitigating plastic pollution [135]. Developing global standards and addressing gaps in international microplastic regulation are essential for effective policy and environmental governance [136]. Adopting biodegradable plastics and other eco-friendly materials is necessary for reducing microplastic pollution and promoting sustainable development [137]. Installing filters in wastewater treatment and stormwater systems is crucial for capturing microplastics and preventing their release into the environment [136]. Public campaigns are key for informing communities about proper disposal methods and raising awareness about the impacts of microplastics on the environment and human health. Nanotechnology, including the use of nanoparticles, nanotubes, and nanofibers, offers innovative solutions for the adsorption, catalysis, and filtration of microplastics from air, water, and soil [93]. Advanced oxidation processes (AOPs), such as ozone treatment, Fenton's reagent, and $TiO_2$-based photocatalysis, are effective techniques for breaking down plastics into less harmful substances [10]. Bioremediation, utilizing bacteria, fungi, and plants along with enzymes like PETase, offers a promising approach to degrade microplastics [138]. Enzymatic degradation involves the targeted breakdown of plastics such as polyethylene and PET using specific enzymes [136]. Global standards and collaboration focus on sharing technology, data, and expertise between countries to collectively address and mitigate microplastic contamination [137]. Research and development efforts aim to scale remediation technologies, optimize catalysts and microbes, and assess the environmental impacts of microplastic contamination [136]. A circular economy integrates sustainability across product lifecycles, from design to disposal, reducing plastic production and encouraging reuse [26]. Advanced remediation techniques and mitigation strategies for microplastics are essential for combating microplastic pollution in the environment.

Table 5: Comprehensive strategies for addressing microplastic pollution through technical and awareness-based approaches

| Category | Approach | Application | References |
|---|---|---|---|
| **Prevention** | Public awareness | Educating the public on waste reduction, sustainable consumption, and alternatives to plastics. | [26] |
| | Waste management and recycling | Improving recycling infrastructure, promoting biodegradable packaging, and reducing single-use plastics. | [67] |
| | Policy and regulation | Developing global standards and closing gaps in international microplastic regulation. | [10] |
| **Mitigation** | Sustainable materials | Adopting biodegradable plastics and other eco-friendly materials. | [128] |
| | Filtration devices | Installing filters in wastewater treatment and stormwater systems to capture microplastics. | [26] |
| | Public campaigns | Informing communities about proper disposal methods and impacts of microplastics. | [68] |
| **Remediation** | Nanotechnology | Using nanoparticles, nanotubes, and nanofibers for adsorption, catalysis, and filtration of microplastics from air, water, and soil. | [129] |
| | Advanced oxidation processes (AOPs) | Techniques like ozone treatment, Fenton's reagent, and $TiO_2$-based photocatalysis to break down plastics into less harmful substances. | [130] |
| | Bioremediation | Utilizing bacteria, fungi, and plants to degrade microplastics using enzymes like PETase. | [123] |
| | Enzymatic degradation | Targeted enzymatic breakdown of plastics like polyethylene and PET. | [129] |
| **International Cooperation** | Global standards and collaboration | Sharing technology, data, and expertise between countries to tackle microplastic contamination collectively. | [10] |
| **Future Focus** | Research and development | Scaling remediation technologies, optimizing catalysts and microbes, and assessing environmental impacts. | [90] |
| | Circular economy | Integrating sustainability across product lifecycles, from design to disposal, reducing plastic production and encouraging reuse. | [67] |

 

