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Review
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MICROPLASTICS: AN OVERVIEW OF SOURCES, DISTRIBUTION, AND REMOVAL METHODS

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Abstract: Microplastics (MPs), defined as plastic particles smaller than 5 mm, are persistent pollutants increasingly detected in both aquatic and terrestrial ecosystems due to widespread anthropogenic activity. Their small size and non-biodegradable nature allow them to accumulate and exert complex effects on biotic systems not only through physical presence but also by transporting harmful substances such as endocrine-disrupting chemicals and heavy metals. This review identifies primary and secondary sources of MPs, outlines their environmental distribution pathways, and evaluates their behavior in different ecosystems. Furthermore, it critically examines current microplastic removal technologies, highlighting limitations in spectroscopic and microscopic detection methods and comparing the effectiveness of traditional treatment systems with advanced approaches such as membrane filtration and nanomaterials. The study concludes with targeted recommendations for improving removal efficiency and monitoring strategies, emphasizing the need for interdisciplinary collaboration and policy support to address microplastic pollution sustainably.

Keywords: Aquatic and terrestrial ecosystems, Environmental distribution, Microplastics, Plastic pollution

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1. Introduction

Although the rise in plastic production since the Industrial Revolution has often symbolized economic progress, the resulting unsustainable waste generation has become a major contributor to global environmental imbalances. Since the 19th century, plastics have been widely adopted due to their diverse functional characteristics, including mechanical strength, thermal resistance, and sound insulation (Kolluru and Raja; 2025). This lightweight and durable material is used in a wide range of products—including clothing fibers, medical equipment, and paints—to help preserve the freshness of food. Microplastics, particularly those that break down into microscopic particles, are concerning not only due to their small size but also because of their role as chemical carriers and their potential for biological accumulation (Razaviarani et al., 2024; Lin et al., 2025).

Global plastic production has now surpassed 359 million metric tons annually (Pilapitiya and Ratnayake, 2024). Nevertheless, inadequate plastic waste management and insufficient infrastructure for its reduction, reuse, or recycling have turned plastic pollution into a critical environmental issue worldwide (MacLeod et al., 2021). If current production trends continue, it is estimated that human-generated plastic waste will amount to nearly 26 billion metric tons by the year 2050 (Sharma et al., 2020). Insoluble plastic particles measuring between 1 µm and 1000 µm are categorized as microplastics, while those between 1 mm and 5 mm are typically identified as large microplastics (ISO, 2023; Lu et al., 2025). These particles appear in various physical forms—such as fragments, fibers, films, and spheres (Xu et al., 2020)—and are widespread across ecosystems, from oceanic currents to farmland soils. In terrestrial settings, microplastics have been shown to impact soil properties, including structure, porosity, water retention capacity, and nutrient cycling (Dissanayake et al., 2022; Wang et al., 2022). Additionally, they can serve as carriers for chemical additives, heavy metals, antibiotics, and microbial pathogens, thereby expanding the range of contamination and heightening ecological threats (Wang et al., 2020; Noornama et al., 2024).

In scientific references, the term "microplastic" was first coined by Thompson and is defined as synthetic particles, mostly <5 mm in size (Palansooriya et al., 2020). Microplastics are found everywhere in the environment (Bourzac, 2022). They are categorized based on their morphology, size, density, and different polymer properties. Based on their size, plastics are classified as macroplastics (>25 mm), mesoplastics (5-25 mm), and microplastics (1 µm-5 mm).

Microplastics are very persistent and have a slow degradation process (Andrady, 2011). The small size and larger surface area of microplastics increase their ability to adsorb heavy metals, metalloids, polycyclic aromatic hydrocarbons, pharmaceuticals, and different dyes (Bourzac, 2022). The uncontrolled release of high concentrations of plastics continually pollutes the environment and causes adverse effects on human health, animal health, the natural environment, and ecosystems. Potential human impacts include obesity, asthma, respiratory irritation, cardiovascular disease, and cancer (Malankowska et al., 2021). Therefore, removing microplastics from natural environments is considered a priority for environmental and public health (Wang et al., 2019).

Microplastics enter both aquatic and terrestrial ecosystems through various pathways, including wastewater discharge, surface runoff, river runoff, and atmospheric transport (Hasan Anik et al., 2021; UNEP, 2021; Kalipci et al., 2024). They have been detected in nearly all environmental compartments, including shorelines, surface waters, the water column, sediments, soil, air, ice, and biota (Hasan Anik et al., 2021; UNEP, 2021;). The complexity and scale of microplastic pollution pose significant challenges to global management efforts due to gaps in understanding their distribution, behavior, and impacts in different environments. Furthermore, inconsistencies in classification and the lack of standard analysis methods create significant uncertainties in monitoring and risk assessment processes (UNEP, 2021).

Because there is no obligation to remove microplastics from receiving environments, it is not possible to achieve any limit values in national and international legislation. Therefore, wastewater treatment plants are not designed with microplastic removal in mind. However, findings in the literature indicate that most advanced treatment methods provide high efficiency in microplastic removal. Advanced treatment technologies such as membranes, rapid sand filtration, dissolved air flotation, and disk filters have been shown to yield successful microplastic removal results in wastewater treatment plants. It has also been reported that the effectiveness of microplastic removal can be increased in biological granular activated carbon filter treatment systems by adding electrocoagulation, biological active filters, powdered activated carbon ultrafiltration, and ultrafiltration to conventional treatment systems (Talvitie et al., 2017).

In the current scientific literature, studies on the formation mechanisms, environmental behavior, and biological impacts of microplastics are increasing; however, most of these studies are limited to local sampling and are insufficient to reach generally accepted conclusions. Furthermore, interactive modeling of the meteorological, geochemical, and biotic interactions that influence the environmental behavior of microplastics is still in its early stages. In this context, in developing strategies to prevent and control microplastic pollution, holistic models that include not only engineering-based approaches but also socio-political contexts are needed.

This study critically evaluates the sources, dispersal pathways, and removal strategies of microplastics, particularly the application limits and potential development areas of advanced treatment technologies. The aim is not only to describe the current situation but also to provide conceptual frameworks that will pave the way for new research areas.

