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Microplastics and Nanoplastics: Environmental Pathways, Ecological Impacts, and Regulatory Perspectives

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Abstract

A growing concern among the global population is the presence of Microplastics (MPs) and Nanoplastics (NPs) within various environmental compartments due to their pervasive, persistent presence. Through atmospheric, aquatic, terrestrial, and biological pathways, these particles enter and traverse ecosystems as a result of fragmentation of larger plastics and primary sources such as industrial abrasives and cosmetics. Since they are widely distributed, their presence in soil, freshwater, marine environments, air, human tissues and food chains has been documented. To understand MPs and NPs' prevalence, behavior, and impacts, this review synthesizes findings from key case studies analyzing environmental and biological samples. It has been shown that both human and animal health can be negatively impacted, including inflammation and oxidative stress, reproductive toxicity, and developmental toxicity. Further, we discuss contaminants' transport, accumulation, and interactions in food and water systems. There is a special emphasis on ecological consequences, such as bioaccumulation and trophic transfer, which intensify risks across ecosystems in the long run. Additionally, this paper summarizes global and national regulatory frameworks and provides science-based mitigation recommendations, including source reduction strategies, circular economy strategies, and improved analytical methods. Microplastics and nanoplastics pose significant health and environmental risks due to rapid technological advancements and increasing scientific insight. This review stresses the need for harmonized regulations and robust monitoring in addition to interdisciplinary research to address these issues.