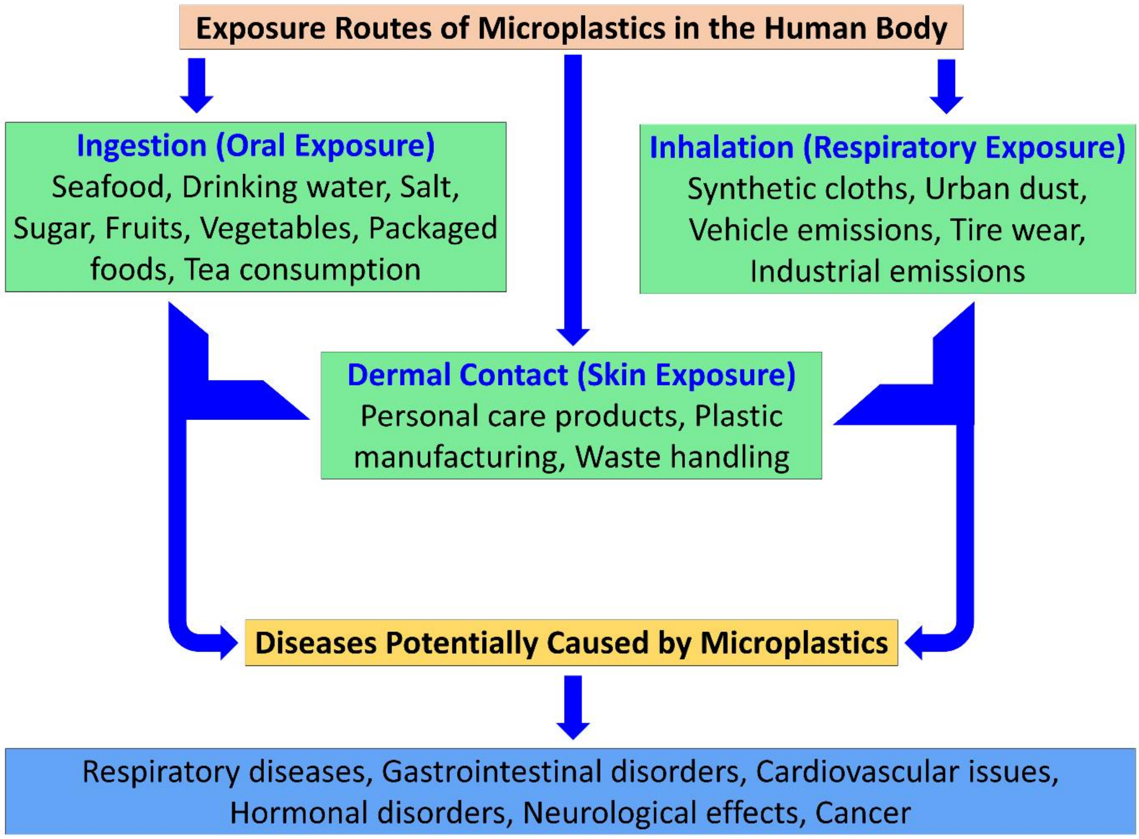


Fig. 2. Exposure routes of microplastics in the human body: ingestion, inhalation, and potential health risks

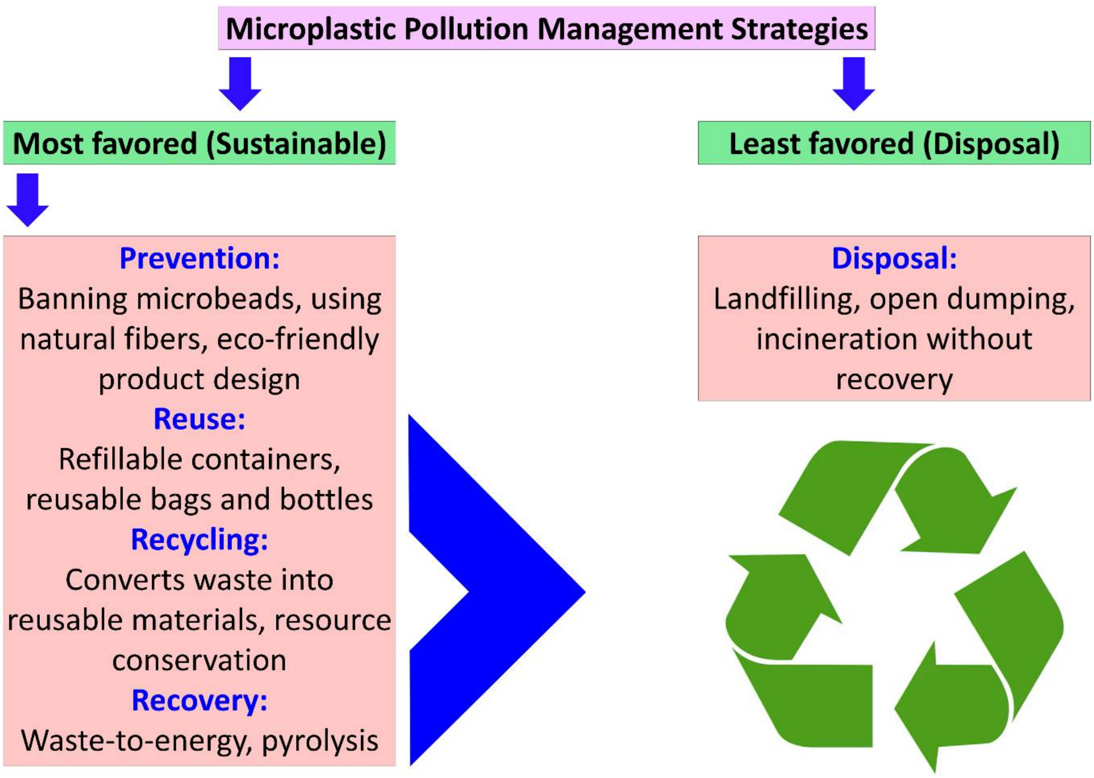


Fig. 3. Microplastic pollution management strategies: most and least favoured approaches