2. Sources of Microplastics

To understand the spread of microplastics in the environment, it is necessary to thoroughly analyze the sources of their production and release. Microplastic sources are generally classified into two main groups: primary and secondary. This distinction is not only a matter of definitional convenience but also a critical parameter in determining control strategies.

Primary microplastics are microscopic plastic particles produced directly during industrial processes and widely used in areas such as cosmetics, cleaning products, paint, textiles, and pharmaceuticals. These microplastics are intentionally included in commercial products and are often transported directly into aquatic environments through sewage systems. This, combined with the inability of wastewater treatment systems to capture particles of this size, poses a serious environmental risk (Duis and Coors 2016; Ahmad et al., 2022; Shaji et al., 2025).

Secondary microplastics, on the other hand, are formed when large plastic materials transform into micro-sized materials over time as a result of physical, chemical, and biological decomposition processes. This process accelerates with the interaction of environmental factors such as UV radiation, temperature fluctuations, mechanical abrasion, and microbial degradation. This process promotes fragmentation by causing changes in the surface morphology of plastics, such as fracture, cracking, and bifurcation (Andrady, 2017; Hidayaturrahmab and Lee, 2019).

Figure 1 shows the classification of microplastics into primary and secondary categories based on their origin. When evaluated by polymer type, common plastic types such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), and polyethylene terephthalate (PET) are seen as the dominant components in microplastic pollution (Enfrin et al., 2019). The specific gravity, surface hydrophobicity, additives, and chemical stability of these materials directly affect their behavior in environmental environments. For example, while low-density polymers can float on the water surface for a longer time, those with higher densities quickly pass into the sediment layer (Patidar et al., 2024; Kılıç et al., 2025).

Another important source is the textile industry. Recent research provides experimental evidence of the textile industry's role in microplastic pollution, showing that hundreds of thousands of microfibers can be released in a single wash cycle (Lin et al., 2025). In light of all these findings, the management of microplastic resources is not limited to waste reduction alone, but necessitates systemic interventions such as redesigning production processes, conducting product life cycle analyses, and tightening regulations.

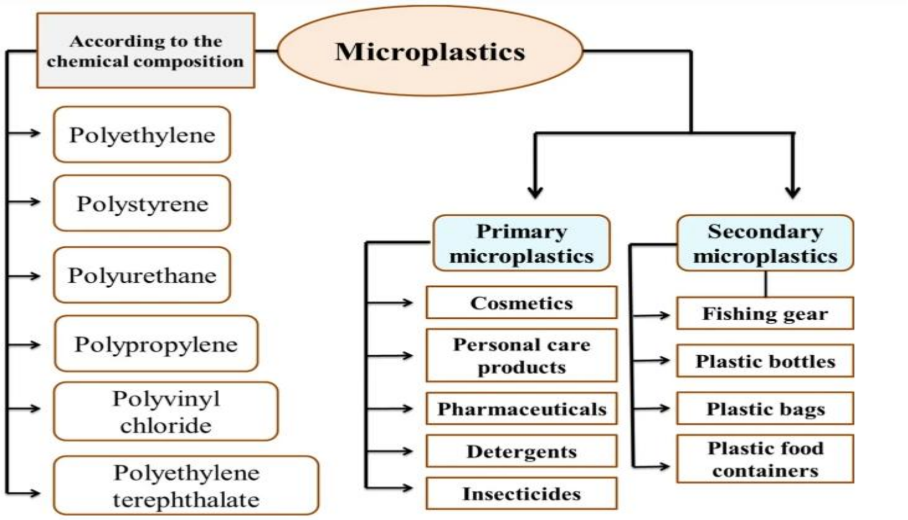

Figure 1. Classification of microplastics according to their sources and chemical components (Andrady, 2017).

3. Dispersion Mechanism of Microplastics

The behavior of microplastics in the environment is not limited to their physical mobility; it is determined by the interaction of chemical, biological, and atmospheric factors. In this context, understanding the dispersal mechanisms of microplastics is critical not only for the distribution of the pollutant but also for toxicological risk assessments, ecosystem modeling, and policy development.

3.1. Water and Sediment Environment

The interaction between water column dynamics and sediment matrices plays a pivotal role in the fate of microplastics. In natural systems, suspended sediments significantly enhance the downward transport and settlement of microplastics, with higher sediment loads increasing the scavenging of microplastic particles toward the bed (Mancini et al., 2023). Turbulent shear conditions further promote heterogeneous aggregation of microplastics with sediment particles, accelerating settlement compared to sediment-free environments; these aggregates may also be subject to resuspension under strong shear flows, potentially leading to secondary contamination events (Li et al., 2022) PubMed. In marine settings, sedimentary processes such as gravity-driven deposits reworked by persistent bottom currents form extensive drift deposits that act as long-term sinks for microplastics—particularly fibers—which can become entrained within these strata and preserved in the sedimentary record. Additionally, microplastics influence ecosystem engineers like tubificid worms, reducing their bioturbation activity and impairing nutrient fluxes at the sediment–water interface (Wazne et al., 2023)

The mobilization of microplastics in aquatic environments varies depending on current regimes, water density, temperature gradients, and particle specific gravity. The tendency of low-density polymers to remain suspended at the surface brings them into more frequent contact with planktonic organisms, while denser materials tend to settle in benthic zones. This sedimentation process is influenced by microenvironmental factors such as sediment structure, organic matter content, and the presence of microbial biofilms (Kopatz et al., 2023; Patidar et al., 2024).

Molecular interactions such as hydrogen bonds, Van der Waals interactions, and electrostatic attraction can facilitate the aggregation of microplastics with particulate matter and biopolymers in the environment. This increases the likelihood of microplastics undergoing chemical transformation processes, altering their reactive surface area and carrying capacity (Leiser et al, 2020; Zhang et al., 2022).

Furthermore, the potential for microplastics to be transported across trophic levels through biocondensation could have novel systemic effects on the structuring of food chains. Such transport has implications not only at the ecological but also at the socioeconomic level, potentially increasing public health risks, particularly in societies with high seafood consumption (Rao et al., 2020; Mutlu et al., 2025).