Subject Areas

Analytical Chemistry

Keywords

Micro- and Nano-Plastics, Pathways, Ecological, Human Health, Regulatory

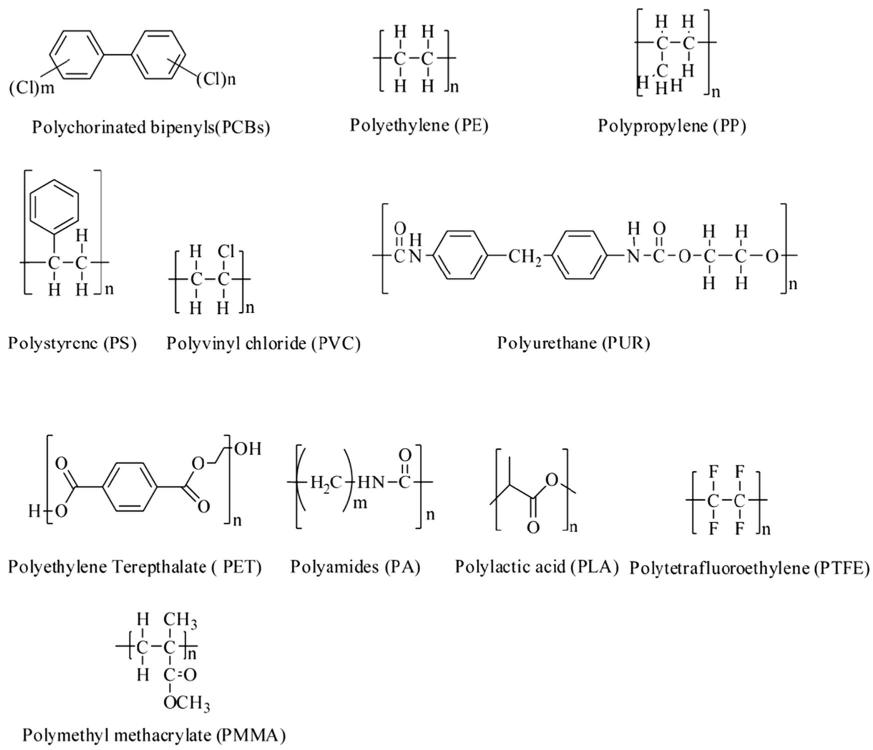
1. Introduction

A growing class of pollutants has developed as a result of the proliferation of plastics in the environment, such as Microplastics (MPs) and Nanoplastics (NPs), which have now become ubiquitous across the terrestrial, aquatic, and atmospheric realms. A microplastic is a small plastic particle, usually measuring less than 5 mm in size, while a nanoplastic is less than 100 nanometers in size. Microbeads, for example, are derived both from primary sources and secondary degradation of large plastic debris through weathering and mechanical forces [1]. MPs and NPs are highly durable and can penetrate biological systems because of their small size, durability, and chemical properties. They threaten ecosystems and human health alike. In addition to drinking water, seafood, soil, and even human blood, microplastics have been found in a number of other products, demonstrating their pervasiveness and potential to be long-term contaminants [2]. As a result of the ingestion and inhalation of these particles, cellular damage, inflammation, and endocrine disruption can result [3]. Although there is a growing body of evidence pertaining to their environmental behavior, toxicity mechanisms, and long-term impacts, there is still much to understand about their environmental impacts. The purpose of this review is to examine the diverse environmental pathways of MPs and NPs, their interactions with organisms and pollutants, and the policies being implemented around the world. Through the integration of case studies, environmental monitoring data, and regulatory analysis, this paper provides an overview of microplastic and nanoplastic pollution, identifies research gaps, and proposes mitigation and regulation strategies.

2. Case Studies

2.1. Environmental Sample Analysis

In southeastern Spain, there is a coastal saltwater lagoon called Mar Menor, which has been affected by numerous human pressures over the years, including plastic pollution. In order to determine whether MNPs were present in the lagoon's surface waters, researchers conducted a study 112. In this case study, the analysis of micro-plastics and nano-plastics in the Mar Menor lagoon is examined, illustrating advanced analytical chemistry techniques used and the challenges of analyzing environmental samples. In the summer of July 2018 and winter of March 2019, two sampling studies were conducted. At each sampling point, samples were taken from the first 5 cm of water, with nine sampling points located in the lagoon. Different types of analytical techniques were employed in this study. Liquid Chromatography coupled to High-Resolution Mass Spectrometry (LC-HRMS) is used for suspect screening, Kendrick Mass Defect analysis is used for polymer identification, and standards are used for confirmation and quantification. Several types of MNPs were identified in the Mar Menor lagoon water, including Polystyrene (PS), Polyethylene (PE), Polyisoprene (PI), Polybutadiene (PBD), Polypropylene (PP), Polyamides (PA), Polyvinylchloride (PVC), N-isopropylacrylamide, and Polydimethylsiloxanes (Figure 1). A quantitative analysis of the MNP concentrations in lagoon water provided valuable information on the pollution caused by these polymers. In this study, nanometer-range particles up to 20 µm were analyzed using advanced analytical techniques, such as LC-HRMS. Several inorganic and organic materials are present in seawater samples that interfere with the detection of MNP. For accurate identification of polymer types present in the environment, Kendrick Mass Defect analysis was employed. In order to measure polymers accurately in complex samples, reference standards and standard procedures were used to confirm and quantify the presence of specific polymers [5] [6].



Source: https://link.springer.com/article/10.1007/s13762-022-04261-1/figures/2.

Figure 1. Some major polymer products found in microplastics [4].

2.2. Soil Sample Analysis

An overview of the challenges and advances in analytical chemistry techniques used for the detection and analysis of microplastics in agricultural soils is presented in this case study. There is a growing concern about the presence of microplastics in agricultural soils, due to their potential impact on the health of soils, plant growth, and ecosystems. As microplastics accumulate in soil, they may alter soil structure, affect water retention, and cause crops to accumulate pollutants. In order to understand how microplastics impact the environment and the ecosystem, accurate detection and analysis is vital. Soil samples were collected from different locations of agricultural fields containing varying amounts of plastic material. In order to capture recent microplastic deposition, soil samples were collected from the top 10 cm of the soil profile. On the basis of density differences, zinc chloride and sodium chloride solutions were used to separate microplastics from soil components. In order to detect microplastics, hydrogen peroxide was used to break down organic matter. A stereomicroscope was employed to visually identify large-sized microplastics (>1 mm) [7]. Fourier Transform Infrared (FTIR) spectroscopy was utilized to identify microplastic polymer types, and a Thermogravimetric Analysis (TGA) coupled with Mass Spectrometry (MS) method for quantifying microplastic content and identification of polymers. In this case study, the quantity of microplastics such as Polyethylene (PE) and Polypropylene (PP) was successfully detected in all agricultural soil samples. These two components are commonly used in agricultural mulching films and are the most prevalent microplastics. Microplastic extraction and analysis of soil samples is challenging due to soil heterogeneity. This problem can be addressed through density separation and organic matter removal. Organic matter can affect spectroscopic analyses and by removing organic matter with hydrogen peroxide, FTIR results were more accurate [8]. There is currently no reliable method for detecting microplastics less than 1 mm particle size. In order to improve detection capabilities, new techniques like tomography using neutron beams and X-rays are being explored [9]. It is necessary to develop standardized protocols to analyze microplastics in soil to ensure comparable results across different studies. As part of this process, consistent sample sizes and pretreatment procedures must be established [10].

