World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Microplastic Pollution: An In-depth Review of its Sources, Formation Mechanisms, Quantification Techniques, Environmental Impacts, Toxicological Effects and Remediation Strategies

Gift Kiisi Nkin *

Department of Chemistry, Faculty of Science, Rivers State University, P.M.B 5080 Nkpolu-Oroworukwo, Port Harcourt, Rivers State, Nigeria.

World Journal of Advanced Research and Reviews, 2025, 27(01), 228-262

Publication history: Received on 18 May 2025; revised on 22 June 2025; accepted on 28 June 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.27.1.2483

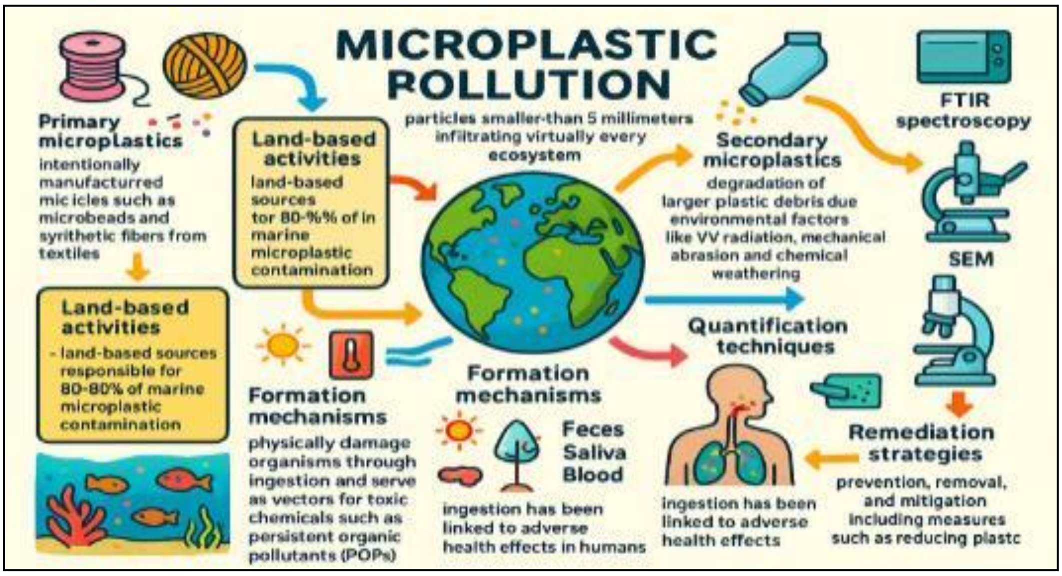
Abstract

Microplastic pollution has become a prevalent environmental issue, with particles smaller than 5 millimeters infiltrating virtually every ecosystem. This review provides a comprehensive analysis of microplastic sources, formation mechanisms, quantification techniques, environmental impacts, toxicological effects, and remediation strategies. Microplastics originate from both primary and secondary sources. Primary microplastics include deliberately manufactured particles such as microbeads and synthetic fibers from textiles. Secondary microplastics result from the degradation of larger plastic debris due to environmental factors such as UV radiation, mechanical abrasion, and chemical weathering. Land-based activities, including industrial processes, agriculture, and improper waste disposal, contribute tremendously to microplastic pollution, with land-based sources responsible for 80–90% of marine microplastic contamination. Accurate quantification of microplastics is imperative for assessing pollution levels and informing reduction strategies. Techniques such as Fourier-transform infrared (FTIR) spectroscopy, Raman spectroscopy, and scanning electron microscopy (SEM) are commonly used to identify and characterize microplastic particles. Microplastics cause remarkable threats to aquatic ecosystems. They can physically damage organisms through ingestion, resulting in blockages, malnutrition, and death. Moreover, microplastics serve as vectors for injurious chemicals, including persistent organic pollutants (POPs), which can leach into the environment and accumulate in the food chain. The presence of microplastics in marine environments disrupts habitats and affects biodiversity, with potential long-term consequences for ecosystem stability. The ingestion of microplastics has been linked to different adverse health effects in humans and wildlife. In humans, microplastics have been detected in biological samples like feces, saliva, blood, and placenta, raising concerns about potential health risks. Animal studies show that microplastics can cause oxidative stress, inflammation, and genotoxicity, even at low concentrations. Tackling microplastic pollution requires a multifaceted approach circumscribing prevention, removal, and mitigation. Microplastic pollution is a complex and escalating issue that necessitates concerted global efforts. Effectual management requires a combination of reducing plastic generation, improving waste management, advancing remediation technologies, and conducting further research to comprehend the full extent of microplastic impacts on health and ecosystems. Synergetic actions at the international, national, and local levels are crucial to mitigate the prevalent threat caused by microplastics and protect environmental and public health.

Keywords: Microplastic Pollution; Sources; Formation Mechanism; Microplastic Detection; Environmental and Health Impacts; Microplastic Toxicity; Microplastic Mitigation

*Corresponding author: Nkin Gift Kiisi

Graphical abstract



1. Introduction

Microplastics, defined as plastic particles less than 5 millimeters in size, have appeared as a widespread environmental pollutant. Their ubiquity spans oceans, freshwater bodies, soils, air, and even remote regions like the Arctic and Mount Everest [1, 18, 17]. These particles start from both primary sources, such as microbeads in personal care products, and secondary sources, resulting from the degradation of larger plastic items under environmental stressors [17, 18]. Microplastics are categorized into primary and secondary types. Primary microplastics are intentionally manufactured tiny plastic particles, including microbeads used in cosmetics and personal care products, and plastic pellets (nurdles) used in industrial manufacturing. Secondary microplastics result from the degradation of larger plastic items like bottles, bags, and synthetic clothing fibers due to environmental factors such as sunlight, heat, and mechanical wear [2, 18, 42]. The degradation of plastics into microplastics is influenced by various environmental factors. Ultraviolet (UV) radiation from sunlight, thermal degradation, oxidation, and mechanical abrasion give rise to the fragmentation of larger plastic debris into smaller particles [3]. These microplastics are then transported via various pathways, including wastewater runoff, entering freshwater and marine systems, and posing tremendous environmental threats. Microplastics have been detected in various biological samples, including feces, sputum, saliva, blood, and placenta, showing widespread human exposure. Their small size allows them to penetrate biological barriers, leading to potential health risks. Studies have linked microplastic exposure to various health issues, such as cancer, intestinal, pulmonary, cardiovascular, infectious, and inflammatory diseases [100]. In aquatic ecosystems, microplastics pose significant threats to marine life. Organisms ingest microplastics, leading to alterations in gastrointestinal tract physiology, immune system depression, oxidative stress, cytotoxicity, differential gene expression, and growth inhibition [4, 100, 105, 107]. The bioaccumulation of microplastics in aquatic organisms can have adverse effects on the aquatic ecosystem, with potential transmission of microplastics to humans and birds. Precise quantification of microplastics is challenging due to their small size and diverse forms. Traditional methods include visual identification under microscopes, but these can be time-consuming and may not detect all types of microplastics. Advanced techniques such as Fourier-transform infrared (FTIR) spectroscopy and Raman spectroscopy offer more precise identification and quantification by analyzing the chemical composition of the particles [5, 88, 89, 93, 94]. Efforts to mitigate microplastic pollution involve various remediation strategies. These include coagulation, membrane bioreactors, sand filtration, adsorption, photocatalytic degradation, electrocoagulation, and magnetic separation. Each method has its advantages and limitations, and often, a combination of these approaches is employed to enhance efficiency. A promising development in microplastic removal is the use of bio-inspired materials. Researchers at the University of Wuhan have developed a sponge made from cotton and squid bone that can absorb 99.9% of microplastics in water [6]. This sponge has shown remarkable reusability and scalability, offering a potential solution to the growing problem of microplastic pollution [6]. Microplastics represent a significant environmental and public health challenge. Their widespread presence in various ecosystems and potential health impacts necessitate urgent action. Implementing effective remediation strategies, reducing plastic usage, and promoting behavioral changes are essential steps toward mitigating microplastic pollution. Continued research and innovation are crucial in developing sustainable solutions to address this pervasive issue [6,5,2,4].

2. Sources of Microplastics

Microplastics are prevelent environmental pollutants resulting from both primary and secondary sources. Understanding these sources is important for developing strategies to mitigate their impact.

Figure 1 Sources of Microplastics(17 Modified)

2.1. Primary Sources of Microplastics

Primary microplastics are purposely manufactured plastic particles designed to be small, typically less than 5 millimeters in size, from the outset. Unlike secondary microplastics, which form when larger plastic items degrade over time due to environmental factors. Primary microplastics are directly introduced into the environment through various human activities [7]. Their extensive presence in ecosystems and potential health implications underscore the importance of understanding their origins and the reasons for their production. Below are some examples of primary microplastics sources [8].

2.2. Personal Care and Cleaning Products

Microbeads are tiny plastic particles, typically less than 1 millimeter in diameter. Microbeads, small plastic particles used in exfoliating products like facial scrubs and toothpaste, are major contributors to primary microplastics. These microbeads are often made from polyethylene and are not biodegradable. Studies have found that products such as facial scrubs can contain up to 350,000 microbeads per tube, and toothpaste can have between 1,700 to 6,400 microbeads per gram. These particles are washed down drains and are not completely removed by wastewater treatment plants, leading to their release into aquatic environments [9, 7, 8].

2.2.1. Prevalence and Composition of Microbeads

Microbeads are purposely incorporated into personal care and cleaning products for their exfoliating and abrasive properties. They are typically made up of synthetic polymers like polyethylene, polypropylene, or polystyrene. These materials are chosen for their durability and effectiveness in cleansing. In facial scrubs, for instance, a single tube can contain up to 350,000 microbeads. Toothpaste products may contain between 1,700 to 6,400 microbeads per gram. These figures highlight the significant quantities of microbeads present in everyday personal care items [10].

2.2.2. Environmental Impact of Microbeads

After use, microbeads are washed down the drain and enter wastewater systems. Due to their small size and buoyancy, they always pass through wastewater treatment plants without being filtered out. This inefficiency leads to the release of microbeads into rivers, lakes, and oceans. Once in aquatic environments, microbeads can be ingested by marine organisms, leading to potential physical harm and the accumulation of toxic substances. These particles can absorb and concentrate pollutants like pesticides and polycyclic hydrocarbons, which may then enter the food chain [11].

2.2.3. Global Response and Legislation on Microbeads

Recognizing the environmental threat constituted by microbeads, several countries have enacted legislation to prohibit their use in personal care and cleaning products. For example, the United States passed the Microbead-Free Waters Act in 2015, mandating the phase-out of microbeads in rinse-off cosmetics by July 2017. Similarly, the European Union and other nations have implemented related bans. These legislative actions have prompted manufacturers to seek alternative exfoliating agents, such as natural materials like jojoba beads, ground walnut shells, and sugar crystals, which are biodegradable and less harmful to the environment [12].

2.2.4. Consumer Awareness and Alternatives of Microbeads

Consumer awareness plays an important role in mitigating the impact of microbeads. By choosing products labeled as "microbead-free" or "biodegradable," consumers can reduce their contribution to microplastic pollution. Additionally, opting for natural exfoliating products and supporting brands that prioritize environmental sustainability can drive industry-wide change. Educational campaigns and clear product labeling are vital in empowering consumers to make informed choices and encourage the adoption of environmentally friendly alternatives [13].

2.3. Synthetic Textiles

Synthetic fibers from clothing, such as polyester, nylon, and acrylic, shed microplastics during washing. Each wash can release hundreds of thousands of fibers, which pass through wastewater treatment plants and enter water bodies. These fibers are also found in biosolids applied to soil, contributing to terrestrial microplastic pollution [14, 15].

2.3.1. Microplastics from Synthetic Fibers in Clothing: Environmental Pathways and Impacts

Synthetic fibers, such as polyester, nylon, and acrylic, have become ubiquitous in modern textiles due to their durability, affordability, and versatility. However, these materials are notably contributors to microplastic pollution, particularly through the shedding of microfibers during washing processes. Each laundry cycle can release a substantial number of microfibers into the environment, leading to widespread contamination of aquatic and terrestrial ecosystems [15, 14].

2.3.2. Shedding of Microfibers During Washing

The primary mechanism by which synthetic textiles release microplastics is through mechanical abrasion during washing. As garments made from polyester, nylon, and acrylic fibers are agitated in washing machines, small fibers detach from the fabric. These microfibers are typically less than 5 millimeters in length and are small enough to pass through standard wastewater treatment plant filters. For instance, a single fleece jacket can release up to 250,000 microfibers per wash cycle [16, 18].

2.3.3. Transport and fate of microfibers in Wastewater Systems

Once released, these microfibers enter the wastewater system, where they often evade filtration due to their minute size. While some microfibers are captured by advanced treatment processes, a significant portion remains in the effluent and is discharged into rivers, lakes, and oceans. Studies have shown that up to 35% of microplastics in the ocean originate from synthetic textile fibers released during washing [17] . Furthermore, microfibers can be retained in the sludge produced by wastewater treatment plants. This biosolid is often used as fertilizer in agriculture, leading to the introduction of microplastics into soil ecosystems. Research shows that biosolids can contain hundreds of microplastic particles per gram, with microfibers being the most prevalent type [18].

2.3.4. Environmental and Ecological Impacts of microfibers

The pervasive existence of microfibers in aquatic environments contributes several ecological risks. Marine organisms, ranging from zooplankton to large fish, can ingest these particles, mistaking them for food. This ingestion can lead to physical harm, such as blockages or internal injuries, and may also result in the accumulation of toxic substances adsorbed onto the microfibers. Consequently, microfibers can enter the food chain, potentially affecting human health through seafood consumption [19]. In terrestrial ecosystems, the application of biosolids containing microfibers to agricultural land introduces these pollutants into the soil. Microfibers can affect soil structure and function, potentially impacting plant growth and soil organism health. Additionally, the persistence of microfibers in soil raises concerns about their long-term environmental impact [20].

2.4. Tire Wear

As vehicles operate, tire abrasion releases microplastics into the environment. These particles are transported through different pathways into rivers, lakes, and oceans. Tire wear is considered a tremedous source of microplastics, particularly in urban areas [21]. It is a significant yet often overlooked contributor to microplastic pollution, especially in urban environments. As vehicles operate, the friction between tires and road surfaces causes the release of tiny particles known as tire wear particles (TWPs) [21, 22]. These particles, which are typically smaller than 5 millimeters, consist of a mixture of rubber, asphalt, and other materials. Once released, they enter the environment via various pathways, including stormwater runoff, atmospheric deposition, and direct deposition on road surfaces [21].

2.4.1. Pathways of Tire Wear Particles into the Environment

Tire wear particles (TWPs) are a significant and often overlooked source of microplastic pollution, entering the environment through various pathways. These particles, resulting from the abrasion of tires on road surfaces, contribute to environmental degradation in multiple ways. One of the common pathways for TWP pollution is stormwater runoff. During rainfall, tire wear particles are washed off road surfaces into storm drains, which eventually discharge into rivers, lakes, and oceans. A study conducted in Queensland, Australia, found that during rain events, approximately 95% of microplastics in stormwater were tire wear particles. This highlights the significant role of TWPs in contributing to aquatic microplastic pollution. The presence of synthetic rubber in tires, which contains up to 2,500 chemicals, exacerbates the issue, as these substances can leach into water bodies, posing risks to aquatic life and ecosystems [22, 21]. Another concerning pathway is atmospheric deposition. Some tire wear particles are light enough to become airborne. These particles can travel long distances, even reaching remote areas like the Arctic. Research indicates that the smallest tire wear particles can remain suspended in the atmosphere for nearly a month, allowing them to disperse globally. This extensive distribution raises concerns about the impact of TWPs on ecosystems far from their source, including potential effects on the Arctic's albedo, which could accelerate ice melting and global warming. Direct deposition is another significant pathway, especially in areas with high traffic density. In such regions, tire wear particles can accumulate directly on road surfaces and adjacent environments. Over time, these particles can degrade, contributing to soil and water pollution. The accumulation of TWPs in urban areas accentuates the need for effective management strategies to mitigate their environmental impact. Addressing the issue of tire wear particle pollution requires a multifaceted approach, including improving stormwater management systems, developing tire materials that shed fewer particles, and increasing public awareness about the environmental impact of tire wear. By understanding and mitigating the pathways through which TWPs enter the environment, we can take steps toward reducing their harmful effects on ecosystems and human health [22].

2.4.2. Environmental Impact of Tire Wear

The accumulation of tire wear particles (TWPs) in aquatic environments poses significant environmental risks, impacting both aquatic life and human health. These particles, primarily composed of synthetic rubbers, fillers, and additives, are released into the environment through vehicle tire wear. Once in aquatic systems, TWPs can have harmful effects on different aspects of the ecosystem. One of the primary concerns is the toxicity of TWPs to aquatic organisms. Studies have shown that leachates from TWPs can induce oxidative stress, inflammation, and histopathological changes in aquatic species [23]. For instance, research on black-spotted frogs revealed that exposure to TWP leachates led to increased levels of reactive oxygen species and activation of immune-related signaling pathways, indicating significant health impacts on these organisms [23, 24, 26]. Additionally, exposure to TWP leachates has been linked to acute mortality in coho salmon, with concentrations as low as 0.095 μg/L causing lethal effects [24]. Beyond direct toxicity, TWPs contribute to bioaccumulation in the food chain. Microplastics, including those from tire wear, can be ingested by marine organisms ranging from plankton to larger fish and mammals. This ingestion can lead to the accumulation of toxic substances within the organisms, which may then be transferred up the food chain, potentially affecting human health through seafood consumption. Furthermore, the physical presence of TWPs in aquatic environments can cause harm to marine life. Ingested microplastics can lead to physical injury, blockages in digestive systems, and malnutrition. For example, studies have observed that ingestion of microplastics can cause physical harm to marine animals, leading to injury or death [25, 26]. Additionally, these particles can block digestive systems, leading to malnutrition or starvation. The environmental impact of tire wear particles is multifaceted, encompassing toxicity, bioaccumulation, and physical harm to aquatic life [24, 26]. Addressing this issue requires comprehensive strategies, including reducing tire wear, improving road runoff management, and conducting further research to fully understand the extent of the problem and develop effective solutions.