Aquatic plants and organisms are also important biological factors affecting the movement and distribution of microplastics in the environment. Aquatic plants can limit the free movement of microplastics by adsorbing them on their surfaces, which can contribute to maintaining water quality. Aquatic organisms such as fish, crustaceans, and plankton can ingest microplastics or absorb them through their skin, integrating them into the food chain (Hossain and Olden, 2022).

Furthermore, microorganisms attach to the surface of microplastics and form biofilms, affecting both the distribution of microplastics in the aquatic environment and their degradation processes. Aerobic microorganisms can alter the dispersal mechanism by breaking down microplastics into smaller particles (Ifeanyi et al., 2025).

3.2 Land Environment

As a balancing element between air and water, soil plays a crucial role in regulating the vital carbon, oxygen, and water cycles in the atmosphere and biosphere. Therefore, it is necessary to evaluate the mechanisms of microplastic dispersion in soil and to thoroughly understand the effects of microplastics on soil. Microplastics that become incorporated into the soil in any way can be transported vertically and horizontally through the soil.

Agricultural activities such as harvesting and plowing, the porous structure and cracks on the soil surface, the extended plant roots, and the use of earthworms in their digestion processes all contribute to the transport of microplastics deep into the soil (Gabet et al., 2003).

Considering urban and rural living spaces and the activities in these areas, fragments from vehicle tires, waste from industrial activities, and the use of many products containing plastic can contaminate soil with microplastics (Fuller and Gautam, 2016).

Agricultural activities can undergo both horizontal and vertical transport due to earthworm movement, root development, and soil porosity. However, the mechanisms of this transport are still not fully understood (Gabet et al., 2003). The use of wastewater treatment sludge as fertilizer and plastic materials used in agriculture, such as greenhouse covers and water pipes, cause soil pollution (Gündoğdu et al., 2018).

Soil erosion is also a contributing factor in the transport of microplastics. Microplastics, particularly those transported from erosion-prone areas to aquatic ecosystems, are a significant source of pollution (Rehm et al., 2021). The mechanism of microplastic transport through runoff and soil erosion involves gaps. Microplastic transport is generally said to originate from canal beds and lake shores. However, the vast majority of studies have focused on large basins, and the sources are generally urban areas (Kiss et al., 2021; Rodrigues et al., 2018).

3.3. Atmospheric Dispersion

Microplastics can be resuspended from land surfaces into the atmosphere and travel long distances on wind. These particles can be directly inhaled by humans and other living organisms (Evangeliou et al., 2020).

The concentration, transport, and accumulation of microplastics in the atmosphere vary depending on meteorological conditions. Microplastic concentrations are higher in indoor areas, particularly due to lower air renewal rates (Chen et al., 2020; Dong et al., 2021).).

Microplastics can serve as nuclei in atmospheric cloud formation and contribute to climate change (Ganguly and Ariya, 2019). This suggests that microplastics in the atmosphere pose not only an environmental but also a climatic threat.

Sources of atmospheric microplastics are typically traffic emissions in urban areas, construction activities, open-air garbage burning, and textile abrasion. The respirable fractions of these particles (below PM2.5) are particularly important for human health (Shruti et al., 2022); Because they have the potential to reach alveoli directly through the respiratory tract, this poses a health risk that could have long-term effects on the cardiopulmonary system.

Meteorological factors (precipitation, drought, wind, sunlight) are decisive in the environmental spread of microplastics (Figure 2).

- Precipitation: Increases surface runoff, transporting terrestrial microplastics to aquatic environments.
- Drought: Increases particle concentration by reducing water volume (Haijiouni et al., 2022; Khalid et al., 2021).
- Wind: Can carry lightweight plastics long distances in the atmosphere.
- UV rays: Cause microplastics to break down into nanoplastics (Andrady et al., 2011).

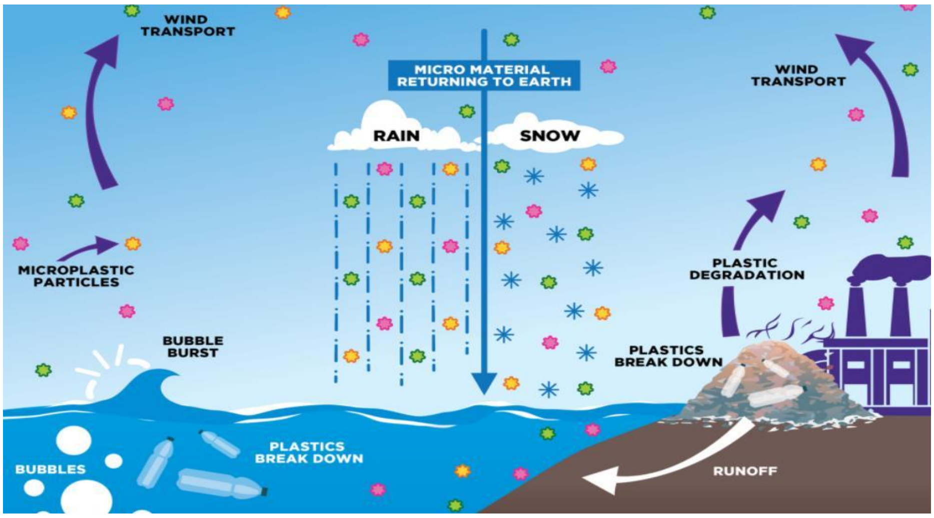

Figure 2. Dispersion of microplastics in the atmosphere (URL-1).

Rainfall facilitates the transport of microplastics from terrestrial to aquatic environments. Furthermore, microplastics suspended in the atmosphere reach water bodies with rainwater. The duration and intensity of rainfall directly affect the amount of microplastics in the aquatic environment. Hydrodynamic conditions influence the horizontal migration of microplastics, directing their deposition processes. For example, strong currents reduce deposition, while calm waters can cause microplastics to be trapped in sediments. It has been reported that microplastic density is high at the beginning of a rainfall and decreases as the rainfall progresses (Rao et al., 2020).