2.3. Aquatic Sample Analysis

The objective of this case study is to determine how microplastics are detected in freshwater lakes and to highlight the challenges and advancements in analytical chemistry techniques that can be used to assess them. There is an increasing concern about the impact of microplastic pollution on the ecosystem and human health in freshwater lakes. Microplastics must be detected and analyzed accurately in these environments in order to understand their ecological and health impacts. In both freshwater and saltwater environments, surface water samples were collected using a Manta net, a common device for sampling microplastics at the surface. In order to assess the distribution of microplastics across the lake, multiple samples were taken from different locations [11] [12]. Microplastics were isolated from other particulate matter by filtering samples through a 0.3-mm mesh [13]. An organic matter digested by Wet Peroxide Oxidation (WPO) was used for microplastic identification. A microscopic examination was carried out to identify microplastics by their shape, size, and color [14]. Microplastic composition was determined by Fourier Transform Infrared (FTIR) and Raman spectroscopy [15]. The mass of microplastics found in each sample was quantified using gravimetric analysis [13]. Several types of microplastics were identified in the freshwater lake, including Polyethylene (PE), Polypropylene (PP), and Polyvinyl Chloride (PVC). A higher level of concentration was detected near areas with significant human activity, compared with other sampling locations. Standardized sampling protocols are needed to ensure comparability across studies. Surface sampling can be accomplished with manta nets consistently [11]. Organic matter is effectively removed by wet peroxide oxidation, improving microplastic identification accuracy. There is currently no reliable method for detecting small plastics and nano-plastics. In order to overcome this challenge, advanced technologies such as thermal analysis and mass spectrometry are being explored. For accurate identification of polymers in aquatic environments, spectroscopic methods like FTIR and Raman are necessary [15].

2.4. Atmospheric Sample Analysis

The purpose of this case study is to review the challenges and advances in analytical chemistry techniques used to analyze microplastics in urban atmospheric samples. Microplastics in the atmosphere have become a major concern due to their potential consequences for human health. As these particles are capable of traveling long distances, they contribute to global microplastic pollution. To understand atmospheric microplastic sources, transport mechanisms, and ecological impacts, accurate detection and analysis are essential. Air samples were collected from the atmosphere using a pump-driven air sampling system. This method collects particulate matter of various sizes. Microplastics were collected from atmospheric fallout using aluminum trays or funnels. Microplastics were fractionated by size using 125 μm mesh, 63 μm mesh, and 25 μm mesh sieves, to facilitate the removal of larger non-organic particles. The microplastics were isolated using membrane filters with pore sizes of 12 and 1.2 μm [16]. The carbon-rich particles were identified by light microscopy and their morphologies were assessed by Scanning Electron Microscopy (SEM). Several types of polymers were identified using micro-Raman spectroscopy, which provided chemical information about microplastics [17]. Although less commonly used, thermochemical methods and mass spectrometry could be used to identify atmospheric microplastics [18]. It was found that microplastics were present in urban atmospheric samples, and a variety of polymer types, including Polyethylene (PE) and Polypropylene (PP), were identified. A higher level of microplastics was found in areas with significant human activity, irrespective of location and sampling method. To ensure comparability across studies, standardized protocols are needed for atmospheric microplastic sampling. Analyzing active and passive data requires different approaches but provides complementary data. Using sieves and filters reduces organic matter interference, improving spectroscopic analysis accuracy [16]. There are challenges associated with detecting microplastics and nanoplastics using current methods.

Laser direct infrared spectroscopy is an advanced technique being explored for improving detection capabilities [18]. To identify atmospheric samples accurately, spectroscopic methods such as Raman must be used due to the variety of polymer types of present [17].