2.4.3. Tire Wear Urban Challenges and Solutions

Urban environments, notably those with high vehicle density and extensive impervious surfaces, are particularly vulnerable to microplastic pollution originating from tire wear. The friction between tires and road surfaces generates tiny particles, known as tire wear particles (TWPs), which are a significant source of microplastics in urban areas. These particles are often washed into stormwater systems during rainfall, leading to their accumulation in water bodies and posing threats to aquatic ecosystems. The combination of heavy traffic and limited natural filtration systems exacerbates the issue, making it crucial to implement effective mitigation strategies. One of the primary approaches to addressing this issue is enhanced road cleaning. Regular street sweeping, especially before anticipated rainfall, can effectively remove accumulated TWPs from road surfaces. For instance, in the United Kingdom, authorities have utilized detailed traffic data to target the busiest roads for cleaning, ensuring that areas with the highest potential for pollution are addressed punctually [27]. Additionally, employing advanced cleaning technologies, such as truck-mounted sweepers equipped with high-efficiency filters, can capture finer particles, preventing them from entering stormwater systems. Improved stormwater management is another crucial strategy. Upgrading stormwater infrastructure to include filtration systems can greatly reduce the amount of TWPs entering water bodies. For example, in Australia, researchers have assessed the effectiveness of stormwater treatment devices like mesh bags retrofitted to drains, which have shown up to an 88% reduction in microplastics in treated water [28]. Moreover, constructing stormwater wetlands has proven effective in capturing and removing microplastics from runoff, with studies indicating a significant decrease in particle concentration after passing through these systems. Incorporating such infrastructures can improve the resilience of urban areas against microplastic pollution. Public awareness campaigns play a pivotal role in mitigating microplastic pollution from tire wear. Educating the public on the environmental impact of TWPs can encourage responsible driving habits and support for policies aimed at reducing microplastic pollution. Campaigns can focus on promoting practices such as maintaining proper tire pressure, avoiding sudden accelerations and braking, and reducing vehicle weight, all of which can decrease tire wear. Additionally, raising awareness about the importance of using public transportation, cycling, and walking can contribute to reducing the overall number of vehicles on the road, thereby lessening the generation of TWPS. Incorporating these strategies into urban planning and policy-making can significantly mitigate the impact of tire wear on microplastic pollution. By enhancing road cleaning, improving stormwater management, and fostering public awareness, cities can move towards a more sustainable and environmentally friendly future. Collaborative efforts between governments, communities, and industries are crucial to address this pressing environmental challenge effectively [27, 28].

2.4.4. Global Perspective of Tire Wear

Tire wear is a global issue, with studies indicating that it is one of the largest sources of microplastics in the environment. For example, a study published in *Nature Communications* estimated that 52,000 tons of the smallest tire wear particles end up in the sea each year, while 20,000 tons are deposited in remote regions like the Arctic [29].

2.4.5. Research and Future Directions of Tire Wear

Tire wear particles (TWPs) have emerged as a significant yet often overlooked source of microplastic pollution, especially in urban environments. These particles are generated through the abrasion of tires on road surfaces, releasing a complex mixture of synthetic rubbers, carbon black, oils, and chemical additives. Due to their small size and lightweight nature, TWPs can be transported over long distances by wind and water, leading to extensive environmental contamination. The accumulation of these particles in various ecosystems raises concerns about their potential impacts on both the environment and human health.

Quantifying the emissions of TWPs is a critical step in understanding their environmental impact. Recent studies have provided estimates of TWP emissions, with per capita emissions ranging from 0.23 to 4.7 kg per year, averaging around 0.81 kg per year globally. In urban areas, where vehicle density is high, these emissions can be significantly higher. For instance, in the San Francisco Bay area, it was estimated that approximately 15 to 19 million kilograms of TWP are emitted annually, with a substantial portion entering the bay through stormwater runoff [30]. These figures underscore the need for accurate measurement techniques to assess the scale of TWP pollution and to inform mitigation strategies. Assessing the environmental impact of TWPs involves examining their effects on various ecosystems. Studies have shown that TWPs can be ingested by aquatic organisms, leading to adverse effects on feeding, growth, and behavior. For example, exposure to TWPs has been found to affect the growth and swimming behavior of marine species such as the silverside Menidiaberyllina and the mysid shrimp Americamysisbahia [30]. Additionally, the leaching of toxic chemicals from TWPs, such as the preservative 6PPD-quinone, has been linked to the mortality of coho salmon in freshwater systems. These findings highlight the potential for TWPs to disrupt aquatic ecosystems and the need for further research to fully understand their ecological risks. In response to the growing concern over TWP pollution, there is a concerted effort to develop sustainable alternatives to traditional tire materials. Research is underway to create tires using bio-based materials, such as guayule and dandelion rubber, which may reduce the release of harmful particles upon wear. Moreover, innovations in tire design aim to enhance durability and reduce wear, thereby decreasing the overall generation of TWPs. For instance, the development of tires with optimized tread patterns and compounds can minimize abrasion and extend tire life. These advancements not only promise to mitigate environmental pollution but also contribute to the sustainability of the automotive industry [30]. The issue of TWP pollution necessitates a multifaceted approach, combining rigorous research, technological innovation, and public awareness. By quantifying TWP emissions, assessing their environmental impact, and developing sustainable alternatives, it is possible to reduce the ecological footprint of tire wear and move towards a more sustainable future. Continued collaboration among researchers, industry stakeholders, and policymakers is essential to address this pressing environmental challenge effectively [30].

2.5. Paints and Coatings

Paints, varnishes, and coatings always contain microplastics to enhance durability and finish. These microplastics are released during application, wear, and removal processes. For example, marine coatings can release microplastics into the ocean, contributing to marine pollution [31]. while paints, varnishes, and coatings serve essential functions in enhancing the durability and appearance of surfaces, their contribution to microplastic pollution cannot be overlooked. By adopting sustainable practices and materials, it is possible to mitigate the environmental impact of these products and protect our ecosystems [31].

2.5.1. Composition and Function of Microplastics in Coatings

Microplastics are added to coatings to enhance attributes such as opacity, scratch resistance, and durability. Common polymers used include polyurethanes, polyesters, polyacrylates, polystyrenes, alkyls, and epoxies. These additives contribute to the longevity and resilience of the coatings, making them suitable for various applications, including marine environments, road markings, and building exteriors. However, the very properties that make these coatings effective also facilitate the release of microplastics into the environment [32].

2.5.2. Release Mechanisms of Microplastics from Coatings

Microplastics enter the environment through several pathways, particularly from the degradation and handling of coatings. These pathways include the application process, wear and tear, maintenance activities, and the removal of coatings. During the application of paints and coatings, especially in industrial settings, overspray and spillage can result in microplastic particles being released into the air and subsequently settling into water bodies. For example, when ships are painted, the excess paint that drifts away can contain microplastics, which in time find their way into the ocean. This not only contributes to marine pollution but also poses risks to aquatic life as these microplastics can be ingested by marine organisms, leading to potential health hazards [33]. Over time, the continuous exposure to environmental factors such as UV radiation, moisture, and mechanical abrasion leads to the degradation of coatings, releasing microplastics into the environments. UV radiation causes the polymer chains in coatings to break, leading to embrittlement and fragmentation into smaller particles. Similarly, mechanical abrasion from wind, rain, or physical contact can wear down the coating surface, further contributing to the release of microplastics. These particles can then be transported by wind or water, spreading pollution across various ecosystems [34]. Routine maintenance, including sanding, scraping, and pressure washing of coated surfaces, can dislodge microplastic particles, which are then washed into stormwater systems and eventually reach oceans and rivers. For instance, when old paint layers are removed from buildings or ships, the process often generates significant amounts of microplastic debris. If not properly managed, these particles can enter the environment, exacerbating pollution levels. The process of removing old coatings, especially through abrasive methods, generates tremendous amounts of microplastic debris. Traditional methods such as sandblasting or high-pressure water jets can release a substantial amount of microplastics into the environment. Innovative technologies, such as the use of vacuum-assisted systems during paint removal, have been developed to capture these particles at the source, preventing their release into the environment [35]. Implementing such technologies can significantly reduce the environmental impact of coating removal processes. The release of microplastics from coatings occurs via various mechanisms, each contributing to environmental pollution. Understanding these pathways is imperative for developing strategies to mitigate their impact and protect ecosystems from further degradation and damage.

2.5.3. Marine Coatings and Oceanic Microplastic Pollution

Marine coatings, especially antifouling paints applied to ship hulls, have become notable contributors to oceanic microplastic pollution. These coatings are designed to avert the accumulation of marine organisms, such as barnacles and algae, on the hulls of ships. By reducing biofouling, these paints help maintain fuel efficiency and avert the spread of invasive species. However, the very properties that make these coatings effective also lead to their degradation and the subsequent release of microplastics into the marine environment [36]. One primary mechanism of microplastic release is the cleaning process of ships. To maintain optimal performance, vessels undergo methodical cleaning to remove accumulated biofouling. Methods like hydroblasting, which use high-pressure water jets, can dislodge both the marine organisms and the underlying antifouling paint. A study focusing on hydroblasting a ship's hull stated that this process generated approximately 44.1 kg of paint particles, with 36.5 kg being smaller than 5 mm in size. Extrapolating this data suggests that globally, hydroblasting could release around 665.6 tons of plastics annually, with approximately 550.2 tons being in the form of microplastics [37]. Another significant source of microplastics is the wear and tear of coatings during a ship's operation. As vessels move through water, the constant friction causes gradual degradation of the antifouling paint, leading to the release of microplastic particles. These particles can persist in the marine environment, contributing to the growing issue of microplastic pollution. The environmental impact of these microplastics is compounded by the presence of harmful additives in many antifouling paints. Substances such as copper, zinc, and various biocides are always incorporated to enhance the paint's effectiveness. When these paints degrade, these toxic substances can leach into the surrounding water, posing risks to marine life and ecosystems. Addressing the issue of microplastics from marine coatings requires a multifaceted approach. Implementing stricter regulations on the use of harmful additives in antifouling paints can help reduce their environmental impact. Additionally, adopting alternative cleaning methods that minimize paint degradation, such as ultrasonic cleaning or the application of biodegradable cleaning agents, can mitigate the release of microplastics [36, 37]. Furthermore, the development and adoption of more durable and environmentally friendly coatings can play a vital role in reducing the overall contribution of marine coatings to oceanic microplastic pollution.

2.5.4. Urban Sources of Paint-Related Microplastics

In urban environments, paints and coatings contribute tremendously to microplastic pollution through numerous pathways, impacting both terrestrial and aquatic ecosystems. The degradation of road markings, weathering of building exteriors, infrastructure maintenance activities, and the removal of coatings all play pivotal roles in the release of microplastics into the environment. Road markings, essential for traffic safety and navigation, are composed of materials such as thermoplastics, epoxy resins, and glass beads. Over time, these markings undergo wear and tear due to vehicle abrasion and environmental factors like UV radiation and moisture. This degradation process results in the release of microplastic particles into the surrounding environment. Studies have estimated that the wear and tear of road markings can generate significant amounts of microplastics, contributing to urban pollution. For example, a study in Sweden estimated that the wear of road markings could release between 40 to 570 tonnes of microplastics annually, comparable to emissions from other sources like antifouling paints and artificial turf [38]. Building exteriors, particularly those exposed to outdoor elements, are coated with paints that can degrade over time due to UV exposure, moisture, and mechanical abrasion. This degradation leads to the release of microplastic particles into the environment. Research indicates that exterior paints, especially those used in construction and renovation, are significant sources of microplastics. These particles can be washed into stormwater systems during rainfall, eventually reaching rivers and oceans. In Europe, it's estimated that between 231,000 and 863,000 tonnes of microplastics enter the environment annually from paint waste, highlighting the considarable contribution of building exteriors to urban microplastic pollution [39]. Infrastructure maintenance activities, such as repainting and cleaning of urban structures, can generate microplastic debris if not properly managed. The process of sanding, scraping, or pressure washing surfaces to remove old coatings can release microplastic particles into the air and water. Without proper containment and disposal measures, these particles can enter stormwater systems, contributing to the overall microplastic load in urban environments [40]. The removal of coatings, particularly through abrasive methods such as sandblasting or high-pressure washing, creates significant amounts of microplastic debris. If not properly managed, these particles can enter the environment, exacerbating pollution levels. Innovative technologies, such as the use of vacuum-assisted systems during paint removal, have been developed to capture these particles at the source, averting their release into the environment. Implementing such technologies can remarkably reduce the environmental impact of coating removal processes [41]. Urban sources of paint-related microplastics encircles a range of activities and materials, each contributing to the overall microplastic load in both terrestrial and aquatic environments. Addressing this issue requires a multifaceted approach, including the development of sustainable materials, implementation of effectual maintenance practices, and adoption of technologies that reduce the release of microplastics during coating application and removal. By comprehending and mitigating these sources, urban areas can move towards a more verifiable and environmentally friendly future [42].

2.5.5. Environmental and Ecological Impacts of Paint-Related Microplastics

The release of microplastics from paints and coatings has profound environmental and ecological implications, especially in marine ecosystems. These small particles infiltrate various habitats, leading to a cascade of detrimental effects on marine life, biodiversity, and ecosystem health. Marine organisms, ranging from microscopic plankton to large mammals, are increasingly ingesting microplastics, often mistaking them for food. This ingestion can lead to physical harm, such as internal abrasions and digestive blockages, which impair feeding efficiency and can result in malnutrition and stunted growth [43]. For instance, filter-feeding species like mussels and oysters accumulate microplastics in their gills, affecting their ability to filter feed and breathe properly. Moreover, these particles can leach toxic chemicals, including bisphenol A (BPA), phthalates, and persistent organic pollutants (POPs), into the tissues of marine organisms. Such chemical exposure can disrupt endocrine systems, cause cellular damage, and even lead to the development of tumors. As these contaminants move up the food chain, they pose increasing risks to higher trophic levels, including humans who consume seafood [43]. The accumulation of microplastics in marine environments also disrupts the structural and functional integrity of ecosystems. In coral reefs, microplastics can smother corals, blocking sunlight essential for the symbiotic relationship between corals and their algal partners. This interference can lead to coral bleaching and increased susceptibility to diseases. Additionally, microplastics can alter the physical properties of sediments, affecting benthic organisms that rely on stable substrates for feeding and shelter. The presence of these particles can also change the optical properties of water, impacting the growth and distribution of phytoplankton, the foundation of marine food webs. Furthermore, microplastics serve as vectors for harmful bacteria and pathogens, facilitating their spread across marine environments. The surface of microplastics provides an ideal habitat for microbial colonization, potentially introducing diseases into marine food webs. This microbial hitchhiking can lead to the spread of invasive species and pathogens across ocean basins, disrupting local ecosystems and biodiversity patterns. The environmental and ecological impacts of paint-related microplastics are multifaceted, affecting marine organisms at various levels and disrupting the balance of marine ecosystems [44, 43]. Addressing this issue requires concerted efforts to reduce microplastic emissions, develop sustainable materials, and implement effective waste management practices to mitigate their release into the environment.

2.5.6. Mitigation Strategies of Paint-Related Microplastics

Mitigating the environmental impact of microplastics from paints and coatings necessitates a multifaceted approach encompassing the development of alternative materials, the adoption of improved application techniques, the implementation of enhanced maintenance practices, and the establishment of regulatory measures. One of the primary strategies involves the development and utilization of alternative materials that do not contain microplastics or hazardous additives. This includes formulating coatings with biodegradable polymers, natural resins, or recycled materials to minimize the release of microplastics into the environment. For instance, research into sustainable polyurethane polymers derived from renewable resources such as soybean oil has shown promise in reducing the environmental footprint of coatings. Additionally, the incorporation of natural fibers in place of synthetic polymers can further contribute to reducing microplastic pollution [38, 45]. Improved application techniques are also crucial in minimizing the release of microplastics during the application process. Adopting methods that reduce overspray and spillage can prevent microplastic particles from being released into the air and subsequently settling into water bodies. For example, the use of precision equipment and controlled environments during the application of coatings can significantly decrease the amount of excess material that becomes airborne or enters stormwater systems [38, 39]. Enhanced maintenance practices play a vital role in reducing the degradation and removal of coatings, thereby limiting the release of microplastics. Implementing routine maintenance activities that minimize wear and tear on coated surfaces can extend the lifespan of coatings and reduce the frequency of repainting. Moreover, when maintenance is necessary, employing techniques that prevent the dislodging of microplastic particles like using vacuum-assisted systems during sanding or scraping, can notably reduce environmental impact. Regulatory measures are essential in guiding and enforcing the reduction of microplastics in paints and coatings [38, 46, 39]. Establishing regulations that limit the use of microplastics in coatings can help mitigate their environmental impact. For instance, the European Union has implemented restrictions on the intentional addition of synthetic polymer microparticles in products, including paints and coatings, to prevent their release into the environment. Such regulations encourage the industry to innovate and adopt more sustainable practices, ensuring that environmental considerations are integrated into product development and application processes [46]. Addressing the environmental impact of microplastics from paints and coatings requires a comprehensive approach that includes the development of alternative materials, the adoption of improved application techniques, the implementation of enhanced maintenance practices, and the establishment of regulatory measures. By integrating these strategies, it is possible to significantly reduce the release of microplastics into the environment, thereby mitigating their detrimental effects on ecosystems and human health.