Drought has the opposite effect of rainfall, leading to increased microplastic concentrations. A positive correlation has been reported between the length of dry periods and the concentration of microplastics in water. Exposure to sunlight is another factor affecting dispersal. Ultraviolet (UV) rays can alter the surface morphology and chemical structure of microplastics, causing them to decompose into smaller nanoplastics (Andrady et al., 2011).

Wind, especially during stormy conditions, can be effective in transporting microplastics to aquatic environments. When wind speeds decrease, microplastics are likely to settle into deeper layers. While low-density microplastics can be carried farther distances by wind, high-density microplastics tend to accumulate more locally (Liu et al., 2022).

4. Ecological and Health Impacts of Microplastics

The impacts of microplastics on ecosystem components are assessed not only at the level of physical obstruction or chemical contamination, but also through systemic dynamics that threaten ecological integrity. These impacts involve multilayered and interactive processes, from the organismal level to the biosphere.

4.1. Impacts on Ecological Systems

The effects of microplastics on environmental biota vary depending on trophic level-specific sensitivities and organismal life strategies. Laboratory and field-based studies in diverse taxonomic groups, such as zooplankton, benthic invertebrates, fish, and birds, indicate that microplastic ingestion can cause numerous physiological effects, such as digestive tract obstructions, reduced energy budgets, growth retardation, and behavioral disruptions (Wright et al., 2013).

At the ecosystem level, microplastics have the potential to alter habitat structure, reduce the permeability of benthic substrates, and disrupt trophic network relationships. This reduces ecological resilience and increases the system's vulnerability to external stressors. Furthermore, microplastics interact with other persistent organic pollutants (POPs) in the environment, acting as vectors, enabling the transport of contaminants to distant ecosystems (Mercogliano et al., 2020).

Due to their surface properties that promote biofilm formation, microplastics can restructure microbial diversity and lead to ecological niche occupation. This poses significant risks to public health, particularly in terms of the transmission and spread of pathogenic microorganisms in aquatic environments (Yan et al., 2024; Wu et al., 2024).

4.2. Effects on Human Health

4.2.1. Possible effects of microplastics on human health

While scientific data on the effects of microplastics on human health is still limited, recent studies have documented the entry of these particles into the human body through oral, dermal, and inhalation routes.

- Microplastics, which enter the human body through a variety of exposure routes, including drinking water, seafood, salt, air, and even breast milk, are thought to have the potential to migrate from the gastrointestinal tract to epithelial cells and enter the systemic circulation (Schwabl et al., 2019).
- Among the additives carried by these particles are chemicals with endocrine-disrupting and neurotoxic effects, such as phthalates, bisphenol A, brominated flame retardants, and heavy metals. Numerous in vitro and in vivo studies have shown that these substances cause oxidative stress by increasing reactive oxygen species at the cellular level, can lead to mitochondrial dysfunction, and can trigger genetic damage (Smith et al., 2018; Akbulut et al., 2025).
- Microplastics with a respirable fraction (PM2.5 and below) can trigger inflammatory processes in the pulmonary epithelium, increase fibrotic responses, and exacerbate chronic respiratory diseases such as asthma. Furthermore, microbial biofilms carried by microplastics are a mechanism that should be considered for pathogen transfer to the respiratory tract (Agull et al., 2021; Eberhard et al., 2024).

4.2.2. Some studies and findings

Figure 3 schematically illustrates the routes of human exposure to MPs and their potential harms. There are no clear results on whether microplastics inhaled by living organisms can enter the bloodstream, their effects on various lung diseases, or the tissue damage caused by microparticles (Amato-Lourenço et al., 2020).

In a study conducted on patients with malignant lung masses, 97% of the samples contained microfibers (Pauly et al., 1998). It is known that microplastics tend to accumulate in the alveoli and bronchi. The human body has defense mechanisms to prevent microplastic accumulation, including sneezing, phagocytosis, and the lymphatic system. However, these mechanisms cannot exclude conditions such as dust overload, cytotoxicity, and oxidative stress (Prata, 2017).

There are studies indicating that microplastics have been detected in the circulatory systems and tissues of some organisms, in addition to the digestive system. Studies on the placentas of women undergoing healthy pregnancies have shown the presence of microplastics (Ragusa et al.; 2021; Huang, 2022).

Microplastics, which are suggested to have suppressive effects on the human immune system, are assumed to have more serious effects, particularly in individuals with immunological compromise (e.g., children, the elderly, and chronically ill patients). However, supporting these hypotheses with robust epidemiological data should be a priority for future science. Given this data, multidisciplinary research, long-term monitoring studies, and molecular biomarker-based analyses are needed to comprehensively assess the health impacts of microplastics.

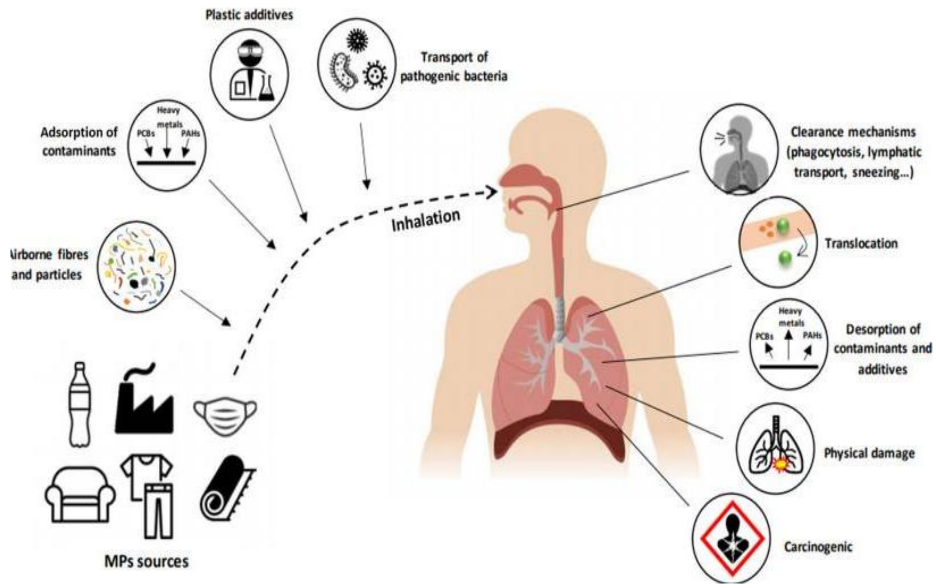

Figure 3. Human exposure pathways to microplastics and potential harms (Agullo et al., 2021).