2.5. Human Health Impact Studies

As part of this case study, examine potential ill effects of microplastic exposure on humans and focus on cardiovascular risks as well as challenges and advancements in analytical chemistry associated with these risks. Human tissues and biological samples have tested positive for microplastics, raising concerns about their potential health effects. Recent studies show microplastic exposure may increase heart attack and stroke risk. Patients with microplastics in their carotid arteries have twice the risk of heart attack or stroke than those without microplastics, according to a recent study. This study highlights the need for more research into microplastics and cardiovascular health. Microplastic particle detection and quantification in human tissues is one of the biggest challenges in studying their health effects. Microplastics identification in biological samples requires advanced analytical techniques, such as spectroscopy (e.g., FTIR, Raman), and microscopy [18] [19]. Ingestion, inhalation, and dermal contact are all ways humans are exposed to microplastics. A comprehensive understanding of these exposure routes is essential for assessing health risks, as well as developing methods for measuring microplastic intake through these routes. When exposed to microplastics, toxic chemicals and pathogens can be released into the body and chemical analysis plays an important role in identifying and assessing these contaminants. According to the study, microplastics in the carotid arteries were significantly associated with cardiovascular risk. Microplastics contribute to inflammation and vascular damage, aggravating cardiovascular issues [20].

2.6. Animal Health Impact Studies

The purpose of this case study is to evaluate the impact of microplastics on aquatic organisms, highlighting the analytical chemistry techniques used as well as the challenges encountered during the assessment. Microplastics in aquatic environments have become a significant pollutant, affecting a wide range of organisms, including invertebrates and fish. As a result of swallowing microplastics, aquatic animals can become physically injured. In addition, toxicity from associated chemicals can result in a change in feeding behavior, and reproduction may be negatively affected as well. The effects of microplastics on aquatic organisms have been comprehensively reviewed, and they include the following. There is a reduction in aquatic invertebrates' feeding activity, fertility, and larval growth and development due to microplastics. As a result of microplastics, fish can suffer structural damage to their intestines, livers, gills, and brains, which affects their metabolism and behavior. It has been reported that microplastics trigger the production of reactive oxygen species in aquatic organisms, causing them to undergo oxidative stress. Visual identification of microplastics in biological samples can be accomplished using optical microscopy and Scanning Electron Microscopy (SEM). Microplastic polymer compositions are determined using Fourier Transform Infrared (FTIR) and Raman spectroscopy. Microplastic exposure can cause tissue damage and organ morphology changes, which are assessed histologically. In aquatic organisms, microplastics accumulate in a wide variety of tissues, causing biochemical changes and structural damage. Depending on the particle size, dose, and duration of exposure, these effects will vary [21].

Food consumption exposes humans and other organisms to microplastics constantly. Further research is needed to evaluate the effects of long-term exposure to microplastics and their toxicity. Microplastics analysis requires removing organic matter and other contaminants from biological samples. Microplastics are isolated using density separation and chemical digestion. Identification of microplastic types in biological samples is crucial for understanding their potential toxicity via spectroscopic methods. A standardized sampling and analysis protocol is needed to ensure comparability among studies [22].

The case study illustrates the significant health risks associated with microplastics in the aquatic environment. In the future, research should focus on refining analytical methods, exploring molecular mechanisms of microplastic toxicity, and developing strategies to mitigate microplastic pollution in aquatic environments. As a result, marine ecosystems will be protected more effectively, and broader ecological implications will be understood.

3. Microplastics in Food and Water

Microplastics have become widespread contaminants in our food and water systems, posing challenging research questions for environmental and public health communities. According to recent studies, their infiltration into human consumption pathways and health risks presents a critical concern. The term microplastic refers to small plastic particles, less than 5 milli meters diameter, that come from a variety of sources. A primary microplastic can be manufactured intentionally, or a secondary microplastic can arise from the degradation of a large plastic item. Microplastics are derived from plastic bottles, bags, and packaging materials. Microbeads in personal care products and industrial pellets contribute to primary microplastics.