2.5.7. Global Perspective of Paint-Related Microplastics

The issue of microplastics originating from paints and coatings has emerged as a significant global environmental concern, contributing notably to marine pollution. These microplastics are released into the environment through various channels, including the application, wear, and removal of paints on surfaces such as roads, buildings, ships, and infrastructure. The degradation of these coatings over time results in the shedding of microplastic particles, which are then transported via wind, water runoff, and other means into oceans and waterways, causing threats to marine ecosystems and biodiversity [47]. International efforts are increasingly focusing on tackling this issue via comprehensive research, regulatory measures, and the development of sustainable alternatives. Organizations such as the United Nations Environment Programme (UNEP) have been instrumental in raising awareness and promoting actions to mitigate microplastic pollution. For instance, the UNEP has supported the development of international agreements and regional programs aimed at reducing marine plastic debris and microplastics, providing a foundation for establishing robust international rules on marine microplastic pollution at both global and regional levels [47]. In the European Union, significant strides have been made to regulate microplastics in paints and coatings. In 2023, the European Commission finalized a ban on synthetic polymer microparticles in mixtures, including paints, at concentrations of 0.01% or higher. This regulation aims to reduce the intentional addition of microplastics in products and is part of broader efforts under the Ecodesign for Sustainable Products Regulation (ESPR) to promote sustainability and minimize environmental impact. Similarly, countries like Japan and the United Kingdom have implemented measures to address microplastic pollution. Japan passed a bill in 2018 to reduce microplastic production and pollution, focusing on the personal care industry. The UK introduced the Environmental Protection (Microbeads) Regulations in 2017, banning the production of rinse-off personal care products containing microbeads, which are a significant source of microplastics. Furthermore, the Clean Oceans Initiative, launched in 2018 by public institutions including the European Investment Bank, aims to provide funding for projects that remove pollution from waterways before it reaches the oceans. As of December 2023, the initiative had funded almost €3.2 billion, exceeding 80% of its €4 billion objective, supporting projects in countries such as Sri Lanka, China, Egypt, South Africa, and several others. In conclusion, the global perspective on paint-related microplastics underscores the need for concerted international efforts to mitigate their environmental impact. Through collaborative research, stringent regulations, and the development of sustainable alternatives, significant progress can be made in reducing the release of microplastics from paints and coatings, thereby protecting marine ecosystems and promoting environmental sustainability [47].

2.6. Plastic Pellets (Nurdles)

Nurdles are small plastic pellets used as raw materials in plastic manufacturing. Accidental spills during transportation and handling can release these pellets into the environment. Once released, they can persist in aquatic ecosystems, posing threats to marine life [48]. Nurdles, though small in size, pose significant environmental challenges due to their persistence and impact on marine life. Mitigating nurdle pollution requires comprehensive strategies involving legislation, industry accountability, and community engagement. By addressing the root causes of nurdle spills and promoting sustainable practices, we can work towards safeguarding our oceans and marine ecosystems for future generations [48].

2.6.1. Environmental Impact of Nurdle Spills

Once released into the environment, nurdles can persist for extended periods, posing severe threats to marine ecosystems. Their small size allows them to be easily ingested by marine life, including fish, seabirds, and turtles, who often mistake them for food [49]. Ingestion of nurdles can lead to malnutrition, internal injuries, and even death due to the blockage of digestive systems. Furthermore, nurdles can absorb toxic chemicals from the surrounding environment, such as pesticides and heavy metals. When ingested by marine organisms, these toxins can enter the food chain, leading to bioaccumulation and adverse health effects on both wildlife and humans [49].

2.6.2. Notable Nurdle Spill Incidents

The environmental impact of nurdle spills has become a significant global concern, with notable incidents highlighting the widespread nature of this issue. Two such incidents, the X-Press Pearl disaster in 2021 and the MSC ELSA 3 spill in 2025, underscore the urgency of addressing microplastic pollution from maritime activities [50]. In May 2021, the Singapore-registered container ship X-Press Pearl caught fire and sank off the coast of Sri Lanka, releasing an estimated 1,680 tons of plastic nurdles into the ocean. These tiny plastic pellets, used as raw material in plastic manufacturing, washed up on Sri Lankan beaches, causing extensive environmental damage and affecting local communities. The spill was considered the world's worst plastic marine pollution incident at the time, with nurdles found along beaches from Mannar in the north to Kirinda in the south. The United Nations and local authorities collaborated on cleanup efforts, but the long-term ecological impacts remain a concern. More recently, in May 2025, the Liberian-flagged cargo vessel MSC ELSA 3 sank off the coast of India, releasing large amounts of plastic pellets into the sea. These nurdles spread through the Arabian Sea into the Bay of Bengal, with approximately two tonnes washing ashore in Tamil Nadu's Dhanushkodi flamingo sanctuary. This area, part of the ecologically sensitive Gulf of Mannar Biosphere Reserve, supports diverse species, including over 128 bird species and various marine life [50]. The spill has raised concerns about the potential ingestion of nurdles by marine organisms and the long-term effects on the ecosystem. These incidents highlight the need for stricter regulations and preventive measures to mitigate the environmental impact of nurdle spills. Implementing better containment systems on vessels, enhancing spill response capabilities, and promoting the use of biodegradable alternatives to plastic pellets are essential steps in addressing this global issue. Furthermore, international cooperation and information sharing are crucial in managing and preventing future nurdle spills, ensuring the protection of marine ecosystems and coastal communities worldwide [50].

2.6.3. Efforts to Address Nurdle Pollution

Addressing nurdle pollution necessitates a multifaceted approach encompassing legislative measures, community engagement, and industry accountability. These efforts aim to mitigate the environmental impact of plastic pellets, which are integral to plastic production but pose significant ecological risks when released into marine environments [51]. In the United States, legislative action has been initiated to curb nurdle pollution. The Plastic Pellet Free Waters

Act (HR 7634) was introduced to establish zero discharge limits for pre-production plastic pellets, thereby aiming to protect waterways and marine life from the adverse effects of plastic pellet pollution. This bill represents a proactive step in regulating the handling and transportation of plastic pellets, emphasizing the need for stringent controls to prevent environmental contamination [51]. Community initiatives play a pivotal role in addressing nurdle pollution by raising awareness and fostering public participation. In the United Kingdom, organizations like Nurdle Hunt have mobilized thousands of volunteers to collect data on nurdle sightings along coastlines. This citizen science project has documented the widespread presence of nurdles, providing valuable information that supports advocacy efforts for stricter regulations and industry accountability. Similarly, in Sri Lanka, The Pearl Protectors launched the Nurdle Free Lanka campaign in response to the X-Press Pearl disaster, engaging volunteers in cleanup activities and advocating for preventive measures to avoid future spills. These grassroots efforts underscore the importance of community involvement in combating plastic pollution [51]. Industry accountability is crucial in mitigating nurdle pollution. Advocacy groups have highlighted the inadequacies of voluntary industry measures, such as the Operation Clean Sweep initiative, in preventing pellet spills. For instance, the Plastic Soup Foundation has taken legal action against companies like Ducor Petrochemicals in the Netherlands, urging them to implement stricter controls and cleanup efforts to prevent plastic pellet leakage. These legal actions aim to enforce compliance and encourage the adoption of best practices in pellet handling and transportation. Additionally, the settlement of a lawsuit against Formosa Plastics in Texas, which resulted in a $50 million fine and a commitment to a zero-discharge policy, exemplifies the potential impact of legal measures in holding companies accountable for environmental damage [51]. Collectively, these efforts highlight the need for a comprehensive approach to addressing nurdle pollution. While legislative measures provide a framework for regulation, community initiatives and industry accountability ensure that these regulations are effectively implemented and enforced. Continued collaboration among governments, industries, and communities is essential to mitigate the environmental impact of nurdle pollution and protect marine ecosystems for future generations [51].

2.7. Industrial Abrasives

Industries use plastic microbeads as abrasives in processes like sandblasting and cleaning. These microbeads are often made from materials such as polyester and polycarbonate. If not contained, they can be released into the environment, contributing to microplastic pollution [52]. Plastic microbeads, while effective in industrial applications, contribute to microplastic pollution when not properly managed. Their persistence in the environment and potential harm to marine life highlight the need for alternative materials and improved waste management practices. Through regulatory measures, the adoption of biodegradable alternatives, and enhanced public awareness, the negative environmental impact of plastic microbeads can be reduced, leading to healthier aquatic ecosystems [52].

2.7.1. Environmental Impact of Industrial Abrasives

Plastic microbeads, small synthetic particles commonly found in personal care products like facial scrubs and toothpaste, have become a significant environmental concern due to their persistence, potential for ingestion by marine life, and ability to absorb harmful chemicals [53]. One of the most concerning aspects of microbeads is their persistence in the environment. These particles are designed to be small and often pass through water treatment facilities without being filtered out. As a result, they accumulate in aquatic ecosystems, contributing to the growing problem of microplastic pollution. For instance, a study conducted in Hong Kong found that microbeads accounted for 3.6% of the total microplastics collected in coastal waters, with concentrations ranging from 0 to 380,129 pieces per square kilometer [53]. Marine organisms can mistake microbeads for food due to their size and appearance. This ingestion can lead to physical harm, such as internal injuries or blockages, and may interfere with the digestive systems of these organisms. Moreover, microbeads can absorb toxic substances from the surrounding environment, including pesticides and heavy metals. When marine organisms ingest these contaminated microbeads, the toxic substances can enter the food chain, posing risks to both marine life and humans who consume seafood [53]. The environmental impact of microbeads is not limited to their ingestion by marine life. Their accumulation in aquatic ecosystems can disrupt the balance of these environments, affecting biodiversity and the health of marine habitats. Efforts to mitigate the environmental impact of microbeads include banning their use in personal care products, promoting the use of natural exfoliants, and improving waste management practices to prevent these particles from entering water systems. However, the persistence of microbeads in the environment underscores the need for continued research and action to address this pressing issue [54].

2.7.2. Regulatory Measures on Industrial Abrasives

In response to the growing environmental concerns associated with plastic microbeads, several countries have enacted regulations aimed at reducing their presence in consumer products. These legislative measures focus on minimizing the release of microbeads into the environment, particularly in aquatic ecosystems where they pose significant risks to marine life and human health [55]. In the United States, the Microbead-Free Waters Act of 2015 was signed into law, prohibiting the manufacture of rinse-off cosmetic products containing plastic microbeads. The law mandated that these products be removed from the market by July 1, 2018.This legislation was a significant step in addressing the environmental impact of microbeads, which are often used in products like facial scrubs and toothpaste. However, the law's scope was limited to rinse-off products, and it did not extend to other personal care items or cleaning products, leaving potential loopholes that some states have sought to address through more comprehensive regulations [55]. The European Union has also taken substantial steps to regulate microplastics. In October 2023, the EU implemented Regulation (EU) 2023/2055, which restricts the use of synthetic polymer microparticles intentionally added to products. This regulation targets a wide range of products, including cosmetics, detergents, waxes, polishes, air fresheners, fertilizers, and certain medical devices. The regulation sets specific transitional periods for the application of the ban, with deadlines ranging from 2027 to 2035, depending on the type of product. For instance, the ban on rinse-off cosmetic products is set to take effect in 2027, while the ban on lip products and nail products is scheduled for 2035.This phased approach allows industries time to transition to alternative formulations and ensures that the regulatory measures are effectively implemented [55]. These regulatory measures reflect a growing recognition of the need to address the environmental impact of microbeads and other microplastics. By limiting their use in consumer products, these laws aim to reduce the release of microplastics into the environment, thereby mitigating their harmful effects on marine ecosystems and human health. However, the effectiveness of these regulations depends on their comprehensive implementation and enforcement, as well as the development and adoption of sustainable alternatives to microplastics in consumer products [55].

2.7.3. Alternatives and Mitigation Strategies of Industrial Abrasives

To address the environmental challenges posed by plastic microbeads, several alternatives and mitigation strategies have been explored and implemented across various sectors. In the realm of industrial abrasives, biodegradable materials such as walnut shells, corncobs, and sand are being utilized as eco-friendly substitutes for plastic microbeads. These natural abrasives offer effective cleaning and polishing properties without contributing to microplastic pollution. For instance, walnut shells are used in abrasive blasting applications, providing a biodegradable option that reduces environmental impact [56]. Enhancing wastewater treatment processes is another critical strategy in mitigating microplastic pollution. Advanced filtration technologies, such as membrane bioreactors, have been implemented to improve the removal efficiency of microplastics from wastewater. These systems combine biological treatment with membrane filtration, effectively capturing microplastics before they are released into the environment [56]. Public awareness campaigns and industry commitments play a vital role in reducing the demand for plastic microbeads. Educational initiatives inform consumers about the environmental impacts of microbeads and encourage the use of products containing natural alternatives. Additionally, many companies have pledged to eliminate plastic microbeads from their products, opting for biodegradable materials instead. Collectively, these alternatives and strategies contribute to mitigating the environmental impact of plastic microbeads, promoting a shift towards more sustainable practices in industrial and consumer applications [56].

2.7.4. Secondary Sources of Microplastics

Secondary microplastics are not intentionally produced but arise from the breakdown of larger plastic items due to environmental factors. These microplastics are a remarkable concern due to their extensive presence and persistence in the environment. Below are some examples of their sources.

2.8. Degradation of Larger Plastic Items

Larger plastic debris, like bottles, bags, and fishing nets, degrade into smaller microplastic particles due to environmental factors such as UV radiation, thermal degradation, and mechanical wear. This process, called abiotic degradation, results in the fragmentation of plastics into microplastics that can continue in the environment [57].

2.9. Agricultural Practices

Agricultural activities contribute to microplastic pollution through the application of plastic mulches, which degrade over time into microplastics. Additionally, the application of sewage sludge as fertilizer introduces microplastics into soils. These microplastics can then enter the food chain, causing risks to human health. The degradation of larger plastic items into microplastics through agricultural activities represents a notable source of secondary microplastic pollution. By adopting sustainable agricultural practices, improving waste management, and implementing effectual regulations, the impact of microplastics in agriculture can be minimized, protecting both environmental and human health [58].

2.9.1. Plastic Mulches and Microplastic Pollution

Plastic mulches, often used in agriculture to suppress weeds, retain soil moisture, and enhance crop yields, are typically made from polyethylene (PE) or biodegradable polymers. Over time, exposure to sunlight, temperature fluctuations, and mechanical wear poses these mulches to degrade into smaller particles, resulting in microplastics. These microplastics can accumulate in the soil, affecting its structure and fertility. For example, studies have demonstrated that microplastics can change soil density and porosity, impacting water dynamics and soil aggregation. Furthermore, microplastics in the soil can alter the amount of carbon, nitrogen, and phosphorus, disrupt the nutrient cycle and probably harm soil organisms [59].

2.9.2. Sewage Sludge as a Source of Microplastics

Sewage sludge, the residual material from wastewater treatment plants, is commonly applied as a fertilizer due to its high organic matter content. However, this sludge can contain microplastics originating from different sources, including synthetic textiles, personal care products, and household waste. When applied to agricultural soils, these microplastics can accumulate and persist, resulting in long-term contamination. In the UK, for instance, more than 90% of sewage sludge is applied to agricultural land as a fertilizer and soil conditioner. Despite treatment processes, microplastics are not completely removed from the final product, resulting in their introduction into soils [60].

2.9.3. Entry into the Food Chain

Once in the soil, microplastics can be absorbed by plants through their roots. This uptake can lead to the incorporation of microplastics into eatable parts of crops, like fruits and vegetables. Additionally, soil organisms, including earthworms and insects, can ingest microplastics, which may then be transferred up the food chain to higher trophic levels, including humans. This bioaccumulation causes potential risks to human health, as the ingestion of microplastics has been associated with numerous adverse effects, including inflammation, oxidative stress, and potential endocrine disruption [61].

2.9.4. Mitigation Strategies

To tackle the issue of microplastic pollution in agriculture, several methods can be implemented. One approach is to reduce the application of plastic mulches by adopting alternative materials, like biodegradable mulches or organic mulching materials such as straw or wood chips. Additionally, improving the management of sewage sludge by enhancing treatment processes to remove microplastics and contaminants can decrease their introduction into soils. Implementing regulations to limit the use of contaminated sewage sludge and promoting the application of alternative fertilizers can further reduce the risks associated with microplastics in agriculture [62].