5. Microplastic Removal Methods

Effectively removing microplastics from the environment is critical for reducing the negative impacts of these pollutants on the ecosystem and human health. Conventional and advanced treatment methods are used for this purpose. Removal efficiency varies depending on the type of method used, the size and density of the microplastics, and the characteristics of the environment.

5.1. Wastewater Treatment Technologies

Wastewater treatment plants (WWTPs) are one of the most significant sources of microplastics for aquatic and terrestrial environments (Alvim et al., 2020). Microplastics arriving at plants from primary and secondary sources accumulate in primary and secondary treatment sludge (Masia et al., 2020).

Figure 4 shows the MP sources entering WWTPs. Wastewater treatment plants consist of primary, secondary, and tertiary treatment processes, which are advanced treatment processes. Because these processes are not designed for microplastic removal, no specific microplastic removal process is implemented (Enfrin et al., 2019). Many factors, such as urban and industrial activities in the region, the economic status and lifestyle of the population, population density, facility type, and meteorological conditions, influence the amount of microplastics entering wastewater treatment plants (Okoffo et al., 2019).

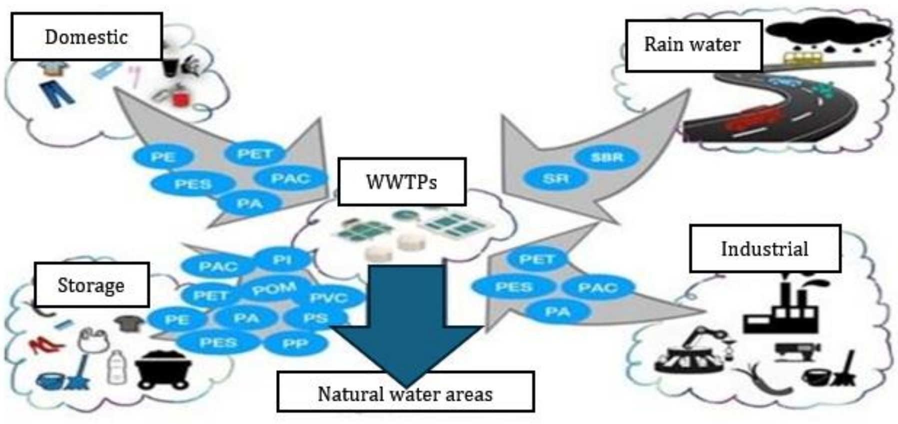

Figure 4. MP sources coming to WWTPs (Ngo et al., 2019).

It is known that microplastic removal in conventional systems, combined with primary and secondary treatment, yields efficient results (Carr et al., 2016; Talvitie et al., 2017). While conventional systems provide good results in removing microplastics from treatment plants, it is considered possible that daily microplastic discharges are high because these plants operate at high flow rates (Mason et al., 2016; Lee and Kim, 2018; Liu et al., 2021).

Furthermore, it has been determined that a conventional membrane system can efficiently remove some microplastics from wastewater. Membrane technologies, one of the most widely used microplastic removal methods, demonstrate their suitability for microplastic treatment by enabling the removal of highly resistant pollutants found in a wide variety of complex industrial wastewaters (Gurung et al., 2016).

5.1.1. Physical methods

These methods are aimed at removing microplastics directly through physical processes.

- Filtration and Membrane Technologies:
  - Classical membrane systems can effectively remove some microplastics (Gurung et al., 2016).
  - Nanofiltration (NF) is a promising method for removing small particles between 1 nm and 1 μm in size. It can also separate microplastics and the contaminants adsorbed on them based on electrical charge differences (Enyoh et al., 2025).
  - NF also stands out with its low energy consumption and compact system advantages.
- Sedimentation:
  - It is possible to remove microplastics by sedimentation along with heavy metal salts (Lee et al., 2012; Shirasaki et al., 2016).
- Filtration-Sorption Combinations:
  - These systems provide high efficiency when used in conjunction with biological and chemical processes (Liu et al., 2021).

5.1.2. Chemical methods

Chemical methods allow microplastics to react with other substances to form larger structures or to settle.

- Coagulation and Agglomeration (Coagulation-Flocculation):
  - Fe and Al-based salts are used to convert small microplastics into larger, settleable particles.
  - This allows microplastics to be physically separated.
- Electrocoagulation:
  - This is an energy-efficient, low-sludge, and automation-friendly method applied in stirred-batch reactors. It is effective in removing microplastics such as polyethylene (Perren et al., 2018).

5.1.3. Biological methods

These are treatment systems that use microorganisms. Although microplastics are not directly biodegraded, they can be retained in biological processes.

- Activated Sludge Systems:
  - These systems, used in conventional treatment plants, can retain a significant portion of microplastics (Carr et al., 2016; Talvitie et al., 2017).
- Membrane Bioreactors (MBRs):
  - They combine activated sludge systems with membrane technology.
  - They offer higher efficiency in removing microplastics than traditional biological systems (Liu et al., 2021).

Table 1 summarizes the advantages and disadvantages of microplastic removal methods.

5.1.4. Integrated systems (Combinations)

These are systems that utilize physical, chemical, and biological methods together. They are preferred in advanced treatment facilities.

- Biological + Physical + Chemical Methods:
  - For example, MBR + electrocoagulation + coagulation systems can be used together to capture microplastics both mechanically and chemically.
  - Such integrated systems, combined with advanced physical-chemical processes, provide high microplastic removal throughout the entire process (Enfrin et al., 2019; Liu et al., 2021).

Because highly efficient microplastic removal cannot be achieved with a single method alone, interest in integrated systems has increased in recent years. Systems combining chemical flocculation and physical filtration, or hybrid approaches incorporating biological reactors supported by membrane modules, offer success rates exceeding 90% in particle removal (Liu et al., 2023).