3.1. Contamination Pathways

Food products such as dairy products, meat, beverages, and processed foods can become contaminated with microplastics through direct contact with plastic packaging materials. This can lead to nutritional quality being altered and synthetic particles being introduced into food [23]. Microplastic contamination can also occur during food processing and packaging. This is because microplastics can be released from plastic packaging materials during storage, transportation, or by the abrasion of equipment during processing [24]. Microplastic particles are released from bottles and containers of bottled water and beverages, especially if they are stored at a fluctuating temperature [23]. A large amount of microplastics have been detected in bottled water, tap water, and other beverages. Contamination may occur during bottling, storage, and distribution [25]. There is a risk that microplastics will accumulate in soil, water, and fruits, vegetables, and grains that are contaminated by contaminated soils and waters. Plastic mulch films tend to increase microplastic accumulations in soil [26]. Agricultural plastics fragments enter soil and groundwater; contamination of groundwater deposits microplastics on crops. Microplastics are introduced into soil as fertilizer and absorbed into crops by root systems [23]. The marine environment ingests microplastics, causing bioaccumulation in seafood such as fish, mussels, and crustaceans; humans are particularly vulnerable to exposure when eating small fish [23]. Humans are exposed to airborne microplastics via crops and water sources. The proportion of microplastics inhaled contributes to 16.2% of the total amount found in the environment [18]. Nano-plastic particles often remain in water from taps and bottles after they have been filtered by conventional filtration systems [23].

3.2. Health Implications

There is still much uncertainty as to the health effects of microplastics. However, researchers have identified several potential mechanisms of toxicity, allowing microplastics to release harmful chemicals. A variety of additives are used in plastic materials (e.g., plasticizers, flame retardant chemicals, stabilizers). Many of these additives are known to cause reproductive problems and cancer [27]. As a result, microplastics can adsorb Persistent Organic Pollutants (POPs) and heavy metals from the environment, causing toxic effects in the body once ingested [28]. In particular, microplastics can damage the gastrointestinal tract, which can be irritated, inflamed, and ulcerated. MPs are characterized by their size, shape, and concentration, which influence how much damage they will cause [29]. As a result of toxic exposure to microplastics, immune responses can lead to inflammation and allergic reactions. The immune system may recognize MPs as foreign bodies, causing a cascade of inflammatory reactions [30]. A chronic exposure to toxins causes dysbiosis, which increases the chances of developing inflammatory bowel disease. There are gastrointestinal inflammations and metabolic disorders associated with microplastics, as they carry heavy metals and hydrophobic pollutants. Type 2 diabetes, and insulin resistance are linked to particles causing cellular damage and impairing lipid metabolism. Microplastics in carotid arteries were linked with doubled heart attack and stroke risks, as well as an increase in cardiovascular patient death rates over the next 3 years, according to a cohort study published in 2024. The inhalation of particulate matter leads to oxidative stress, mitochondrial damage, and increased risk of chronic obstructive pulmonary disease [31]. When exposed repeatedly, immune cells lose efficiency and pathogenic bacteria are encouraged to multiply. Neurological inflammation and cognition deficits were caused by nano-plastics in animal models. There is a correlation between increased levels of placental microplastics and preterm birth, and cellular damage is amplified by co-exposure to cadmium or antibiotics [18].

4. Pathways of Microplastic Pollution

A range of sources contribute to microplastics, which can pose a threat to ecosystems and potentially harm human health when they spread in the environment via water, air, and soil.

4.1. Atmospheric Transport of Microplastic

A significant part of microplastics global distribution occurs through atmospheric transport, which enables them to travel across vast distances and into remote areas. Airborne microplastics are emitted, transported through atmospheric currents, and eventually accumulate in a variety of environments due to this pathway.

4.1.1. Sources of Atmospheric Microplastics

Microplastics in the atmosphere are primarily resulting from the synthetic fibers in clothing, the abrasion of synthetic rubber tires, the incomplete incineration of plastic waste, and dust storms. Additionally, road traffic contributes significantly to Particulate Matter (PPM), particularly Tire Wear Particles (TWPs) and Brake Wear Particles (BWPs). A major source of indoor microplastic emissions is synthetic textiles, furniture, and carpets [32] [33].

4.1.2. Transport Mechanisms

A microplastic particle can be transported over thousands of kilometers via atmospheric currents, including jet streams and trade winds. Fibers travel farther than spherical particles, affecting their efficiency of transport. This plastic is found in a vast variety of environments, including oceans, lands, and remote regions like Antarctica. Microplastics are transported into the atmosphere through the ocean, contributing to their global spread.

4.1.3. Environmental and Health Implications

Microplastics are transported throughout the atmosphere, affecting ecosystems worldwide. Even remote regions such as the Arctic and Antarctica can accumulate microplastics and have a negative impact on their ecosystems [34] [35]. Microplastics can be inhaled and introduced directly to the human body through direct inhalation, posing health risks. Microplastics are found in human lungs, highlighting the need for further research into their health effects [32].