2.10. Urban Runoff

Urban areas are notable sources of microplastic pollution due to runoff from roads, construction sites, and other surfaces. Stormwater can transport microplastics from these areas into nearby water bodies, contributing to aquatic pollution. In urban environments, impermeable surfaces like roads, sidewalks, and parking lots accumulate various pollutants, including microplastics. When it rains, stormwater runoff washes these pollutants into nearby water bodies, resulting in contamination [63]. For instance, in Tijuana, Mexico, stormwater runoff from urban areas has been identified as a remarkable source of microplastic pollution in water bodies. The study found that the highest microplastic concentrations were recorded in industrial land-use sites, with polyethylene fibers being the most abundant polymer type. The estimated annual total microplastic loads ranged from 8×10^5 to 3×10^6 particles per hectare, highlighting the considerable contribution of urban runoff to microplastic pollution [63]. Similarly, in Hong Kong, a study collected stormwater and rainwater samples from different locations over multiple rainfall events. The results showed that microplastic concentrations in the initial road runoff were specifically high during rainfall episodes. The median microplastic abundance in the collected runoff samples was 185 particles per liter, which was 4.6 times higher than that in rainwater. Polyethylene, polypropylene, and polystyrene were the most common polymers identified, with fragments being the dominant shape. Over 60% of microplastic sizes were smaller than 300 μm in the runoff samples. Risk assessments showed moderate to high ecological risks associated with microplastic pollution from road runoff [64]. These studies emphasize the significant role of urban runoff in transporting microplastics to aquatic ecosystems. The high concentrations of microplastics in stormwater runoff, particularly during initial stages of rainfall, cause threats to water quality and aquatic life. The persistence and accumulation of microplastics in water bodies can lead to long-term environmental impacts, including the ingestion of microplastics by aquatic organisms and potential bioaccumulation via the food chain [64]. Tackling microplastic pollution from urban runoff requires comprehensive stormwater management strategies. Implementing measures like improved drainage systems, green infrastructure such as rain gardens and permeable pavements, and public education on reducing plastic waste can help reduce the transport of microplastics into water bodies. Moreover, monitoring and regulating industrial discharges and construction activities can further mitigate the contribution of microplastics from urban sources. Urban areas are notable contributors to microplastic pollution through runoff from roads, construction sites, and other surfaces. Stormwater serves as a major pathway for transporting microplastics into aquatic ecosystems, causing risks to water quality and aquatic life. Implementing effectual stormwater management strategies and regulatory measures is crucial to reduce the impact of microplastics and protect aquatic environments [63, 64].

2.11. Atmospheric Deposition

Atmospheric deposition is an emerging and remarkable source of secondary microplastic pollution. Microplastics can become airborne through numerous processes, including the abrasion of synthetic materials and the degradation of larger plastic items. Once airborne, they can be transported over long distances and deposited into terrestrial and aquatic environments, contributing to extensive pollution. In urban environments, microplastics are released into the atmosphere via activities like vehicle emissions, tire and brake wear, and the degradation of synthetic materials such as textiles and plastics. These particles can remain suspended in the air for longer periods, depending on their size and density [65]. For example, a study in Guangzhou, China, found that atmospheric deposition fluxes of microplastics ranged from 51 to 178 particles per square meter per day, with fibers being the most abundant type. Similarly, in central London, microplastics were found in all atmospheric samples, with deposition rates ranging from 575 to 1,008 microplastics per square meter per day, mostly in fibrous forms. Once in the atmosphere, microplastics can be transported over long distances by wind currents. Studies have detected microplastics in remote areas, like the French Pyrenees, far from known pollution sources. This suggests that atmospheric transport plays a pivotal role in the global distribution of microplastics [65]. The deposition of airborne microplastics occurs via both wet and dry processes. Wet deposition involves the removal of particles from the atmosphere by precipitation, while dry deposition occurs when particles settle out of the air due to gravity. These deposited microplastics can accumulate in soils, water bodies, and on vegetation, probably entering the food chain. For instance, microplastics have been found in agricultural soils, where they can affect soil health and crop productivity. The extensive presence of airborne microplastics causes notable environmental and health risks. Inhalation of these particles can lead to respiratory issues, inflammation, and other health problems. Additionally, the accumulation of microplastics in ecosystems can harm wildlife and disrupt ecological balance. For example, a study found microplastics in bird lungs, indicating that airborne particles can be inhaled and accumulate in animals [65].

2.11.1. Mitigation Strategies to address Atmospheric Microplastic

Mitigation strategies to tackle atmospheric microplastic pollution include reducing the use of synthetic materials, improving waste management practices, and implementing air filtration systems in industrial and urban areas. Additionally, further research is needed to understand the sources, transport mechanisms, and impacts of airborne microplastics to develop effectual policies and regulations. In conclusion, atmospheric deposition is a remarkable pathway for the distribution of microplastics, contributing to their extensive presence in the environment. Tackling this issue requires comprehensive strategies that encircle source reduction, pollution control, and increased public awareness [66].

3. Formation Mechanisms of Microplastics

Microplastics are formed via distinct processes. Understanding these formation mechanisms is imperative for addressing the pervasive environmental and health challenges they cause.

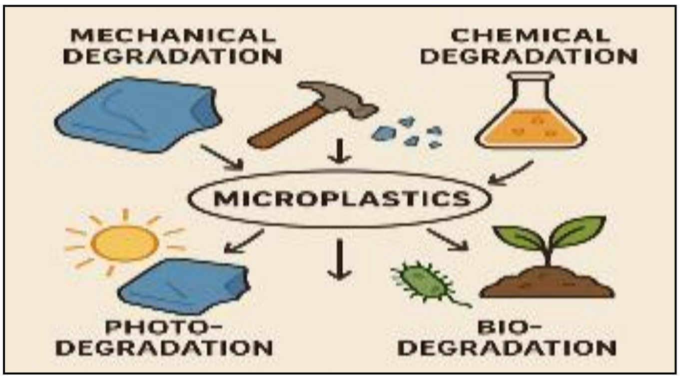


Figure 2 Formation Mechanisms of Microplastics

3.1. Mechanical Degradation or Fragmentation

Mechanical degradation is a remarkable pathway for the formation of microplastics, resulting from the physical breakdown of larger plastic items into smaller particles because of various mechanical forces such as abrasion, collision, and shear stress [67]. These forces can trigger the plastic to crack and fragment into smaller pieces. This process is especially widespread in everyday human activities and natural environmental conditions, leading to the common presence of microplastics in ecosystems. Mechanical degradation is an outstanding contributor to microplastic pollution, with various human activities and natural processes resulting to the breakdown of plastic materials into smaller particles. Addressing this issue requires a many-sided approach involving technological advancements, policy interventions, and public engagement to reduce the environmental and health impacts of microplastics [68].

3.1.1. Mechanisms of Mechanical Degradation

- **Abrasion** occurs when plastic materials experience frequent friction against other surfaces. In domestic settings, the washing of synthetic textiles such as polyester, nylon, and acrylic is a primary source of microplastic production. Each wash cycle can liberate thousands of microfibers into wastewater systems, which always lack adequate filtration to remove them, resulting to their discharge into rivers and oceans. These microfibers are small enough to be taken in by marine organisms, entering the food chain and causing ecological and health risks [69].

- **Wear and Tear** involves the progressive degradation of plastic materials as a result of continuous use and mechanical stress. For example, vehicle tires, composed of synthetic rubber, undergo regular friction with road surfaces, resulting in the shedding of tiny rubber particles. These particles, often less than 5 millimeters in size, are released into the environment via tire wear and tear. Studies have estimated that tire wear contributes tremendously to microplastic pollution, with emissions ranging from 0.23 to 4.7 kg per capita annually, depending on factors like vehicle type and driving conditions [69, 70].

- **Mechanical Fragmentation** can also occur as a result of production, maintenance, and disposal of plastic products. Processes like cutting, sanding, and grinding can produce microplastic particles. Additionally, plastic items introduced to mechanical stress during daily use, like opening and closing plastic containers or bottles, can develop microcracks that propagate over time, resulting in the release of microplastic fragments [70].

3.1.2. Environmental Implications of Microplastics generated through mechanical Degradation

The microplastics produced via mechanical degradation are persistent in the environment because of the durability of plastic materials. These particles can accumulate in different ecosystems, including marine, freshwater, and terrestrial habitats. Once in the environment, microplastics can be taken in by a wide range of organisms, from plankton to large marine mammals, resulting to potential health impacts such as physical harm, chemical toxicity, and bioaccumulation of toxic substances. Moreover, microplastics can serve as vectors for injurious chemicals and pathogens, further exacerbating their environmental impact.

3.1.3. Mitigation Strategies of microplastic pollution resulting from mechanical degradation

Tackling microplastic pollution resulting from mechanical degradation necessitates a many-sided approach encompassing technological advancements, sustainable product design, public education, and meticulous scientific research. Upgrading wastewater treatment facilities is key in capturing microplastics before they infiltrate natural water bodies. Traditional treatment methods always fall short in filtering out these tiny particles. However, the integration of advanced filtration systems, like as membrane bioreactors, electrocoagulation, and chemical coagulation, has proven promise in enhancing removal efficiencies. For example, electrocoagulation has demonstrated removal efficiencies exceeding 90% for microplastics under optimal conditions [71]. These innovations represent significant strides toward reducing microplastic contamination at the source. Product design plays a vital role in mitigating microplastic pollution. Encouraging manufacturers to adopt materials less susceptible to shedding microplastics can greatly decrease environmental impact. The development and utilization of biodegradable alternatives, like bioplastics derived from renewable resources like cornstarch or algae, offer a sustainable solution to this problem. These materials are designed to break down more readily in the environment, thereby mitigating the persistence of microplastics [71]. Public awareness and behavior change are integral to fighting microplastic pollution. Educational campaigns can inform individuals about the sources and impacts of microplastics, resulting in more responsible consumption and disposal practices. Initiatives such as beach cleanups, school programs, and social media campaigns have shown effective in engaging communities and fostering a culture of environmental stewardship. By empowering the public with knowledge, these efforts can bring collective action toward mitigating microplastic pollution. Investing in research and monitoring is vital to understand the sources, distribution, and impacts of microplastics. Regular scientific inquiry aids the development of effective policies and interventions. Innovations like biodegradable sponges made from cotton and squid bone have shown the capacity to absorb up to 99.9% of microplastics in water, highlighting the potential of new materials in addressing this problem. Furthermore, real-time monitoring systems can track microplastic concentrations, informing timely responses and management strategies. A comprehensive approach involving technological innovation, sustainable design, public engagement, and scientific research is imperative in reducing microplastic pollution resulting from mechanical degradation. Concerted efforts across various sectors can lead to significant mitigations in microplastic contamination, safeguarding aquatic ecosystems and public health [71].

3.2. Photodegradation

Photodegradation, or photo-oxidation, is a remarkable environmental process contributing to the formation of microplastics. This mechanism involves the breakdown of plastic polymers when exposed to ultraviolet (UV) radiation from sunlight, resulting in the fragmentation of larger plastic items into smaller microplastic particles [72].

Mechanism of photodegradation of plastics to microplastics

Photodegradation, also called photo-oxidation, is a notable environmental process contributing to the formation of microplastics. This mechanism involves the breakdown of plastic polymers when exposed to ultraviolet (UV) radiation from sunlight, resulting in the fragmentation of larger plastic items into smaller microplastic particles. The photodegradation process can be divided into many stages: initiation, propagation, branching, and termination [73].

- **Initiation**: The process begins when UV radiation is absorbed by the plastic polymer chains, particularly by chromophores like carbonyl groups present in the polymer structure. This energy absorption results to the formation of excited states in the polymer molecules, making them more reactive. As a result, chemical bonds within the polymer chains, particularly carbon–carbon (C–C) bonds, become weakened and prone to breaking. This bond scission generates free radicals, which are extremely reactive species that initiate the degradation process.
- **Propagation:** As soon as free radicals are formed, they react with molecular oxygen present in the environment to produce reactive oxygen species (ROS) like peroxyl and alkoxyl radicals. These ROS further attack the polymer chains, resulting in the formation of hydroperoxides and other oxygenated functional groups. The presence of these functional groups, such as carbonyl and hydroxyl groups, indicates ongoing oxidative degradation of the polymer. This stage results in the gradual reduction of the polymer's molecular weight, making the material more brittle and susceptible to fragmentation.
- **Branching:** In this stage, the degradation process becomes more complex. The hydroperoxides formed during propagation can decompose to generate additional free radicals, leading to chain branching. This branching creates a network of interconnected polymer chains, further reducing the material's structural integrity. The accumulation of these branched structures contributes to the formation of microplastics, as the material becomes increasingly fragmented and less cohesive.
- **Termination:** The degradation process concludes when the free radicals recombine or disproportionate, resulting in the formation of stable, inert products. These products, which may include smaller polymer fragments, volatile organic compounds, and other degradation by-products, are typically less injurious than the original polymer. Nevertheless, the accumulation of these microplastic particles in the environment contributes significant ecological and health risks. Throughout these stages, various environmental factors can influence the rate and extent of photodegradation. For example, temperature, humidity, and the presence of other substances can accelerate or inhibit the degradation process. Additionally, the chemical structure of the polymer plays a vital role; polymers with aromatic groups or conjugated double bonds are more prone to photodegradation due to their ability to absorb UV radiation effectively. Understanding the mechanisms and stages of photodegradation is essential for developing strategies to reduce the formation of microplastics and their associated environmental impacts [73].

3.2.1. Examples of Photodegradation in Different Plastics

Different types of plastics exhibit varying susceptibilities and degradation pathways under UV exposure, influenced by their chemical structures and environmental conditions [74]. Expanded polystyrene (EPS), commonly used in packaging, is highly susceptible to photodegradation due to its unique foamed structure, composed of thin layers. A study found that EPS exposed to sunlight for 24 months produced approximately 6.7×10^7 micro- and nanoparticles per square centimeter. The foamed structure of EPS makes it more vulnerable to fragmentation than bulk plastics. Under UV irradiation, the polymer chains in EPS undergo photo-oxidation, leading to the formation of free radicals that initiate the breakdown of the material into smaller particles. These microplastics can persist in the environment, contributing to pollution. Polypropylene (PP), another commonly used plastic, undergoes photodegradation through free radical chain reactions when exposed to UV radiation. In marine environments, UV irradiation can produce free radicals that lead to the dissociation of carbon-carbon (C–C) and carbon-hydrogen (C–H) bonds from the polymer backbone, inducing chain scission and cross-linking reactions. This process contributes to the formation of microplastics in the marine environment. The presence of salts and dissolved organic matter in seawater can further accelerate the photodegradation of PP, leading to more rapid fragmentation and increased microplastic formation. Polylactic acid (PLA), a biodegradable plastic, degrades differently under UV exposure. The photodegradation of PLA occurs mainly through the cleavage of ester bonds, leading to the formation of smaller fragments. The degradation mechanism of PLA involves Norrish type I and II reactions, as well as radical oxidation reactions, resulting in the formation of microplastics in the marine environment. These processes are influenced by the chemical structure of PLA, which contains ester linkages that are susceptible to hydrolysis and photolysis under UV radiation. The photodegradation of different plastics involves complex chemical processes that lead to the formation of microplastics. The rate and extent of degradation depend on factors such as the chemical structure of the polymer, the presence of environmental factors like UV radiation and seawater, and the duration of exposure. Understanding these mechanisms is crucial for developing strategies to mitigate the environmental impact of microplastics and to design more sustainable materials [74].

3.2.2. Factors Influencing Photodegradation of plastics

The photodegradation of plastics is influenced by a combination of factors, including the color of the plastic, its polymer composition, and prevailing environmental conditions. Understanding these factors is essential for predicting the lifespan of plastic materials in various environments and for developing strategies to mitigate their environmental impact. By considering these variables, we can better address the challenges posed by plastic pollution and work towards more sustainable material usage and waste management practices [75].

3.2.3. Color of Plastics

The color of plastic materials significantly affects their susceptibility to photodegradation. Brightly colored plastics, such as red, blue, and green, tend to degrade more rapidly when exposed to environmental conditions [76]. This increased degradation rate is due to the presence of specific pigments that absorb ultraviolet (UV) radiation, leading to the formation of free radicals that initiate the breakdown of the polymer chains. For instance, a study found that polypropylene bottle tops with red, blue, and green pigments exhibited significant degradation over a three-year period, while black, white, and silver plastics remained largely unaffected. The black and white plastics often contain carbon black and titanium dioxide, respectively, which can act as stabilizers, reducing the rate of photodegradation. Conversely, the specific pigments in brightly colored plastics can enhance UV absorption, accelerating the degradation process [76].

3.2.4. Polymer Composition

The chemical structure of the polymer plays a pivotal role in determining its resistance to photodegradation. Polymers with aromatic groups or conjugated double bonds are more susceptible to UV-induced degradation due to their ability to absorb UV radiation effectively. For example, polyethylene terephthalate (PET) exhibits moderate UV resistance, while polyolefins like polypropylene (PP) and polyethylene (PE) are highly susceptible to photodegradation. The presence of ester bonds in PLA makes it more prone to hydrolytic degradation, especially under humid conditions. These structural characteristics influence how the polymer absorbs UV radiation and undergoes chemical transformations, leading to the formation of microplastics [77].

3.2.5. Environmental Conditions

Environmental factors such as temperature, humidity, and the presence of other substances can significantly influence the rate of photodegradation. Elevated temperatures can accelerate the degradation process by increasing the kinetic energy of molecules, leading to more frequent and energetic collisions [78]. For instance, studies have shown that the photodegradation of PET is more pronounced at higher temperatures, with the formation of carboxylic acids and other degradation products. Humidity also plays a crucial role, particularly in hydrolytic and biological degradation. The presence of water is essential for hydrolysis reactions and provides a conducive medium for microbial growth and enzyme activity. High humidity conditions promote the absorption of moisture into the polymer matrix, accelerating hydrolytic degradation. For example, in tropical regions with high humidity, polymers are more prone to rapid degradation. Conversely, in arid environments, the scarcity of moisture limits hydrolytic and biological degradation, thus preserving the integrity of polymers for a longer duration [78].

3.2.6. Environmental Implications of photodegradation of plastics

The fragmentation of plastics into microplastics through photodegradation has several environmental implications [79].