 

**Authors' Contribution**
**Dusmant Maharana** contributed to data curation, graphical representation, and validation and played a key role in both the original drafting and manuscript review and editing. Shaktidhar Nahak contributed to the drafting of the manuscript, its subsequent review and editing, and also supported the funding requirements. Prashantkumar Sathvara was responsible for data curation, graphics, and drafting the manuscript. Pratyush Das supplied essential resource materials for data compilation. Shreya Pandey provided resources and actively participated in the editing process. Dinesh Kumar Naik provided resources and contributed to the editing process.

**Consent to Participate**
We hereby declare that we have read and understood the information provided above and give our consent to participate in the study. All participants were thoroughly informed about the nature and purpose of the research. Participation was entirely voluntary, and participants had the right to withdraw at any time without any consequences.

**Consent to Publish**
We hereby provide our consent for the publication of the research findings presented in this study. We affirm that the work is original, has not been published elsewhere, and is not under consideration by any other publication. We acknowledge that our participation in this study, along with any data provided, will be used exclusively for the purposes of this publication, with appropriate anonymization applied where necessary.

**Competing Interests**
All authors of this research declare that they have no competing interests related to the study presented. There are no financial or non-financial conflicts of interest that could have influenced the results or interpretation of this work.

**Data Availability Statement**
All data supporting the findings of this study are included within the main text of the manuscript. Additional supporting data are available from the corresponding author upon reasonable request.

**CONCLUSION**
Microplastic pollution has escalated into a pervasive and urgent environmental challenge, affecting both aquatic and terrestrial habitats worldwide. Tackling this complex issue requires swift, coordinated, and multidisciplinary actions at global and local levels. This review synthesizes current knowledge by examining the origins, environmental distribution, transport mechanisms, toxicological impacts, detection methods, and mitigation approaches for microplastics. By integrating these diverse facets, it offers a comprehensive perspective while drawing attention to existing gaps in research. Despite significant advancements, several critical obstacles persist. Foremost among these is the absence of universally accepted, scalable protocols for sampling and analysis, which limits the consistency and comparability of data across different studies and geographic regions. Moreover, the variable physical and chemical properties of microplastics including their size, shape, polymer type, and the presence of associated contaminants complicate accurate toxicological assessment. These challenges hinder the establishment of reliable global baselines and the development of effective intervention strategies. To address these issues, an integrated and forward-thinking strategy is crucial, one that merges scientific innovation with robust policy frameworks, public education, and community engagement. Key recommendations include the standardization of analytical methods to enhance data reliability and comparability; the advancement of detection technologies, such as AI-driven and high-throughput systems, to improve identification accuracy and efficiency; and the implementation of regulatory measures to curtail plastic production and consumption alongside the promotion of sustainable alternatives. Additionally, fostering circular economy practices can significantly reduce plastic leakage into ecosystems, while improving waste management infrastructures, particularly in resource-limited regions, will further aid pollution control. Importantly, elevating public awareness is essential to inspire behavioral changes and empower communities to participate actively in mitigation efforts. Looking ahead, research priorities should emphasize large-scale, longitudinal studies that monitor temporal and spatial trends while elucidating the long-term ecological and human health consequences of microplastic exposure. The deployment of advanced data analytics, including machine learning and remote sensing technologies, holds considerable promise for enhancing source tracking and risk evaluation. Ultimately,

 

interdisciplinary collaboration uniting expertise from environmental sciences, public health, engineering, and social sciences will be vital to designing practical and scalable solutions. In conclusion, overcoming the multifaceted challenge of microplastic pollution demands not only scientific excellence but also a unified global commitment. Developing and implementing a strategic, evidence-based roadmap is imperative to mitigate current impacts and safeguard the future resilience of both ecosystems and human populations.


**ACKNOWLEDGMENTS**

We would like to express our sincere gratitude to the School of Sciences, P P Savani University, Gujarat, India, for providing the academic resources and infrastructure that facilitated the completion of this review paper. We are also deeply appreciative of our mentors, colleagues, and reviewers for their invaluable guidance, constructive feedback, and insightful suggestions, all of which greatly contributed to improving the quality of this manuscript. Additionally, we extend our thanks to the researchers whose work we have referenced, as their contributions served as the foundation for this review.


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