4.2. Aquatic Pathways of Microplastic Pollution: Rivers, Oceans, and Wastewater Systems

There are a variety of pathways through which microplastics enter aquatic ecosystems, including rivers, oceans, and wastewater treatment systems. These pathways contribute significantly to the distribution and accumulation of microplastics in both marine and freshwater environments.

4.2.1. River Pathways

There are several ways microplastics can get into rivers from land to ocean. Stormwater runoff, agricultural runoff, and industrial effluent are all ways they can get into rivers. A study found that microplastics can linger in riverbeds for years before being transported downstream, trapped near river sources by hyporheic exchange processes. As a result of microplastics being retained, aquatic organisms may be exposed to them for a prolonged period of time, potentially affecting the health of ecosystems [36].

4.2.2. Ocean Pathways

Many microplastics accumulate in marine environments through a number of routes, such as river discharge and atmospheric deposition, making them the ultimate sink for these particles. Ingesting microplastics in the ocean can cause physical harm and the transfer of pollutants through the food chain once they reach the ocean. Microplastics, due to their floatability, are prevalent in marine environments, where they spread pollution [37].

4.2.3. Wastewater Systems

A significant amount of microplastics is discharged into rivers and oceans by Wastewater Treatment Plants (WWTPs). Even though they are treated, WWTPs still discharge substantial amounts of microplastics into the environment. According to studies, treated effluent from WWTPs contains high levels of microplastics, which exceed those found in other environmental matrices [38]. It is evident that WWTPs cannot effectively remove microplastics, raising the need for improved treatment technologies to mitigate this pollution pathway.

4.3. Terrestrial Pathways and Soil Contamination

There are multiple pathways by which microplastics enter terrestrial ecosystems, causing soil contamination, affecting soil quality, plant growth, and ecosystem services, endangering human health and the environment.

4.3.1. Sources of Terrestrial Microplastic Pollution

There are a number of sources of microplastic pollution in the terrestrial environment. In agricultural soils, microplastic contamination is primarily caused by the use of plastic mulch films and sewage sludge fertilizer. Microplastics introduced into the soil by these practices can persist for centuries and have an effect on soil fertility and structure [39] [40]. The introduction of microplastics into terrestrial ecosystems is also possible through atmospheric deposition, where they fall from the sky to land surfaces [41]. A large part of the microplastic pollution in soils is due to improper waste disposal, including littering and landfill leaks [42] [43].

4.3.2. Effects on Soil Ecosystems

Biodiversity and soil fertility can be influenced by microplastics in soil, altering their physical properties like water holding capacity and bulk density [40]. In addition, they can make other pollutants more bioavailable and toxic by interacting with them.

A microplastic, for instance, changes the microbial community in soil, resulting in changes in nutrient cycling and plant growth [40] [44].

4.3.3. Impact on Terrestrial Organisms

A number of terrestrial organisms, such as earthworms and insects, are susceptible to ingesting microplastics, which could affect their health or survival. Earthworms, in particular, can spread microplastics throughout the soil through their burrowing activities [39]. As microplastic accumulates in insects, it may be transferred to higher trophic levels, affecting ecosystem dynamics [45].

4.4. Biological Pathways: Trophic Transfer and Bioaccumulation

This process of trophic transfer and bioaccumulation involves the movement of microplastics through food chains, potentially affecting ecosystem health and human health.

4.4.1. Trophic Transfer

The translocation of microplastics occurs when lower-trophic organisms ingest microplastics, which are then consumed by higher-trophic predators. This phenomenon has been observed in both freshwater and marine ecosystems. A study demonstrated that nanoparticles of polystyrene can reach higher trophic levels through dietary exposure through algae, water fleas, and fish, demonstrating that microplastics can reach such levels through dietary exposure [46]. The transfer of microplastics from contaminated prey to predators in marine ecosystems has been shown to occur through copepods and jellyfish [47]. The digestive tracts of Atlantic mackerel and scat samples of grey seals have also been found with microplastics, indicating trophic transfer [48].