3.2.7. Marine Pollution

Microplastics have become pervasive pollutants in marine environments, posing significant threats to aquatic life. Marine organisms, including fish, mollusks, and filter-feeding species like mussels, can ingest microplastics, leading to physical harm and potential toxicological effects [57]. For instance, a study conducted in West Bengal, India, found microplastics in over 80% of freshwater mussels analyzed, with potential risks of microplastics entering tissues like the gastrointestinal tract, potentially causing inflammation, oxidative stress, genetic damage, and even cell death [56, 57]. The ingestion of microplastics by marine organisms can disrupt their feeding and digestive processes, leading to reduced energy intake and potential starvation. Additionally, microplastics can accumulate in the food web, affecting predators higher up the chain, including humans who consume seafood. The persistence of microplastics in marine environments further exacerbates these issues, as they can remain in the ecosystem for extended periods, continuously impacting marine life [80].

3.2.8. Soil Contamination

Microplastics can also accumulate in soils, affecting soil health and potentially entering the food chain. The presence of microplastics in agricultural soils can alter soil properties such as structure, performance, and microbial diversity. For example, microplastics can affect soil density and porosity, which can impact water dynamics and soil aggregation, leading to reduced soil fertility and plant growth. Furthermore, microplastics in soil can serve as vectors for pathogens and antibiotic-resistant bacteria. Studies have shown that microplastics can harbor harmful microorganisms, which can be transferred to plants and subsequently enter the food chain. This poses significant risks to food safety and human health [79, 80].

3.2.9. Human Health Risks

The ingestion of microplastics by humans, either directly or through the food chain, raises concerns about potential health risks. Studies have found microplastics in various human tissues, including blood, semen, and breast milk, indicating widespread exposure [70]. Microplastics can cause inflammation, oxidative stress, and disturbances in lipid metabolism. They can also interfere with the intestinal microbiome, leading to gastrointestinal symptoms such as abdominal pain and bloating. Additionally, microplastics can carry environmental toxins like heavy metals and polycyclic aromatic hydrocarbons, which can enter the body via the gastrointestinal tract, causing nausea, vomiting, and abdominal pain. Furthermore, microplastics have been linked to respiratory symptoms when inhaled, including coughing, sneezing, and shortness of breath due to reduced blood oxygen levels, inflammation, damage, fatigue, and dizziness. Recent research also indicates that nano-sized plastics may cause mitochondrial damage in human respiratory cells [81]. The fragmentation of plastics into microplastics through photodegradation has far-reaching environmental implications. These tiny particles can accumulate in marine environments, affect soil health, and pose significant risks to human health. Addressing the issue of microplastics requires concerted efforts to reduce plastic usage, improve waste management practices, and develop materials that are less prone to degradation into microplastics [81].

3.3. Chemical Degradation of Plastics into Microplastics

Chemical degradation is a significant pathway through which plastics break down into microplastics in the environment. This process involves chemical reactions such as oxidation and hydrolysis, which are influenced by environmental factors like ultraviolet (UV) radiation, temperature, humidity, and the presence of reactive chemicals [82].

3.3.1. Chemical Oxidation

Oxidation is a primary mechanism in the chemical degradation of plastics, particularly polyolefins like polyethylene (PE) and polypropylene (PP). This process involves the reaction of polymer chains with oxygen, leading to the formation of free radicals and subsequent chain scission, which results in the breakdown of large polymer molecules into smaller fragments characteristic of microplastics [82, 83]. In the presence of oxygen and ultraviolet (UV) radiation, polymers undergo oxidative reactions that lead to the formation of free radicals. These free radicals can initiate chain scission, breaking the long polymer chains into shorter fragments. For example, when plastics like polyethylene (PE) or polypropylene (PP) are exposed to UV light, the energy from the UV photons can be absorbed by the polymer chains, weakening the chemical bonds that hold the chains together. This weakening leads to chain scission and the formation of smaller polymer fragments. Additionally, the presence of ozone (O_3) in the atmosphere can accelerate this process. Ozone reacts with unsaturated carbon-carbon (C=C) double bonds in the polymer structure, generating reactive oxygen species such as hydroxyl radicals (•OH), which further degrade the polymer chains into microplastic particles [83].The degradation of polyethylene in molecular oxygen between 150 and 250°C., in ozone-enriched O_2 between 20 and 109°C., and in fuming HNO_3 between 25 and 83°C. has been studied. The solid, liquid, and vapor products have been analyzed by means of their infrared spectra. Kinetically, the O_2 oxidation reaction appears to be second order. The Elvish chemisorption equation ds/dt = ae^−αq was applied to the data and yielded comparable results. The kinetics were followed by pressure change and constant pressure measurements of oxygen uptake, and by the rate of increase of chemical structure image bands in the infrared spectra. The activation energy of the process was found to be 8–9 kcal. /Mole for the volumetric and manometric studies as well as for the ozone-catalyzed reaction, while the HNO_3 oxidation gave a 35.6 kcal. value. The presence of ozone (O_3) in the atmosphere can accelerate this process. Ozone reacts with unsaturated carbon-carbon (C=C) double bonds in the polymer structure, generating reactive oxygen species such as hydroxyl radicals (•OH), which further degrade the polymer chains into microplastic particles.

3.3.2. Hydrolysis

Hydrolysis involves the chemical breakdown of polymers through reaction with water. This process is particularly significant for condensation polymers like polyesters (e.g., polyethylene terephthalate or PET) and polyamides. In the presence of water, hydrolysis can cleave ester or amide bonds in the polymer backbone, leading to the formation of smaller oligomers or monomers. For instance, PET can undergo hydrolytic degradation in aqueous environments, especially under acidic or basic conditions, resulting in the production of terephthalic acid and ethylene glycol. These smaller molecules can further degrade into microplastic particles [84].

3.3.3. Environmental Factors Influencing Chemical Degradation

The rate and extent of chemical degradation are influenced by various environmental factors. Temperature plays a crucial role; higher temperatures can accelerate chemical reactions, leading to faster degradation of plastics. For example, in marine environments, the combination of UV radiation and elevated temperatures can significantly enhance the chemical breakdown of plastics. Humidity also affects degradation; higher humidity levels can facilitate hydrolytic degradation by providing more water molecules for the reaction. Additionally, the presence of pollutants such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) can contribute to the formation of reactive species like ozone, further promoting the chemical degradation of plastics [85].

3.3.4. Implications of Chemical Degradation

Chemical degradation not only leads to the formation of microplastics but also alters the chemical composition and physical properties of the plastic materials. The breakdown products can include a range of smaller organic molecules, some of which may be toxic or persistent in the environment. Moreover, the degradation process can increase the surface area and porosity of microplastics, enhancing their ability to adsorb other pollutants and potentially increasing their toxicity. This transformation underscores the complex environmental challenges posed by microplastics and highlights the need for comprehensive strategies to mitigate their impact. chemical degradation through oxidation and hydrolysis plays a pivotal role in the formation of microplastics. Understanding the mechanisms and influencing factors of this process is essential for developing effective measures to address microplastic pollution and its associated environmental risks [86].

3.4. Biodegradation

Biodegradation is a natural process wherein microorganisms such as bacteria and fungi break down biodegradable plastic polymers into smaller, less complex compounds. This process is particularly significant for plastics like polylactic acid (PLA), which are designed to be biodegradable. However, the efficiency and rate of biodegradation can vary based on several environmental factors, including temperature, humidity, and nutrient availability [87]. Microorganisms capable of degrading PLA typically produce specific enzymes that target the polymer's ester bonds. For instance, certain bacterial strains like *Bacillus safensis* have been isolated from environments such as landfill soils and shown to produce proteases and lipases that facilitate the breakdown of PLA. These enzymes hydrolyze the ester linkages in PLA, leading to the formation of lactic acid monomers and oligomers, which the microorganisms can then utilize as carbon sources. Studies have demonstrated that under optimal conditions, such as a temperature of 30°C and neutral pH, these bacteria can degrade PLA films by approximately 8% over a 30-day period. Scanning electron microscopy analyses reveal surface etching on the PLA films, indicating microbial activity [87]. Additionally, Fourier-transform infrared spectroscopy (FTIR) analyses show a decrease in the intensity of all absorption peaks, suggesting a reduction in the polymer's molecular weight and structural integrity. Fungal species also play a role in PLA biodegradation. For example, *Amycolatopsis* strains produce proteases that can degrade PLA films. Under laboratory conditions, these strains have been observed to degrade PLA films by approximately 60% within 14 days. The enzymatic activity of these fungi contributes to the breakdown of PLA into smaller fragments, which can then be further mineralized by other microorganisms. The rate of PLA biodegradation is significantly influenced by environmental conditions. High temperatures and humidity levels accelerate the hydrolysis of ester bonds in PLA, promoting microbial colonization and enzymatic activity. For instance, industrial composting facilities maintain elevated temperatures and moisture levels that facilitate the rapid degradation of PLA [87]. In contrast, colder and drier environments, such as marine or desert settings, slow down the biodegradation process, leading to the persistence of PLA in these ecosystems. Nutrient availability also affects the efficiency of PLA biodegradation. Microorganisms require essential nutrients like nitrogen and phosphorus to produce the enzymes necessary for plastic degradation. In nutrient-limited environments, the production of these enzymes may be insufficient, hindering the biodegradation process. Supplementing the environment with these nutrients can enhance microbial activity and accelerate the breakdown of PLA. while biodegradation offers a promising method for mitigating plastic pollution, its effectiveness is contingent upon favorable environmental conditions and the presence of specific microorganisms capable of producing the requisite enzymes. Understanding and optimizing these factors are crucial for developing strategies to address plastic waste through biological means [87].

4. Quantification Techniques

Quantifying microplastics in environmental samples is a scrupulous process that involves various critical steps: sampling, separation, analysis, and data interpretation. Each step is designed to ensure appropriate identification, quantification, and characterization of microplastics, which are crucial for comprehending their distribution and impact.

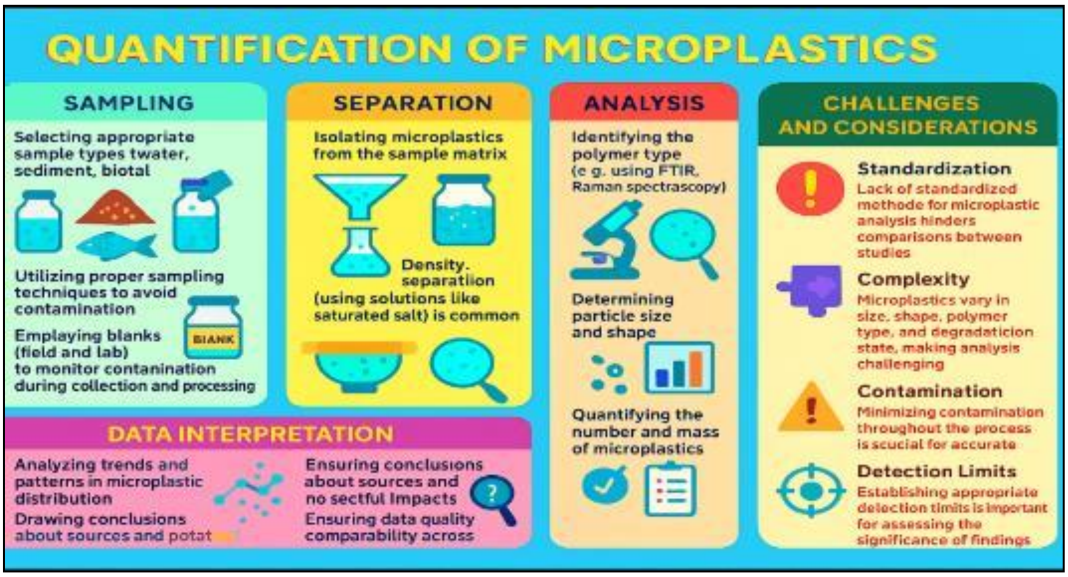


Figure 3 Various Quantification Techniques for Microplastics

4.1. Sampling

Sampling serves as the keystone in the study of microplastics, laying the groundwork for successive analysis and interpretation. The integrity and dependability of research findings hinge on the diligent collection of representative samples from different environmental matrices, including water, sediment, soil, and biota. Each matrix presents outstanding challenges and necessitates tailored sampling methods to ensure precise representation and minimize contamination risks. In aquatic environments, water sampling is frequently conducted using nets or bottles. For example, the GR-91 rod dredger with a 300 cm^3 bucket volume is employed to collect water samples from lakes and rivers. Similarly, the Ruttner bathometer, with a 5 dm^3 volume, is utilized to sample water from particular depths. These methods ease the collection of large volumes of water, which are then filtered to isolate microplastics [88]. It's important to use clean, contamination-free equipment and to follow standardized protocols to avoid introducing external microplastics into the samples. For instance, in a study conducted in Kazakhstan, water samples were collected using metal buckets and bathometers, and filtration was carried out using Sefar polyamide mesh with a 100 µm mesh size to concentrate microplastics. Sediment sampling involves collecting surface layers, typically the top 5 cm, using metal tools such as shovels or corers. In marine environments, devices such as the Ekman grab sampler are used to obtain sediment samples. Once collected, sediments are commonly sieved and subjected to density separation techniques to isolate microplastics [89]. For instance, in a study in the Philippines, beach sediments were collected using metal shovels, dried, sieved, and then subjected to density separation to extract microplastics. Soil sampling requires meticulous consideration of spatial variability. Methods such as random, transect, or incremental sampling are employed to capture the heterogeneity of soil matrices. Soil cores are typically collected using hand augers or split spoon samplers. It's crucial to ensure that all samples are collected at consistent depths and that cross-contamination is minimized. For example, the Interstate Technology & Regulatory Council (ITRC) recommends using non-plastic sample collection and storage containers and implementing accurate cleaning procedures for sampling equipment [90]. Sampling of biota involves capturing organisms from different trophic levels, like plankton, fish, or invertebrates. The sample size should be sufficient to provide statistically remarkable results, with recommendations suggesting at least 50 individuals per research unit. Biota samples are typically stored on ice or frozen at −20°C until analysis. It's imperative to handle these samples in clean air facilities to avoid contamination. For instance, a study published in Environmental Science & Technology emphasizes the importance of clean air conditions and thorough washing of materials and equipment when processing biota samples [88, 89, 90, 91]. To ensure the accuracy and reliability of microplastic analyses, strict contamination control measures must be implemented throughout the sampling process. This includes the application of clean, non-plastic equipment, thorough cleaning and rinsing of tools, and the use of appropriate storage containers. Additionally, procedural blanks should be run to assess contamination during sample processing. For example, in a study assessing microplastics in laundry effluents, field and laboratory blanks were collected and analyzed simultaneously with samples to evaluate potential contamination [92]. Effectual sampling is paramount in microplastic research. By employing appropriate sampling methods tailored to each environmental matrix and implementing rigorous contamination control measures, researchers can obtain dependable data that accurately reflects the presence and distribution of microplastics in the environment.

4.2. Separation

This is the process of isolating microplastics from the collected samples. This step typically involves several techniques to concentrate and purify microplastics

4.2.1. Filtration

Using filters with specific pore sizes to separate microplastics based on their size. Materials such as glass fiber, cellulose, or polytetrafluoroethylene are often used for filtration. The choice of filter material and pore size depends on the expected size range of microplastics and the analytical techniques to be adopted.

4.2.2. Density Separation

Exploiting the difference in density between microplastics and the surrounding matrix. For instance, using salt solutions (e.g., sodium chloride or zinc chloride) to separate microplastics from sediments, as microplastics typically have a lower density and will float to the surface. This method is especially useful for sediment and soil samples [93].

4.2.3. Chemical Digestion

It involves using chemical agents to break down organic matter in the sample, leaving behind the microplastics. Often used chemicals include hydrogen peroxide (H_2O_2) for sediments and potassium hydroxide (KOH) or nitric acid (HNO_3) for biological samples. Care must be taken to avoid damaging the microplastics during this process.

4.3. Analysis

Quantifying microplastics in environmental samples is a complex task that requires accurate and reliable analytical methods. The choice of technique depends on factors like the type of sample, the size and composition of microplastics, and the specific objectives of the study. Spectroscopic techniques, especially Fourier Transform Infrared (FTIR) and Raman spectroscopy, are extensively employed for microplastic identification and quantification. FTIR is effectual for detecting microplastics larger than 20 μm and can identify a broad range of polymers by analyzing their absorption of infrared light. Raman spectroscopy, on the other hand, offers higher spatial resolution and is capable of detecting smaller microplastics, sometimes down to a few micrometers. Both methods provide chemical fingerprints of microplastics, allowing for their identification and quantification within complex environmental matrices [94]. Another advanced technique is Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), which thermally decomposes microplastics into smaller compounds that can be analyzed for identification and quantification. This method is specifically useful for analyzing a wide range of polymers and can be applied to different environmental samples, including soils and sediments. For high-throughput analysis, fluorescent dye staining combined with fluorescence microscopy and image analysis software offers a semi-automated approach to quantify microplastics. Dyes such as Nile Red bind to microplastics, enhancing their visibility under specific lighting conditions. This method is effectual for detecting smaller microplastics and can be coupled with software such as ImageJ to automate counting and categorization. Additionally, techniques like Laser Diffraction Particle Size Analysis and Dynamic Light Scattering are adopted to determine the size distribution of microplastics in environmental samples. These methods are specifically useful for analyzing nano plastics and understanding the particle size distribution, which is imperative for assessing potential environmental and health impacts. The quantification of microplastics involves a combination of sampling, sample preparation, and analytical techniques tailored to the specific characteristics of the microplastics and the environmental matrix. The integration of different methods enhances the reliability and comprehensiveness of microplastic analyses, contributing to a better understanding of their prevalence and impact in the environment [94].