However, to increase the field-scale applicability of these systems, pilot studies, cost-benefit analyses, and lifecycle assessments are needed.

Consequently, instead of single-pronged solutions in microplastic removal technologies, shifting to multi-parameter system approaches and modular, adaptive treatment designs will yield more meaningful results in terms of both technical efficiency and environmental sustainability.

5.2. Prevention Strategies

5.2.1. Personal restrictions

One of the most important factors in preventing microplastic pollution is individual awareness. Consumers can reduce microplastic formation by changing certain habits in their daily lives:

- Choosing microplastic-free cosmetic products and reducing the use of single-use plastics are basic measures that can be taken at the individual level.
- Proper separation and collection of household waste can reduce microplastic formation by preventing waste from dispersing into the environment.
- Clothing containing synthetic fibers releases microplastics during washing and drying. Therefore, it is recommended that clothes be washed only when necessary and dried in sunlight if possible.

Supporting organizations working on the environment and raising social awareness are also among the long-term effective methods (Saini and Sharma, 2022).

Table 1. Comparison of microplastic removal methods: advantages and disadvantages

Method Type	Method	Advantages	Disadvantages	References
Physical	Filtration/Membrane Technologies	Effective for small particle retention- Chemical free treatment- High removal efficiency- Compact systems (especially Nanofiltration)	High installation and energy costs- Membrane fouling- Frequent cleaning required	Gurung et al., 2016; Bayo et al., 2020; Enyoh et al., 2025
	Sedimentation	Cost-effective- Suitable for preliminary treatment- Effective for larger particles	Inefficient for small microplastics- Time-consuming- Incomplete removal	Shirasaki et al., 2016; Zhang et al., 2021
	Filtration-Sorption Combinations	High efficiency when combined with biological and chemical processes	Requires system integration	Liu et al., 2021
Chemical	Coagulation – Flocculation	High removal efficiency for small microplastics- Easy integration into existing systems	High chemical and energy consumption	Wulandari et al., 2024
	Electrocoagulation	Low chemical usage- Automation-friendly- Low sludge production	High energy cost- Requires specific reactors	Perren et al., 2018; Weisbart et al., 2020
Biological	Adsorption on Green Algae	Large surface area-to-volume ratio- Alginates secreted by algae retain microplastics	Limited efficiency- Not commercially widespread	Rios et al., 2007
	Bioremediation and Ingestion	Microbial biofilms facilitate retention- Utilizes natural processes	Mechanisms not fully understood- Slow process- Risk of microplastics entering food chains	Anand et al., 2023
	Activated Sludge Systems	Widely used in conventional treatment plants- Retains significant portion of microplastics	Limited efficiency for very small particles	Carr et al., 2016; Talvitie et al., 2017
	Membrane Bioreactors (MBRs)	Higher efficiency than conventional biological systems- Combines membrane filtration with biological treatment	High investment and operating costs- Risk of membrane fouling	Liu et al., 2021

5.2.2. National strategies

Many countries have implemented legal and policy measures to reduce microplastic pollution:

- The United States banned the use of microbeads in rinse-off cosmetic products with the Microbead-Free Water Act (MFWA) enacted in 2015 (MFWA, 2015; UNEP, 2018).
- The USEPA aimed to prevent micro- and nanoplastics from reaching the environment with the Draft National Strategy to Prevent Plastic Pollution published in 2023 (USEPA, 2023).
- Canada imposed restrictions on plastic use in 2020 and conducted public opinion surveys through the end of 2021 (CCME-ZPW, 2019).
- France, Belgium, Italy, Korea, New Zealand, Brazil, and India are other countries that have restricted the use of microbead-containing products (UNEP, 2018).

5.2.3. Global strategies

- Although the United Nations did not specifically address microplastics within the 2015 Sustainable Development Goals, UNEP has launched various prevention programs in this area (UNEP, 2022).
- UNEA (UN Environment Assembly) has been focusing on marine litter since 2014; by 2017, it had established expert teams to address microplastic pollution and, by 2022, had legally established this fight (UNEA, 2019; UNEP, 2022).
- The UN Sustainable Fashion Alliance is one of the key initiatives established to reduce microplastic pollution from textiles (UNEP, 2022).
- The European Commission prepared regulations on the impacts of microplastics as part of the Circular Economy Action Plan in 2020 (Ritchie and Roser, 2018).

5.3. Policies and Regulations

Increased awareness of plastic pollution has led to the development of prevention policies. However, increasing plastic production and consumption demonstrate that existing regulations are inadequate to address the microplastic problem. Therefore, new, more effective policies need to be developed (UN, 2022).

Country-Based Policies:

- Sweden: The recycling rate is over 95%. The country's goals include banning single-use plastics, innovating on biodegradable materials, and generating energy from waste.
- Germany: Plastic recycling is encouraged through the "Pfand" system, which uses returnable bottles.
- South Korea: Systems are enforced for waste separation and supported by sanctions.

- Japan: Stands out with its advanced waste separation systems and use of biodegradable plastics.
- The Netherlands: Constructs roads from recycled plastic; however, the microplastic impacts of this practice are not yet fully known.
- Canada: Aims to ban single-use plastic products by 2030.
- Costa Rica: Aims to become a plastic-free country by 2050 and promotes sustainability through ecotourism programs (URL-2).
- California: Banned microbeads in cosmetic products.
- Washington State: Mandatory plastic bottle refill stations with HB 1085.
- European Union (EU): Banned single-use plastics as of 2021 and developed programs to promote environmentally friendly products (Schultz, 2021).
- Türkiye: As part of the Zero Waste Program, plastic bags have been charged; according to reports by WWF- Türkiye and Boğaziçi University, Türkiye is among the countries that pollute the Mediterranean Sea the most. Therefore, it is expected to play a more active role in international prevention programs.

International Political Initiatives:

UN Plastics Treaty: This treaty, launched in 2022, aims to reduce plastic and microplastic pollution on a global scale (EPA, 2023).