4.4.2. Bioaccumulation

In bioaccumulation, microplastics accumulate in organisms over time, often increasing their concentrations above those in the surrounding environment. Microplastics are able to become more concentrated as they move up the food chain because of this process. As a result of particle size, shape, and associated contaminants, microplastics can be more toxic to organisms, which can increase their bioaccumulation [46] [49].

4.4.3. Microplastics in the Food Chain: Mechanisms and Implications

It is now clear that microplastics are integrating into the marine food web as they permeate the environment more and more. They have been found in a wide range of animals at lower trophic levels, such as copepods, ichthyoplankton, zooplankton, and chaetognaths. Microplastics have also been found in higher trophic level vertebrates and invertebrates, indicating that contamination is not limited to these levels. Either direct ingestion or trophic transmission from infected prey introduces these particles. There is no risk to human health from the bioaccumulation of microplastics in fish digestive tracts because this part is usually thrown away during preparation and not eaten. The possibility of human exposure to microplastic pollutants is increased by the fact that crustaceans, especially filter feeders, sometimes have their digestive tracts consumed whole [50].

By studying indicator species, it is possible to determine the level of microplastic contamination in seafood and other marine organisms intended for human consumption. Because of their filter-feeding habits and the fact that they are usually eaten whole, mussels and other mollusks are useful bioindicators and may be important vectors of microplastic exposure. Benthic fish can also serve as an indicator of the level of pollution linked to sediments. The risk of human exposure through open-sea food sources is highlighted by the consumption of small pelagic species like sardines and anchovies, which are also eaten whole and offer insights into microplastic contamination in the pelagic zone [51].

Moreover, processed fish products, including canned Sardines and Sprats, contain microplastics. 20 commercially available canned sardines and four packaged sprats were tested [52]. As well as seafood, microplastics are found in terrestrial food products, particularly sugar and honey [53]. Chinese researchers mapped microplastics in rock salt, assuming they were produced by seawater [54].

Microplastics have also been found in bottled water. Microplastic contamination has been found on beverage cartons and disposable and returnable plastic bottles. Some glass bottles contained high levels of microplastics as well. Packaging may be the source of contamination based on the type and amount of microplastics detected [55].

Fish and shellfish have received the majority of research on microplastic contamination in the food chain, but plant-based foods like rice and seaweed are now receiving more attention. Furthermore, contamination has been evaluated in a number of other food items, including milk, vinegar, and salt. A wider range of possible human exposure through other dietary sources is indicated by studies conducted in the beverage industry that have gone beyond bottled water to include products like white wine, energy drinks, and soft drinks [49].

Apart from air and water, soil is a substantial and frequently disregarded source of microplastic pollution in the food chain. Landfill leachate, agricultural soil treatments, sewage sludge fertilizer application, contaminated wastewater irrigation, compost and organic fertilizer use, mulching film degradation, tire wear particles, and atmospheric deposition are some of the ways that microplastics can get into the soil. In addition to lowering the soil's general quality, the buildup of microplastics raises the possibility of further fragmentation, which increases ecological risk and environmental persistence [56].

Water dynamics and soil aggregation may be impacted by microplastics' effects on soil density and porosity. Furthermore, some studies suggest that microplastics in the soil alter the levels of phosphorus, nitrogen, and carbon, which may upset the nutrient cycle [57]. The average American is thought to eat between 39,000 and 52,000 microplastic particles each year, with differences seen across age and gender categories, according to a synthesis of 26 studies. This estimate was calculated by estimating about 15% of the average calorie intake, including microplastics from foods including seafood, honey, sugar, salt, alcohol, and both tap and bottled water, as well as exposure to airborne particles through inhalation [58].

4.4.4. Effect of Microplastics on Human Health

The primary source of microplastics entering the human food chain is contaminated food, and they may be harmful to human health. Another way that the human body might become contaminated is via inhaling microplastics [59]. A minor source of microplastics in the human body is skin contact [60].

There is still much to learn about the impact of microplastics on the human digestive system after consumption. Most micro- and nanoplastics (more than 90%) are thought to be eliminated by feces. Microplastics up to about 150 μm in size have been found in lymphatic tissues in mouse investigations, suggesting that absorption via the intestinal epithelium occurs mainly for particles up to this large. Such absorption could result in exposure throughout the body, while bigger microplastics are more likely to have localized effects on the gut's immune system. Concerns regarding the possible health effects of microplastics are further raised by the fact that the smallest ones, those smaller than 1.5 μm, have the ability to deeply enter a variety of organs [61]. Due to their size, nanoplastics are more dangerous since they can pass through the placenta, the blood-brain barrier, and M-cells in Peyer's patches in the small intestine. From there, they can pollute the liver and gallbladder and enter the blood and lymphatic system [3].