4.4. Data Interpretation

This involves analyzing the results to find out the concentration, distribution, and characteristics of microplastics in the samples. This step requires meticulous statistical analysis to account for potential biases and uncertainties introduced during sampling and analysis. The results are then compared with environmental standards or benchmarks to assess the potential impact of microplastics on ecosystems and human health [95]. Quantifying microplastics is a complex, multi-step process that requires meticulous planning and execution. Each step, from sampling to data interpretation, plays a pivotal role in ensuring accurate and reliable results. Standardized protocols and quality control measures are crucial to minimize errors and ensure the comparability of results across different studies [95].

5. Environmental Impacts of Microplastics

Microplastics have become prevalent pollutants impacting ecosystems across the globe. Their small size, durability, and common presence cause remarkable threats to both environmental and human health.

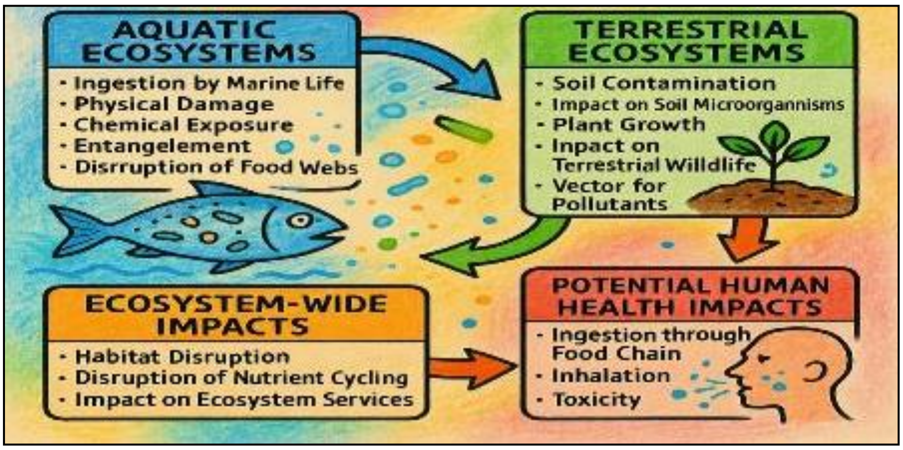


Figure 4 Environmental Impacts of Microplastics

5.1. In marine environments

Microplastics have infiltrated marine ecosystems worldwide, posing notable threats to marine life and the health of oceanic environments. These particles originate from different sources, including the breakdown of larger plastic debris, synthetic fibers from textiles, and microbeads in personal care products. Due to their small size and buoyancy, microplastics are easily taken in by a wide range of marine organisms, from microscopic plankton to large marine mammals [96]. Ingestion of microplastics can result in physical harm in marine organisms. For example, microplastics can accumulate in the digestive tracts of fish, resulting in internal injuries, blockages, and reduced feeding efficiency. This accumulation can result in malnutrition, stunted growth, and decreased reproductive success [96, 97]. In some cases, the ingestion of microplastics can pose false satiation, where organisms feel full despite not obtaining adequate nutrition. Additionally, sharp-edged microplastics may injure gill tissues and the intestinal tract, resulting in inflammation and increased susceptibility to infections. Beyond physical harm, microplastics can also introduce harmful substances into the marine food chain. These particles can absorb injurious chemicals from the surrounding water, like persistent organic pollutants (POPs), heavy metals, and pesticides. When marine organisms ingest microplastics, these toxic substances can enter their bodies, leading to bioaccumulation. As smaller organisms are consumed by larger predators, the concentration of these harmful substances increases up the food chain, a process known as biomagnification. This can have detrimental effects on marine biodiversity, impairing the health of entire ecosystems [97]. The impact of microplastics extends to different marine species. Plankton, the base of the marine food web, is especially vulnerable to microplastic pollution. Zooplankton can mistake microplastics for food, resulting in reduced nutritional intake and lower reproductive success. Since plankton is a primary food source for many marine species, including fish and whales, the impact of microplastics at this level can ripple through the entire food web, potentially affecting higher trophic levels. Fish species have demonstrated reduced energy reserves and stunted growth after consuming microplastics, which can affect their ability to survive and reproduce. Marine mammals, such as whales and dolphins, have been found with microplastics in their stomachs, resulting in chronic and acute toxicity, including blockage of filtering apparatuses and internal injuries. The prevalent presence of microplastics in marine environments underscores the urgent need for combined global efforts to reduce their impact. Reducing plastic production and consumption, improving waste management practices, and developing technologies to remove existing microplastics from the environment are crucial steps in protecting marine ecosystems and the myriad species that depend on them [96, 97].

5.2. In Terrestrial ecosystems

Terrestrial ecosystems are also affected by microplastics. These particles can change soil structure and composition, affecting water retention and nutrient availability. Microplastics in the soil can disrupt the growth and development of plants by interfering with root systems and reducing seed germination rates. Additionally, they can affect soil-dwelling organisms, like earthworms, which play significant roles in soil aeration and nutrient cycling [98]. The presence of microplastics in soil can result in reduced agricultural productivity and compromised food security. Atmospheric deposition of microplastics is another emerging concern. Studies have detected microplastic particles in the air, which can be inhaled by humans and animals. These airborne particles can pose respiratory issues and may carry injurious substances into the lungs. The common presence of microplastics in the atmosphere indicates that they are a global pollutant, affecting even remote and pristine environments. The persistence of microplastics in the environment is a remarkable challenge. Due to their durability, they do not degrade easily and can accumulate over time, resulting in long-term environmental impacts [99]. This accumulation can result in the degradation of habitats, loss of biodiversity, and disruption of ecosystem services. Addressing the issue of microplastics requires concerted global efforts to mitigate plastic production and consumption, improve waste management practices, and develop technologies to remove existing microplastics from the environment. Microplastics represent a many-sided environmental issue with far-reaching consequences. Their impact spans across marine and terrestrial ecosystems, the atmosphere, and human health. Reducing their effects necessitates a comprehensive approach involving policy changes, technological innovations, and public awareness to mitigate their prevalence and reduce their impacts on the environment and human health [98, 99].

6. Toxicological Effects of Microplastics

Microplastics can be harmful to both humans and the environment, with potential impacts on multiple organ systems and ecosystems. They can enter the body via ingestion, inhalation, and skin or dermal contact, leading to cellular toxicity and adverse effects on the digestive, respiratory, nervous, reproductive, and cardiovascular systems [100, 101,122].

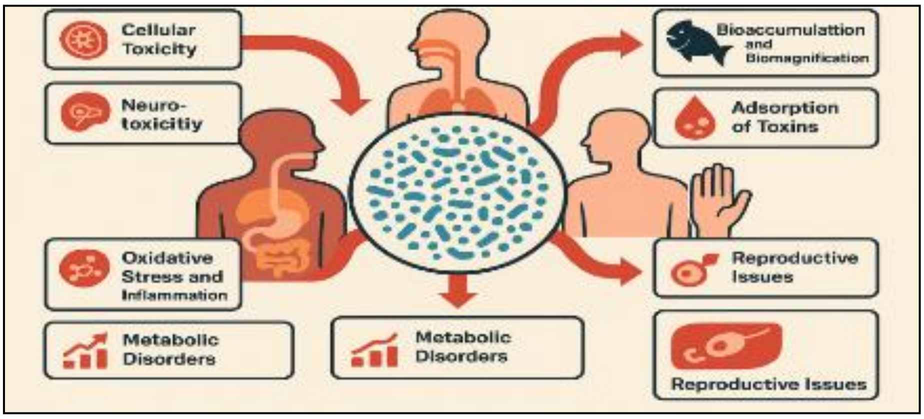


Figure 5 Toxicological Effects of Microplastics (122 Modified)

6.1. Toxicity Mechanisms

6.1.1. Cellular Toxicity

Microplastics can enter cells via endocytosis, resulting in cellular damage and death. For example, exposure to polystyrene microplastics has been demonstrated to cause mitochondrial dysfunction and necroptosis in chicken kidney cells [100].

6.1.2. Neurotoxicity

There is growing evidence that microplastics can affect the nervous system. Inhalation of microplastics may lead to their accumulation in the respiratory tract and potential translocation across the blood-brain barrier, raising concerns about respiratory and neurological health effects [100, 101].

6.1.3. Bioaccumulation and Biomagnification

Microplastics can accumulate in tissues and move up the food chain. For instance, fish ingest microplastics, which can then be consumed by predators, resulting in bioaccumulation and potential biomagnification of toxins [100].

6.1.4. Adsorption of Toxins

Microplastics can adsorb injurious chemicals like heavy metals and pesticides, increasing their toxicity. These adsorbed toxins can then be released into organisms upon ingestion, leading to additional health risks [100].

6.1.5. Oxidative Stress and Inflammation

Microplastics can induce oxidative stress by generating reactive oxygen species (ROS), leading to inflammation. Studies have shown that exposure to microplastics activates immune responses, notably inducing the expression of pro-inflammatory cytokines such as IL-6 and TNF-α in various cell lines [100].

6.1.6. Metabolic Disorders

Exposure to microplastics has been linked to alterations in metabolism. In zebrafish, ingestion of microplastics resulted in changes to the gut microbiome and metabolome, resulting in oxidative stress and inflammation [100].

6.1.7. Reproductive Issues

Microplastics can adversely affect reproductive health. A study found that oral administration of microplastics to female mice resulted to reduced oocyte maturation and fertilization rates, as well as increased oxidative stress and DNA damage in oocytes. Moreover, microplastics have been detected in human ovarian follicular fluid, raising concerns about their impact on fertility [100].

6.2. Exposure Pathways

6.2.1. Ingestion

Microplastics are found in various food and water sources, including drinking water, seafood, and even table salt. Studies have reported microplastics in fish, mussels, and commercial salts, highlighting the prevalent nature of this contamination [102].

6.2.2. Inhalation

Airborne microplastics originate from sources like synthetic textiles, industrial emissions, and agricultural activities. Once inhaled, these particles may lodge in the lungs or enter the digestive system, posing health risks [103].

6.2.3. Dermal Contact

Microplastics can also be absorbed through the skin. Consumer products such as face creams and cosmetics may contain microplastics, increasing the risk of dermal exposure [104].

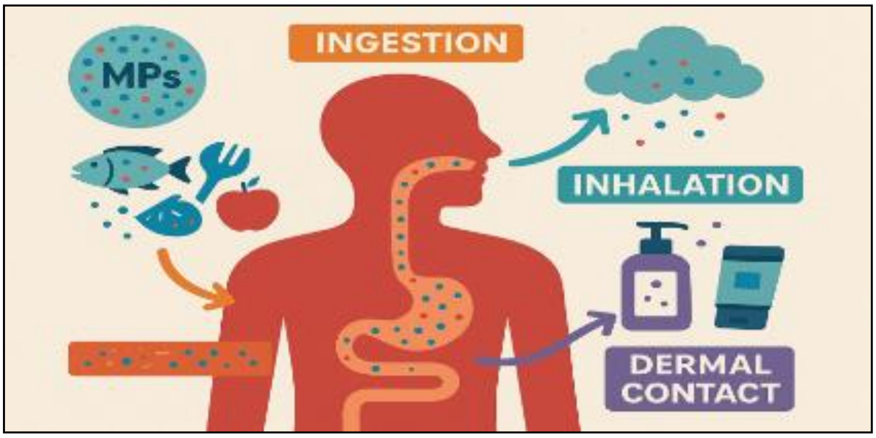


Figure 6 Human Exposure Pathways to Microplastics(43 Modified)

6.3. Examples of Toxicity

Microplastics have become a prevalent environmental contaminant, with growing evidence highlighting their detrimental effects on both animal and human health, as well as on ecosystems. In animal studies, microplastics have been demonstrated to cause remarkable health issues across various species. For example, research on fish, amphibians, and mammals' states that microplastics can lead to liver damage, immune system dysfunction, and reproductive problems. In zebrafish, exposure to polystyrene nanoplastics has resulted in oxidative stress and liver damage, affecting their overall health and survival. Similarly, in mammals, studies have shown that microplastic exposure can impair ovarian function and alter hormone levels, resulting in reproductive toxicity [105]. These findings underscore the potential risks microplastics cause to animal health. Human studies, while still emerging, have begun to shed light on the potential health impacts of microplastics. Research has detected microplastics in human tissues, including the placenta, lungs, liver, and blood, raising concerns about their potential to pose health issues. For instance, a study by researchers from UC San Francisco reviewed over 3,000 studies and found strong evidence linking microplastic exposure to reproductive and immune system damage, with moderate evidence suggesting impacts on ovarian follicles, hormones, and lung function [106]. These findings suggest that microplastics may contribute to health problems such as infertility, colon cancer, and respiratory diseases. The environmental impacts of microplastics are also profound. In aquatic ecosystems, microplastics can harm organisms by affecting their growth, reproduction, and overall health. For example, studies have shown that microplastics can reduce the reproductive capacity of freshwater zooplankton, resulting in population declines. Additionally, microplastics can disrupt the food chain by affecting the health of primary producers such as algae, which are essential for the survival of higher trophic levels. Furthermore, the ingestion of microplastics by marine organisms like fish and turtles can lead to digestive tract blockages, reduced stomach capacity, and even mortality [107]. Concerns about microplastic exposure are especially heightened regarding long-term health effects, as the chronic consequences are still being investigated. The accumulation of microplastics in human tissues over time may lead to persistent health issues, including chronic inflammation and organ damage. Moreover, susceptible populations such as infants and children may be more vulnerable to the harmful effects of microplastics due to their developing bodies and higher exposure levels. For instance, studies have detected microplastics in human placentas, suggesting potential risks to fetal development [108]. Ecosystem health is also at risk as a result to microplastic pollution. The presence of microplastics in various habitats can disrupt ecological balance, affecting biodiversity and the functioning of ecosystems. For example, the accumulation of microplastics in marine environments can lead to the decrease of species that are crucial for ecosystem stability. Additionally, microplastics can serve as vectors for toxic chemicals, further exacerbating their impact on ecosystems. While research is ongoing to better understand the full extent of the toxicity of microplastics, current evidence underscores the need for strategies to mitigate their presence in the environment and minimize their impact on human health and ecosystems [109]. Efforts to reduce microplastic pollution are crucial to protect both environmental and public health.

6.4. Concerns and Ongoing Research

Microplastics, miniature plastic particles less than 5 millimeters in size, have become prevalent in the environment, infiltrating air, water, and food sources. As research into their effects expands, several critical concerns have emerged regarding their impact on human health, susceptible populations, and ecosystem stability [110].

6.4.1. Long-Term Health Effects

The chronic health implications of microplastic exposure are a growing area of concern. Studies have linked prolonged exposure to microplastics with different health issues, such as reproductive problems, respiratory diseases, and potential carcinogenic effects. For example, a comprehensive review of nearly 3,000 studies highlighted strong evidence associating microplastic exposure with reproductive and immune system damage, and moderate evidence suggesting impacts on ovarian follicles, hormones, and lung function [111]. Furthermore, animal studies have demonstrated that microplastics can interfere with hormonal balance and sperm production, raising concerns about their potential to affect human fertility [112]. These findings underscore the necesity for further research to fully understand the long-term health risks associated with microplastic exposure.

6.4.2. Vulnerable Populations

Certain groups, especially infants and children, may be more vulnerable to the injurious effects of microplastics due to their developing bodies and higher exposure levels [113]. Emerging research has found microplastics in human ovarian follicular fluid, showing potential risks to female reproductive health. Additionally, microplastics have been detected in human placentas, suggesting they can cross the placental barrier and potentially affect fetal development [114]. These findings highlight the importance of protecting susceptible populations from microplastic exposure and implementing measures to mitigate environmental contamination.

6.4.3. Ecosystem Health

Microplastic pollution causes notable threats to ecosystems, especially aquatic environments. Marine organisms, like fish and corals, can take in microplastics, resulting in physical harm, impaired feeding behaviors, and disruptions in reproductive processes [115]. For instance, fish that consume microplastics may experience reduced feeding rates and compromised immune systems, weakening their capability to withstand other environmental stressors. Moreover, microplastics can serve as carriers for injurious chemicals and pathogens, introducing additional risks to marine life. The accumulation of microplastics in the food chain can also affect biodiversity and disrupt ecological balance, emphasizing the need for comprehensive strategies to address microplastic pollution [115].

6.5. Mitigation Efforts

Research into the effects of microplastics is ongoing, with studies focusing on understanding their health impacts, exposure pathways, and ecological consequences. Efforts are being made to develop strategies to mitigate microplastic pollution, including improving waste management practices, promoting the application of alternative materials, and raising public awareness about the issue. Additionally, regulatory measures are being considered to limit the production and use of microplastics in consumer products [116]. Continued research and concretive efforts are crucial to reduce the risks associated with microplastics and protect both human health and the environment. While microplastics are a prevalent environmental contaminant, ongoing research and proactive measures can help reduce their impact. By understanding the risks and implementing strategies to mitigate exposure, it is possible to protect susceptible populations and preserve ecosystem health for future generations [116].