6. Current Research and Future Perspectives

6.1. Current Findings on Microplastic Pollution

Microplastic pollution is a complex problem that threatens not only the environment but also human health. Therefore, continuous and multifaceted scientific research is crucial to identify the presence of microplastics in various environments and analyze their impacts.

Studies Conducted in Türkiye

- Salt Products: FTIR analysis was conducted on 36 samples of 9 different brands of rock, lake, and sea salt from across Türkiye, and 10 different types of microplastics were detected. These results are striking in demonstrating the potential risks microplastics pose to safe food (Özçifçi et al., 2023).
- Milk Samples: Samples taken from 588 dairy cows in the Marmara Region were analyzed using SEM-EDS and ATR-FTIR methods, and microplastics were detected in 89% of the samples (Zipak et al., 2024).
- Soft Drinks: There is evidence that microplastics were detected in all soft drink samples from 10 different brands in Türkiye (Altunışık, 2023).
- Milk-producing animals: The study was conducted on samples (n: 588) taken from various milk-producing animals in the Marmara Region, a major industrial and agricultural region in Türkiye. Microplastics were identified, classified, and quantified using microscopic analysis. Surface morphologies and chemical compositions were evaluated using advanced techniques such as Scanning Electron Microscope Energy Dispersive X-Ray Spectroscopy (SEM-EDS) and Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy (ATR-FTIR). According to the results of the study, microplastics were detected in 89% of the milk samples (Zipak et al., 2024).

These findings indicate that microplastics are widespread in terrestrial and urban environments and should be considered for public health reasons.

International Findings

- Microplastics in Human Tissues: A study conducted at the University of New Mexico, USA, investigated the presence of microplastics in autopsy samples between 1997 and 2024, and found 30 times more microplastics in brain tissue than in liver and kidney tissue. Furthermore, the level of microplastics in samples from 2024 increased by 50% compared to 2016. The higher accumulation of microplastics in patients with dementia suggests that microplastics may be associated with neurological disorders by crossing the blood-brain barrier (Campen et al., 2025).
- Microplastic in breast milk storage bags: A study was conducted with six different brands of breast milk storage bags. The study evaluated the release of microplastics from milk bags to babies. The study identified irregularly shaped microplastics ranging in size from 1 to 300 µm in breast milk placed in these bags. Additionally, submicron-sized particles with irregular spherical or oval shapes ranging from 0.1 to 0.6 µm were also observed. Micro-Raman spectroscopy identified microplastic particles primarily as PE, followed by PET and nylon (Liu et al., 2023).

6.2. Advanced Technologies and Emerging Approaches

Laser technologies and nanofiltration systems have become prominent in recent years for the detection and removal of microplastics:

- Laser Techniques: Laser-based methods such as Raman spectroscopy, LDIR (Quantum Cascade Laser Imaging), LA-ICP-MS, and LIBS are frequently used for the analysis of microplastics (Farshidianfar et al., 2024; Yousaf and Bashir, 2024). These techniques enable the high-sensitivity identification of microplastics from environmental media (water, soil, air) (Sommer et al., 2021).
- Plasma-Assisted Removal: Polystyrene microplastics were degraded by non-thermal plasma-assisted catalytic oxidation at low temperatures, converting 98.4% of the CO_2 into CO_2. The reproducibility of the experiments and the increased CO_2 production demonstrate the stability of the method (Sima et al., 2024).
- Laser-Modified Membranes: Nanofiltration (NF) and ultrafiltration (UF) efficiencies are increased thanks to membranes that can be cleaned or modified using lasers. For example, superhydrophilic graphene oxide (LGO) membranes provide high filtration without

harmful additives (Sun et al., 2024; Pizzichetti et al., 2023).

- Laser-Induced Graphene (LIG): Magnetic Fe_3O_4-LIG particles grown using lasers effectively removed microplastics ranging in size from 2–50 µm from water within 300 minutes. This method is a high-throughput example of magnetic filtration integrated with laser technology (Jeong et al., 2023; Aragón et al., 2025).

6.3. Artificial Intelligence-Enabled Applications

Artificial intelligence (AI) offers revolutionary solutions for the detection, separation, and removal of microplastics from the environment. The use of AI is based on the analysis of microplastic detection, accumulation, separation, identification, and degradation using data processing systems, algorithms, and autonomous systems (Huang and Ullah, 2025). Figure 5 provides an example of an AI procedure used to identify microplastics. AI applications and details for microplastic detection and removal are provided below.

- Data Processing and Optimization: AI-powered algorithms make filtration processes more effective by optimizing pressure, flow rate, and membrane performance in filter systems (Cairone et al., 2024; Huang and Ullah, 2025).
- Machine Learning (ML): ML and neural network algorithms are used to identify plastic types by analyzing microscope and spectrometer data (Fang et al., 2023). AI systems integrated with LIBS technology can quickly identify plastic size and composition (Yang et al., 2023).
- Autonomous Robot Systems: AI-powered robots are used to detect, separate, and collect microplastics by analyzing environmental conditions. These systems can also learn the most appropriate strategy based on changing environmental conditions (Sarker et al., 2024).
- Waste Sorting Systems: Waste robots integrate with infrared sensing systems to ensure the accurate separation of plastics. These systems significantly increase separation accuracy (Martinez-Hernandez et al., 2024).
- Adsorbent Design: AI is also being used in the design of specialized magnetic nanoparticles and adsorbents to capture microplastics. This allows the development of specialized materials suitable for different pollution scenarios (Enyoh et al., 2022; Das et al., 2024).