7. Remediation Strategies of Microplastics

Microplastic pollution has emerged as a remarkable environmental challenge, necessitating the development of effective remediation strategies to reduce its impact on ecosystems and human health. Microplastic remediation involves methods to remove, treat, or contain microplastics from the environment, including soil, water, and sediment. These methods can be physical, chemical, or biological, and some promising techniques include bioremediation, membrane filtration, and electrocoagulation [117,120]. Addressing microplastic pollution requires a many-sided approach that combines biological, technological, and innovative strategies. While notable progress has been made in developing remediation techniques, challenges remain in scaling these methods for extensive application. Continued research and development are essential to enhance the efficiency and feasibility of these strategies, ensuring effective reduction of microplastic pollution in different environments [117].

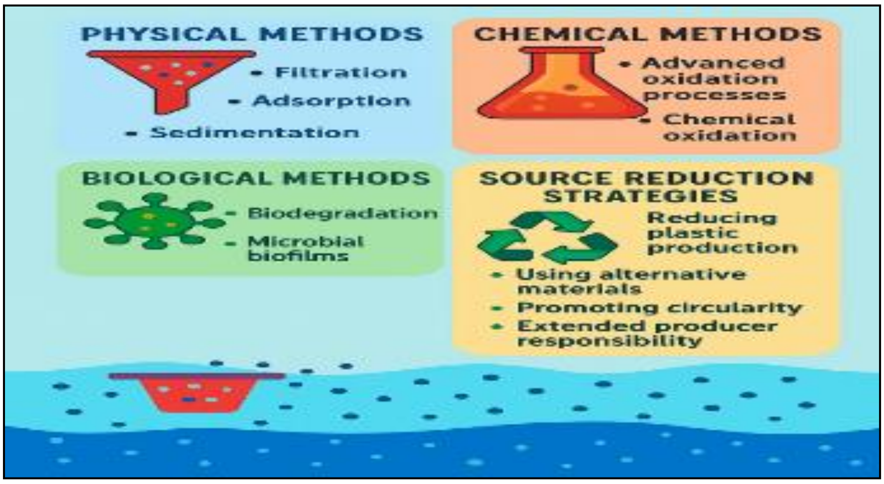


Figure 7 Remediation Strategies of Microplastics(120 Modified)

7.1. Biological Remediation Strategies

7.1.1. Phytoremediation

This involves the application of plants to remove contaminants from the environment. Studies have shown that aquatic plants like *Eichhornia crassipes* (water hyacinth) can effectively adsorb microplastics through their widespread root systems. In controlled experiments, water hyacinths achieved removal efficiencies of up to 68.8% for polystyrene microplastics within 48 hours. The plant's root caps, with a total surface area exceeding 150,000 mm^2 per plant, serve as the principal sites for microplastic entrapment, while a unique vascular structure prevents translocation to aerial tissues, ensuring the plant's resilience and potential for reuse [117].

7.1.2. Mycoremediation

My core mediation utilizes fungi to degrade pollutants. White rot fungi, like *Pleurotus ostreatus*, secrete extracellular enzymes capable of breaking down complex organic compounds. These fungi have demonstrated promise in degrading various pollutants, including certain plastics, through enzymatic processes [118].

7.1.3. Bioengineering-Based Solutions

It explores the application of microorganisms or enzymes to degrade plastics. For instance, the bacterium *Donella akinesis* can degrade polyethylene terephthalate (PET), and the marine fungus *Alerion maritimum* has shown potential in breaking down polyethylene (PE). While promising, these methods are primarily at the laboratory scale, and further research is needed to assess their feasibility for large-scale application [119].

7.2. Technological Remediation Approaches

7.2.1. Advanced Filtration Technologies

Advanced Filtration Technologies include methods such as membrane filtration (ultrafiltration and nanofiltration) and granular activated carbon (GAC) filtration. These technologies have demonstrated the ability to remove microplastics from water, with nanofiltration membranes capable of retaining particles larger than 100 am, achieving removal rates exceeding 72% [120].

7.2.2. Electrocoagulation (EC)

Electrocoagulation (EC) is a process that uses electrical currents to destabilize and aggregate particles, enhancing their removal. In laboratory settings, EC has achieved microplastic removal efficiencies greater than 90% under optimal conditions, suggesting its potential for treating wastewater streams contaminated with microplastics [121].

7.2.3. Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) involve the generation of reactive species such as hydroxyl radicals to degrade pollutants. Techniques such as ozonation and photocatalysis have been explored for microplastic degradation. These methods can break down microplastics into smaller fragments, which can then be removed more easily in subsequent treatment stages [122].

7.2.4. Nano remediation

Nanoremediation utilizes nanoparticles to treat contaminated environments. For instance, nanoscale zero-valent iron has been employed in groundwater cleanup. While some nano remediation methods have been deployed at full-scale cleanup sites, others remain in research phases, and their long-term environmental impacts need further assessment [123].

7.3. Emerging Innovations

- **Magnetic Ferrofluid Technology:** Involves the application of a magnetic fluid that binds to microplastic particles, allowing them to be extracted from water using a standard magnet. Developed by Fionn Ferreira, this method has achieved microplastic extraction rates of up to 87%, particularly effective for polyester-based particles. This approach offers a new solution for removing microplastics that conventional filtration systems struggle to address [124].
- **Biodegradable Sponges:** Made from natural materials such as cotton and squid bone have been developed to absorb microplastics from water. A study from the University of Wuhan demonstrated that these sponges could remove up to 99.9% of microplastics from water samples, with the added benefit of reusability after several cycles. The materials used are less expensive and environmentally friendly, making this technology scalable for wider applications [125].

8. Conclusion

This comprehensive review has outlined the major sources and formation mechanisms of microplastic pollution, explored current quantification techniques, and examined its far-reaching environmental and toxicological impacts across ecosystems. It also assessed existing and emerging remediation strategies aimed at mitigating microplastic contamination. By integrating knowledge across these domains, the study enhances our understanding of the complexity and urgency of the microplastic crisis. This work will benefit society by informing evidence-based policies, promoting sustainable waste management practices, and guiding future research toward innovative, multidisciplinary solutions.

Compliance with ethical standards

Acknowledgments

I am deeply grateful to my supervisor, Professor J. L. Konne, for his invaluable guidance, support, and encouragement, which contributed significantly to the success of this work.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Browne, M. A., Galloway, T. S., & Thomps on, R. C. (2007). Microplastic: An emerging contaminant of potential concern? Integrated Environmental Assessment and Management, 3(4), 578–580. https://doi: 10.1002/ieam.5630030412

[2] Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin, 62(12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

[3] Andrady, A. L. (2011). Microplastics in the marine environment. Marine Pollution Bulletin, 62(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

[4] Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: A review. Environmental Pollution, 178, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031

[5] Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2019). Methods for sampling and detection of microplastics in water and sediment: A critical review. TrAC Trends in Analytical Chemistry, 110, 150–159. https://doi.org/10.1016/j.trac.2018.10.029

[6] Pan, Y., Gao, S.-H., Ge, C., Gao, Q., Huang, S., Kang, Y., Luo, G., Zhang, Z., Fan, L., Zhu, Y., & Wang, A.-J. (2023). Removing microplastics from aquatic environments: A critical review. Environmental Science and Ecotechnology, 13, 100222. https://doi.org/10.1016/j.ese.2022.100222

[7] Andrady, A. L. (2017). The plastic in microplastics: A review. Marine Pollution Bulletin, 119(1), 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082

[8] Du, S., Zhu, R., Cai, Y., Xu, N., Yap, P.-S., Zhang, Y., He, Y., & Zhang, Y. (2021). Environmental fate and impacts of microplastics in aquatic ecosystems: A review. RSC Advances, 11(26), 15762–15784. https://doi.org/10.1039/d1ra00880c

[9] Fendall, L. S., & Sewell, M. A. (2009). Contributing to marine pollution by washing your face: Microplastics in facial cleansers. Marine Pollution Bulletin, 58(8), 1225–1228. https://doi.org/10.1016/j.marpolbul.2009.04.025

[10] Mason, S. A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., & Rogers, D. L. (2016). Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environmental Pollution, 218, 1045–1054. https://doi.org/10.1016/j.envpol.2016.06.081

[11] Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., & Galloway, T. S. (2013). Microplastic ingestion by zooplankton. Environmental Science & Technology, 47(12), 6646–6655. https://doi.org/10.1021/es400663f

[12] Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. Marine Pollution Bulletin, 112(1-2), 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025

[13] Mintenig, S. M., Int-Veen, I., Löder, M. G., Primpke, S., & Gerdts, G. (2017). Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Research, 108, 365–372. https://doi.org/10.1016/j.watres.2016.11.015

[14] Hernandez, E., Nowack, B., & Mitrano, D. M. (2017). Polyester textiles as a source of microplastics from households: A mechanistic study to understand microfiber release during washing. Environmental Science & Technology, 51(12), 7036–7046. https://doi.org/10.1021/acs.est.7b0175

[15] Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines worldwide: Sources

[16] Cai, Y., Yang, T., Mitrano, D. M., Heuberger, M., Hufenus, R., & Nowack, B. (2020). Systematic study of microplastic fiber release from 12 different polyester textiles during washing. Environmental Science & Technology, 54(8), 4847–4855. https://doi.org/10.1021/acs.est.9b07395

[17] Boucher, J., & Friot, D. (2017). Primary microplastics in the oceans: A global evaluation of sources. IUCN International Union for Conservation of Nature.

[18] Henry, B., Laitala, K., & Klepp, I. G. (2019). Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. Science of The Total Environment, 652, 483–494. https://doi.org/10.1016/j.scitotenv.2018.10.166

[19] Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: A review. Marine Pollution Bulletin, 62(12), 2588-2597. https://doi.org/10.1016/j.marpolbul.2011.09.025

[20] Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., & Geissen, V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Science of The Total Environment, 671, 411-420. https://doi.org/10.1016/j.scitotenv.2019.03.368

[21] Kreider, M. L., Panko, J. M., McAtee, B. L., Sweet, L. I., & Finley, B. L. (2010). Physical and chemical characterization of tire-related particles: Comparison of particles generated using different methodologies. Science of The Total Environment, 408(3), 652-659. https://doi.org/10.1016/j.scitotenv.2009.10.016

[22] Kole, P. J., Löhr, A. J., Van Belleghem, F. G., & Ragas, A. M. (2017). Wear and tear of tyres: A stealthy source of microplastics in the environment. International Journal of Environmental Research and Public Health, 14(10), 1265. https://doi.org/10.3390/ijerph14101265

[23] Tian, Z., Zhao, H., Peter, K. T., Gonzalez, M., Wetzel, J., Wu, C., Hu, X., Prat, J., Mudrock, E., Hettinger, R., & Kolodziej, E. P. (2021). A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. Science, 371(6525), 185–189. https://doi.org/10.1126/science.abd6951

[24] Panko, J. M., Kreider, M. L., McAtee, B. L., & Marwood, C. (2013). Chronic toxicity of tire and road wear particles to water- and sediment-dwelling organisms. Ecotoxicology, 22(1), 13–21. https://doi.org/10.1007/s10646-012-0998-9

[25] Rochman, C. M., Tahir, A., Williams, S. L., Baxa, D. V., Lam, R., Miller, J. T., & Teh, S. J. (2015). Anthropogenic debris in seafood: Plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Scientific Reports, 5, 14340. https://doi.org/10.1038/srep14340

[26] Wagner, S., Hüffer, T., Klöckner, P., Wehrhahn, M., Hofmann, T., & Reemtsma, T. (2018). Tire wear particles in the aquatic environment – A review on generation, analysis, occurrence, fate and effects. Water Research, 139, 83–100. https://doi.org/10.1016/j.watres.2018.03.051

[27] Amato, F., Querol, X., Johansson, C., Nagl, C., & Alastuey, A. (2010). A review on the effectiveness of street sweeping, washing and dust suppressants as urban PM control methods. Science of The Total Environment, 408(16), 3070–3084. https://doi.org/10.1016/j.scitotenv.2010.04.025

[28] Ziajahromi, S., Neale, P. A., Rintoul, L., & Leusch, F. D. L. (2017). Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater-based microplastics. Water Research, 112, 93–99. https://doi.org/10.1016/j.watres.2017.01.042

[29] Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., & Stohl, A. (2020). Atmospheric transport is a major pathway of microplastics to remote regions. Nature Communications, 11, 3381. https://doi.org/10.1038/s41467-020-17201-9

[30] Tamis, J. E., Koelmans, A. A., Dröge, R., Kaag, N. H. B. M., Keur, M. C., Tromp, P. C., & Jongbloed, R. H. (2021). Environmental risks of car tire microplastic particles and other road runoff pollutants. Microplastics and Nanoplastics, 1(1)

[31] Yu, R.-S., & Singh, S. (2023). Microplastic pollution: Threats and impacts on global marine ecosystems. Sustainability, 15(17), 13252. https://doi.org/10.3390/su1517132522

[32] Premarathna, K. S. D., Rajapaksha, A. U., & Vithanage, M. (2025). Microplastics in road dust and surrounding environment: Sources, fate and analytical approaches. Trends in Environmental Analytical Chemistry, 45, e00256. https://doi.org/10.1016/j.teac.2024.e00256

[33] Verschoor, A. J., de Poorter, L., Dröge, R., & Kuenen, J. (2016). Emission of microplastics and potential mitigation measures: Abrasive cleaning agents, paints and tyre wear. RIVM Report 2016-0026. National Institute for Public Health and the Environment.

[34] Lassen, C., Hansen, S. F., Magnusson, K., Norén, F., Hartmann, N. B., Jensen, P. R., & Brinch, A. (2015). Microplastics: Occurrence, effects and sources of releases to the environment in Denmark. Danish Environmental Protection Agency.

[35] Kershaw, P. J., Turra, A., & Galgani, F. (2019). Guidelines for the monitoring and assessment of plastic litter and microplastics in the ocean. UNEP & IOC/UNESCO Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). Reports and Studies No. 99.

[36] Kum, G., Berglund, O., & Hollander, J. (2025). Lost in definition: Unravelling microplastics from marine coatings through bibliometrics science mapping in thematic analysis and systematic narrative literature review. Environmental Sciences Europe, 37(38).

[37] Jones, J. (2021). Investigating the exposure and potential impacts of microplastics in the Galápagos marine food web [Doctoral dissertation, University of Exeter]. ProQuest Dissertations & Theses Global. (Publication No. 29072909)

[38] Burghardt, T. E., & Pashkevich, A. (2023). Road markings and microplastics – A critical literature review. Transportation Research Part D: Transport and Environment, 119, 103740. https://doi.org/10.1016/j.trd.2023.103740

[39] Moyo, M., Baloyi, R. B., Sithole, B. B., & Falayi, T. (2024). Microplastics originating from paints and synthetic textile materials. In Microplastic Pollution (pp. 109–125). Springer. https://doi.org/10.1007/978-981-99-8357-5_7

[40] Ihenetu, S. C., Enyoh, C. E., Wang, C., & Li, G. (2024). Sustainable urbanization and microplastic management: Implications for human health and the environment. Urban Science, 8(4), 252. https://doi.org/10.3390/urbansci8040252

[41] Nasir, M. S., Tahir, I., Ali, A., Ayub, I., Nasir, A., Abbas, N., Sajjad, U., & Hamid, K. (2024). Innovative technologies for removal of microplastic: A review of recent advances. Heliyon, 10(4), e25883. https://doi.org/10.1016/j.heliyon.2024.e25883

[42] Thacharodi, A., Hassan, S., Meenatchi, R., Bhat, M. A., Hussain, N., Arockiaraj, J., Ngo, H. H., Sharma, A., Nguyen, H. T., & Pugazhendhi, A. (2024). Mitigating microplastic pollution: A critical review on the effects, remediation, and utilization strategies of microplastics. Journal of Environmental Management, 351, 119988. https://doi.org/10.1016/j.jenvman.2023.119988

[43] Bhuyan, M. S. (2022). Effects of microplastics on fish and in human health. Frontiers in Environmental Science, 10, Article 827289. https://doi.org/10.3389/fenvs.2022.827289

[44] Islam, F. A. S. (2025). The effects of plastic and microplastic waste on the marine environment and the ocean. European Journal of Environment and Earth Sciences, 6(3). https://doi.org/10.24018/ejgeo.2025.6.3.508

[45] Song, J. H., Murphy, R. J., Narayan, R., & Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2127–2139. https://doi.org/10.1098/rstb.2008.0289

[46] European Chemicals Agency (ECHA). (2023). Microplastics restriction: Final regulatory proposal under REACH. https://echa.europa.eu/restrictions-under-consideration

[47] United Nations Environment Programme (UNEP). (2022). Turning off the tap: How the world can end plastic pollution and create a circular economy. Nairobi: UNEP. https://www.unep.org/resources/turning-tap

[48] Karlsson, T. M., Arneborg, L., Broström, G., Almroth-Rosell, E., Eriksson, C., & Hassellöv, M. (2018). The unaccountability case of plastic pellet pollution. Marine Pollution Bulletin, 129(1), 52–60. https://doi.org/10.1016/j.marpolbul.2018.01.041

[49] Lithner, D., Larsson, Å., & Dave, G. (2011). Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition. Science of the Total Environment, 409(18), 3309–3324. https://doi.org/10.1016/j.scitotenv.2011.04.038

[50] De Vos, A., Aluwihare, L., Youngs, S., DiBenedetto, M. H., Ward, C. P., Michel, A. P. M., Colson, B. C., Mazzotta, M. G., Walsh, A. N., Nelson, R. K., Reddy, C. M., & James, B. D. (2021). The M/V X-Press Pearl nurdle spill: Contamination of burnt plastic and unburnt nurdles along Sri Lanka's beaches. ACS Environmental Au, 2(2), 128–135. https://doi.org/10.1021/acsenvironau.1c00031

[51] Surfrider Foundation. (2023). Plastic pellet pollution and legislative actions. Retrieved from https://www.surfrider.org

[52] United Nations Environment Programme. (2021). Dismantling the plastic menace: Microbeads in industrial use. Retrieved from https://www.unep.org

[53] Cheung, P. K., & Fok, L. (2017). Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. Water Research, 122, 53–61. https://doi.org/10.1016/j.watres.2017.05.053

[54] United Nations Environment Programme. (2016). Marine plastic debris and microplastics: Global lessons and research to inspire action and guide policy change. https://www.unep.org

[55] European Chemicals Agency. (2023). ECHA supports EU-wide restriction on microplastics. https://echa.europa.eu/restrictions-on-intentionally-added-microplastics

[56] Rochman, C. M., Browne, M. A., Underwood, A. J., Van Franeker, J. A., Thompson, R. C., & Amaral-Zettler, L. A. (2015). The ecological impacts of marine debris: Unraveling the demonstrated evidence from what is perceived. Ecology, 96(3), 302–312. https://doi.org/10.1890/14-2070.1

[57] Andrady, A. L. (2011). Microplastics in the marine environment. Marine Pollution Bulletin, 62(8), 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

[58] Weaver, F. M., Rose, N. L., Turner, S. D., & Atkinson, B. (2024). The scale and distribution of microplastic pollution in the soils of a UK urban woodland (40 pages). University College London. https://doi.org/10.2139/ssrn.4708306

[59] Machado, A. A. S., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2019). Impacts of microplastics on the soil biophysical environment. Environmental Science & Technology, 53(10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339

[60] Corradini, F., Meza, P., Eguiluz, R., Casado, F., Huerta-Lwanga, E., & Geissen, V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Science of The Total Environment, 671, 411–420. https://doi.org/10.1016/j.scitotenv.2019.03.368

[61] Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., & Wong, M.-H. (2020). Source, migration and toxicology of microplastics in soil. Environment International, 137, 105263. https://doi.org/10.1016/j.envint.2020.105263

[62] Campanale, C., Galafassi, S., Savino, I., Massarelli, C., Ancona, V., Volta, P., & Uricchio, V. F. (2022). Microplastics pollution in the terrestrial environments: Poorly known diffuse sources and implications for plants. Science of The Total Environment, 805, 150431. https://doi.org/10.1016/j.scitotenv.2021.150431

[63] Chia, R. W., Lee, J.-Y., Kim, H., & Jang, J. (2021). Microplastic pollution in soil and groundwater: A review. Environmental Chemistry Letters, 19(4), 3825–3845. https://doi.org/10.1007/s10311-021-01297-6

[64] Ross, M. S., Loutan, A., Groeneveld, T., Molenaar, D., Kroetch, K., Bujaczek, T., Kolter, S., Moon, S., Huynh, A., Khayam, R., Franczak, B. C., Camm, E., Arnold, V. I., & Ruecker, N. J. (2023). Estimated discharge of microplastics via urban stormwater during individual rain events. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1090267

[65] Liu, P., Shao, L., Li, Y., Jones, T., Cao, Y., Yang, C.-X., Zhang, M., Santosh, M., Feng, Z., & Berube, K. (2022). Microplastic atmospheric dustfall pollution in urban environment: Evidence from the types, distribution, and probable sources in Beijing, China. Science of The Total Environment, 838(1), 155989. https://doi.org/10.1016/j.scitotenv.2022.155989

[66] Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. Science of The Total Environment, 702, 134455. https://doi.org/10.1016/j.scitotenv.2019.134455

[67] Galloway, T. S., & Lewis, C. N. (2016). Marine microplastics spell big problems for future generations. Proceedings of the National Academy of Sciences, 113(9), 2331–2333. https://doi.org/10.1073/pnas.1600715113

[68] Lambert, S., & Wagner, M. (2016). Characterisation of nanoplastics during the degradation of polystyrene. Chemosphere, 145, 265–268. https://doi.org/10.1016/j.chemosphere.2015.11.078

[69] Wessel, C. C., Lockridge, G. R., Battiste, D., & Cebrian, J. (2016). Abundance and characteristics of microplastics in beach sediments: Insights into microplastic accumulation in northern Gulf of Mexico estuaries. Marine Pollution Bulletin, 109(1), 178–183. https://doi.org/10.1016/j.marpolbul.2016.06.002

[70] Baensch Baltruschat, B., Kocher, B., Stock, F., & Reifferscheid, G. (2020). Tyre and road wear particles (TRWP): A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Science of the Total Environment, 743, 140979. https://doi.org/10.1016/j.scitotenv.2020.140979

[71] Razeghi, N., Hamidian, A. H., Wu, C., Zhang, Y., & Yang, M. (2021). Microplastic sampling techniques in freshwaters and sediments: A review. Environmental Chemistry Letters, 19, 4225–4252. https://doi.org/10.1007/s10311-021-01296-7

[72] Wright, S. L., Thompson, R. C., & Galloway, T. S. (2013). The physical impacts of microplastics on marine organisms: A review. Environmental Pollution, 178, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031

[73] Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. Environmental Science: Processes & Impacts, 17(9), 1513–1521. https://doi.org/10.1039/C5EM00207A

[74] Roy, P. K., Hakkarainen, M., Varma, I. K., & Albertsson, A. C. (2011). Degradable polyethylene: Fantasy or reality. Environmental Science & Technology, 45(10), 4217–4227. https://doi.org/10.1021/es104042j

[75] Singh, B., & Sharma, N. (2008). Mechanistic implications of plastic degradation. Polymer Degradation and Stability, 93(3), 561–584. https://doi.org/10.1016/j.polymdegradstab.2007.11.008

[76] Yousif, E., & Haddad, R. (2013). Photodegradation and photostabilization of polymers, especially polystyrene: Review. SpringerPlus, 2, 398. https://doi.org/10.1186/2193-1801-2-398

[77] Mishra, S. (2020). Microbial bioremediation of plastic and its future aspects. International Journal of Scientific Research and Engineering Development, 3(6), 275–278. Available at http://www.ijsred.com

[78] Andrady, A. L. (2015). Persistence of plastic litter in the oceans. In Marine Anthropogenic Litter (pp. 57–72). Springer. https://doi.org/10.1007/978-3-319-16510-3_3

[79] Gewert, B., Plassmann, M. M., & MacLeod, M. (2015). Pathways for degradation of plastic polymers floating in the marine environment. Environmental Science: Processes & Impacts, 17(9), 1513–1521. https://doi.org/10.1039/C5EM00207A

[80] Klaus, J., Seeger, M., Bigalke, M., & Weber, C. J. (2024). Microplastics in vineyard soils: First insights from plastic-intensive viticulture systems. Science of The Total Environment, 947, 174699. https://doi.org/10.1016/j.scitotenv.2024.174699

[81] Xu, J.-L., Lin, X., Wang, J. J., & Gowen, A. A. (2022). A review of potential human health impacts of micro- and nanoplastics exposure. Science of the Total Environment, 851(Pt 1), 158111. https://doi.org/10.1016/j.scitotenv.2022.158111

[82] Shah, A. A., Hasan, F., Hameed, A., & Ahmed, S. (2008). Biological degradation of plastics: A comprehensive review. Biotechnology Advances, 26(3), 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005

[83] Rabek, J. F. (1995). Polymer Photodegradation: Mechanisms and Experimental Methods. Springer.

[84] Albertsson, A.-C., & Karlsson, S. (1990). The influence of biotic and abiotic environments on the degradation of polyethylene. Progress in Polymer Science, 15(2), 177–192.

[85] Everaert, G., Van Cauwenberghe, L., De Rijcke, M., Koelmans, A. A., Mees, J., Vandegehuchte, M., & Janssen, C. R. (2018). Risk assessment of microplastics in the ocean: Modelling approach and first conclusions. Environmental Pollution, 242, 1930–1938. https://doi.org/10.1016/j.envpol.2018.07.069

[86] Fotopoulou, K., & Karapanagioti, H. K. (2012). Surface properties of beached plastic pellets. Environmental Science & Pollution Research International, 19(7), 2074–2080

[87] Tokiwa, Y., Calabia, B. P., Ugwu, C. U., & Aiba, S. (2009). Biodegradability of plastics. International Journal of Molecular Sciences, 10(9), 3722–3742. https://doi.org/10.3390/ijms10093722

[88] Kazmiruk, T. N., Kazmiruk, V. D., & Bendell, L. I. (2018). Abundance and distribution of microplastics within surface sediments of a key shellfish growing region of Canada. PLoS ONE, 13(5), e0196005. https://doi.org/10.1371/journal.pone.0196005

[89] Yaranal, N. A., Subbiah, S., & Mohanty, K. (2021). Distribution and characterization of microplastics in beach sediments from Karnataka (India) coastal environments. Marine Pollution Bulletin, 169, 112550. https://doi.org/10.1016/j.marpolbul.2021.112550

[90] Interstate Technology & Regulatory Council (ITRC). (2020). Microplastics in the Environment. https://itrcweb.org/webinars

[91] Hermabessiere, L., Dehaut, A., Paul-Pont, I., Lacroix, C., Jezequel, R., Soudant, P., & Duflos, G. (2017). Occurrence and effects of plastic additives on marine environments and organisms: A review. Environmental Science & Technology, 51(12), 6634–6651. https://doi.org/10.1021/acs.est.7b00494

[92] Gies, E. A., LeNoble, J. L., Noël, M., Etemadifar, A., Bishay, F., Hall, E. R., & Ross, P. S. (2018). Retention of microplastics in a major secondary wastewater treatment plant in Vancouver, Canada. Marine Pollution Bulletin, 133, 553–561. https://doi.org/10.1016/j.marpolbul.2018.06.006

[93] Imhof, H. K., Laforsch, C., Wiesheu, A. C., Schmid, J., Anger, P. M., Niessner, R., & Ivleva, N. P. (2016). Pigments and plastic in limnetic ecosystems: A qualitative and quantitative study on microparticles of different size classes. Water Research, 98, 64–74. https://doi.org/10.1016/j.watres.2016.03.015

[94] Primpke, S., Lorenz, C., Rascher-Friesenhausen, R., & Gerdts, G. (2017). An automated approach for microplastics analysis using focal plane array (FPA) FTIR microscopy and image analysis. Analytical Methods, 9(9), 1499–1511. https://doi.org/10.1039/C6AY02476A

[95] Rochman, C. M., Browne, M. A., Halpern, B. S., Hentschel, B. T., Hoh, E., Karapanagioti, H. K., ... & Thompson, R. C. (2013). Policy: Classify plastic waste as hazardous. Nature, 494(7436), 169–171. https://doi.org/10.1038/494169a

[96] Lusher, A. L., Hollman, P. C. H., & Mendoza-Hill, J. J. (2017). Microplastics in fisheries and aquaculture: Status of knowledge on their occurrence and implications for aquatic organisms and food safety. FAO Fisheries and Aquaculture Technical Paper, No. 615. Food and Agriculture Organization of the United Nations.

[97] Law, K. L., & Thompson, R. C. (2014). Microplastics in the seas. Science, 345(6193), 144–145. https://doi.org/10.1126/science.1254065

[98] Machado, A. A. d. S., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. Environmental Science & Technology, 52(17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212

[99] Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Jiménez, P. D., Simonneau, A., & Galop, D. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nature Geoscience, 12, 339–344. https://doi.org/10.1038/s41561-019-0335-5

[100] Wright, S. L., & Kelly, F. J. (2017). Plastic and human health: A micro issue? Environmental Science & Technology, 51(12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423

[101] Prüst, M., Meijer, J., Westerink, R. H. S. (2020). The plastic brain: Neurotoxicity of micro- and nanoplastics. Particle and Fibre Toxicology, 17, 24. https://doi.org/10.1186/s12989-020-00358-y

[102] Karami, A., Golieskardi, A., Keong Choo, C., Larat, V., Galloway, T. S., & Salamatinia, B. (2017). The presence of microplastics in commercial salts from different countries. Scientific Reports, 7(1), 1–7. https://doi.org/10.1038/srep46173

[103] Wright, S. L., Ulke, J., Font, A., Chan, K. L., & Kelly, F. J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. Environment International, 136, 105411. https://doi.org/10.1016/j.envint.2019.105411

[104] Prata, J. C. (2018). Microplastics in wastewater: State of the knowledge on sources, fate and solutions. Marine Pollution Bulletin, 129(1), 262–265. https://doi.org/10.1016/j.marpolbul.2018.02.046

[105] Pitt, J. A., Kozal, J. S., Jayasundara, N., Massarsky, A., Trevisan, R., Geitner, N., & Di Giulio, R. T. (2018). Uptake, tissue distribution, and toxicity of polystyrene nanoparticles in developing zebrafish (Danio rerio). Aquatic Toxicology, 194, 185–194. https://doi.org/10.1016/j.aquatox.2017.11.017

[106] Leslie, H. A., van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. Environment International, 163, 107199. https://doi.org/10.1016/j.envint.2022.107199

[107] Cole, M., Lindeque, P. K., Fileman, E., Halsband, C., Goodhead, R., Moger, J., & Galloway, T. S. (2013). Microplastic ingestion by zooplankton. Environmental Science & Technology, 47(12), 6646–6655. https://doi.org/10.1021/es400663f

[108] Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., ... & Giorgini, E. (2021). Plasticenta: First evidence of microplastics in human placenta. Environment International, 146, 106274. https://doi.org/10.1016/j.envint.2020.106274

[109] Wang, J., Liu, X., Li, Y., Powell, T., Wang, X., Wang, G., & Zhang, P. (2019). Microplastics as contaminants in the soil environment: A mini-review. Science of the Total Environment, 691, 848–857. https://doi.org/10.1016/j.scitotenv.2019.07.209

[110] Smith, M., Love, D. C., Rochman, C. M., & Neff, R. A. (2018). Microplastics in seafood and the implications for human health. Current Environmental Health Reports, 5(3), 375–386. https://doi.org/10.1007/s40572-018-0206-z

[111] Prata, J. C., da Costa, J. P., Lopes, I., Duarte, A. C., & Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. Science of the Total Environment, 702, 134455. https://doi.org/10.1016/j.scitotenv.2019.134455

[112] Zhang, C., Chen, J., Ma, S., Sun, Z., & Wang, Z. (2022). Microplastics may be a significant cause of male infertility. American Journal of Men's Health, 16(3), 15579883221096549. https://doi.org/10.1177/15579883221096549

[113] Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. Environment International, 163, 107199. https://doi.org/10.1016/j.envint.2022.107199

[114] Ibrahim, Y. S., Tuan Anuar, S., Azmi, A. A., Awaluddin, A. B., & Yunus, M. A. C. (2021). Detection of microplastics in human colectomy specimens. Environmental Science and Pollution Research, 28(42), 59834–59843. https://doi.org/10.1007/s11356-021-14626-5

[115] Barboza, L. G. A., Vieira, L. R., Branco, V., Figueiredo, N., Carvalho, F., Carvalho, C., & Guilhermino, L. (2018). Microplastics cause neurotoxicity, oxidative damage and energy-related changes and affect the neurotransmission system of European seabass (Dicentrarchus labrax) juveniles. Science of the Total Environment, 640–641, 160–173. https://doi.org/10.1016/j.scitotenv.2018.05.329

[116] Galloway, T. S., & Lewis, C. N. (2016). Marine microplastics spell big problems for future generations. Proceedings of the National Academy of Sciences, 113(9), 2331–2333. https://doi.org/10.1073/pnas.1600715113

[117] Li, J., Liu, H., & Paul Chen, J. (2018). Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Research, 137, 362–374. https://doi.org/10.1016/j.watres.2017.12.056

[118] Pointing, S. B. (2001). Feasibility of bioremediation by white-rot fungi. Applied Microbiology and Biotechnology, 57(1-2), 20–33. https://doi.org/10.1007/s002530100754

[119] Yoshida, S., Hiraga, K., Takehana, T., Taniguchi, I., Yamaji, H., Maeda, Y., & Oda, K. (2016). A bacterium that degrades and assimilates poly(ethylene terephthalate). Science, 351(6278), 1196–1199. https://doi.org/10.1126/science.aad6359

[120] Dey, T. K., Uddin, M. E., & Jamal, M. (2021). Detection and removal of microplastics in wastewater: Evolution and impact. Environmental Science and Pollution Research International, 28(14), 16925–16947. https://doi.org/10.1007/s11356-021-12943-5

[121] Perren, W., Wojtasik, A., & Cai, Q. (2018). Removal of microbeads from wastewater using electrocoagulation. ACS Omega, 3(3), 3357–3364. https://doi.org/10.1021/acsomega.7b02037

[122] Anbumani, S., & Kakkar, P. (2018). Ecotoxicological effects of microplastics on biota: A review. Environmental Science and Pollution Research, 25(15), 14373–14396. https://doi.org/10.1007/s11356-018-1999-x

[123] Karn, B., Kuiken, T., & Otto, M. (2009). Nanotechnology and in situ remediation: A review of the benefits and potential risks. Environmental Health Perspectives, 117(12), 1823–1831. https://doi.org/10.1289/ehp.0900793

[124] Shi, X., Zhang, X., Gao, W., Zhang, Y., & He, D. (2022). Removal of microplastics from water by magnetic nano-Fe_3O_4. Science of The Total Environment, 802, 149838. https://doi.org/10.1016/j.scitotenv.2021.149838

[125] Sun, C., Wang, Z., Zheng, H., Chen, L., & Li, F. (2021). Biodegradable and re-usable sponge materials made from chitin for efficient removal of microplastics. Journal of Hazardous Materials, 420, 126599. https://doi.org/10.1016/j.jhazmat.2021.126599