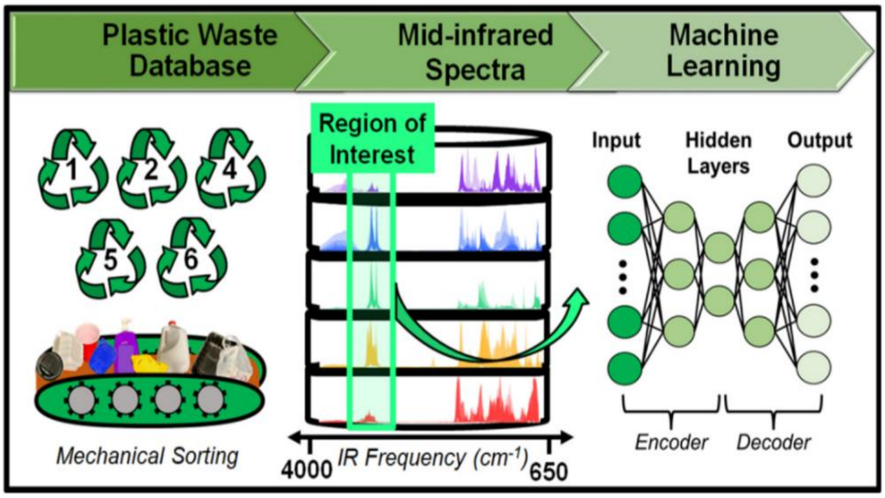

Figure 5. Diagram of the procedure applied in the detection of nano and microplastics with artificial intelligence (Lubongo et al., 2024).

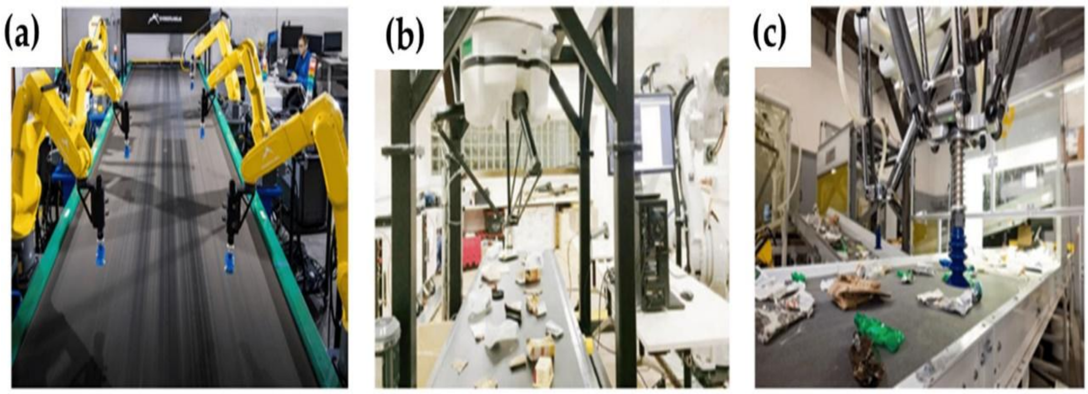

Figure 6. Artificial intelligence-supported separation robots for small plastics (b,c) and plastic waste (a) (Lubongo et al., 2024).

6.4. Emerging Imaging Systems

- Identification with FTIR: Machine learning-based software developed at Monash University that can analyze FTIR data was the first program capable of distinguishing microplastics by recognizing their "chemical signatures" (Frithjof et al., 2025).
- Satellites and Drones: ML systems integrated with image processing algorithms can detect microplastic concentrations on the sea surface and riverbeds, followed by physical cleaning with robotic systems.

Laser systems, nanofiltration technologies, and artificial intelligence applications developed in laboratory environments offer promising solutions for the detection and removal of microplastics. However, the scalability, cost-effectiveness, and environmental impacts of these technologies are still being investigated.

Low-cost alternatives such as biochar, activated carbon, and natural clays, supported by AI, may offer more applicable solutions in large-scale systems (Enyoh et al., 2022). These technologies may make it possible to combat microplastic pollution more effectively in the future.

7. Conclusion

Plastic waste breaks down under environmental conditions through physical and chemical processes, reaching micro-sized particles. When microplastics form as a result of this process, they can exhibit plankton-like behavior and easily enter the food chain. While their low density allows them to drift with plankton on the water surface, studies have shown that these particles also tend to accumulate in the water column and sediment layers.

With developing technologies, plastic products that are more durable and contain various additives pose a significant threat to both current environmental health and future ecosystems due to their potential to absorb toxic chemicals.

In recent years, many countries and international organizations have drawn attention to the impact of microplastics on the environment and living organisms and developed various policies on this issue. These policies include campaigns to raise consumer awareness, legal regulations, usage restrictions, and sanctions.

Microplastic pollution is not limited to aquatic systems but also poses a growing threat to terrestrial environments and the atmosphere. Increasing plastic production and consumption, in particular, increases the plastic load arriving at wastewater treatment plants; however, due to the small size and buoyancy of microplastics, existing treatment systems cannot completely remove these pollutants.

Although various methods have been developed to remove microplastics from environmental environments, most of these studies remain regional and laboratory-scale. To understand the impacts of microplastics on living organisms, greater focus is needed, particularly on exposure through drinking water and food.

Furthermore, one of the main problems noted in the literature is the lack of standard protocols for sampling, analysis, and reporting of microplastics. Studies conducted with different methods and criteria make it difficult to compare results and make generally accepted interpretations.

In this context, the microplastic removal performance of wastewater treatment systems, in particular, needs to be improved. Integrating advanced filtration techniques such as ultrafiltration (UF) and nanofiltration (NF) with conventional treatment systems can significantly increase removal efficiency. Therefore, diversifying research and developing scalable applications is crucial.

With the opportunities offered by today's technology, the use of artificial intelligence (AI)-supported systems in microplastic studies is rapidly becoming widespread. AI algorithms accelerate the detection, classification, distribution monitoring, and impact analysis of microplastics, while also increasing the reliability of the results. In this respect, AI applications are considered a promising tool in the fight against microplastics.

This study examines existing prevention strategies and policy approaches by holistically addressing the sources, environmental distribution, and biodiversity impacts of microplastics. Furthermore, focusing on innovative technologies for the removal of microplastics from the environment, it offers guiding and encouraging recommendations for future research.

Author Contributions

The percentages of the authors' contributions are presented below. All author reviewed and approved the final version of the manuscript.

	Ş.S.	A.Ş.	G.B.
C	40	30	30
D	40	40	20
S	10	20	70
DCP	40	40	20
DAI	40	30	30
L	50	30	20
W	40	40	20
CR	20	40	40
SR	20	60	20

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

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