It was shown for the first time in a 2021 study that microplastics are present in human placenta. 12 pieces, ranging in size from 5 to 10 μm, were found in four placentas. We still don't know how they enter the placenta or whether they have any impact on pregnancy or the developing fetus [62]. It is still unclear how long-term exposure to microplastics may affect human health. During inflammatory responses, reactive oxygen species are produced, which can induce oxidative stress and lead to cytotoxicity, among other possible negative effects. Further research is necessary to fully understand the health hazards associated with microplastic consumption, as it has been proposed that it can interfere with energy homeostasis, metabolic processes, and immune system function [30].

The potential of microplastics to act as vectors for microbial colonization is another issue associated with their consumption. The surfaces of microplastics have been found to harbor a variety of pathogenic microbes, and eating tainted seafood may expose people to more of these dangerous species. Microplastics can also contaminate food with harmful substances such antibiotics, bisphenol A, Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), chlorinated insecticides, and Brominated Flame Retardants (BFRs). There are serious public health concerns since these compounds have been linked to mutagenic, carcinogenic, and endocrine-disrupting effects [63].

There are a number of case studies that have examined the effects of microplastics on human health. A few of these case studies are provided below.

Case Study 1: Airborne Microplastic Contamination and Human Health Impacts

According to recent research from the Seoul Institute of Health and Environment, indoor areas have higher concentrations of microplastics than outdoor ones, and metropolitan air is considerably contaminated. Outdoor air had an average of 1.96 ± 1.65 particles per cubic meter, whereas interior air had an average of 3.02 ± 1.77 particles per cubic meter. Polyethylene (PE), Polypropylene (PP), polyester, acrylic, and polyamide (nylon) made up the majority of the microplastics found [64]. These components are frequently shed from synthetic textiles, packaging, and household dust. Since fibrous particles like polyester and nylon can cause lung irritation, oxidative stress, and persistent immunological responses similar to the consequences of fine particulate pollution, the increasing prevalence of airborne microplastics raises concerns about respiratory health. Toxicological research indicates that extended inhalation of smaller nano-plastic particles may enable them to penetrate deeply into lung tissues, possibly causing inflammation and other respiratory disorders, even though there is currently little direct epidemiological data. Because of increased exposure, workers in businesses that handle synthetic fibers may be more vulnerable. These results highlight the need for more research on the health impacts of airborne microplastics and demand stricter controls on exposure, especially indoors [64].

Case Study 2: Seafood Contamination with Microplastics and Human Health Risks

The Ministry of Food and Drug Safety in South Korea has reported contamination in a number of regularly consumed seafood products, confirming the well-established ubiquitous occurrence of microplastics in marine habitats. Concentrations in shellfish, cephalopods, crustaceans, dried anchovies, and sea salt ranged from 0.07 to 0.86 particles per gram, 0.03 to 0.04 particles per gram, 0.05 to 0.30 particles per gram, and as high as 2.22 particles per gram, indicating a wide range of possible dietary exposure in humans [65]. Among the most common microplastics found were Polypropylene (PP), Polyethylene (PE), Polystyrene (PS), and polyethylene vinyl acetate; these compounds are mostly found in industrial coatings, fishing gear, and packaging. Consuming seafood that contains microplastics poses a number of health risks. Endocrine-disrupting chemical buildup, gut microbiome disruption, and gastrointestinal inflammation are possible hazards. Additionally, microplastics have the ability to bind to heavy metals and persistent organic pollutants, raising the risk of systemic toxicity from prolonged exposure. Smaller particles, particularly nanoplastics, may be able to pass through intestinal barriers and reach the bloodstream, potentially interfering with hormonal and metabolic functions, according to experimental research. Given the level of contamination in seafood, our results highlight the necessity of more thorough investigation into the long-term health implications of dietary exposure to microplastics, stricter regulations, and continuous surveillance [66].

Case Study 3: Occupational Exposure to Microplastics and Toxic Additives in Plastic Processing Facilities

Concern over occupational exposure to microplastics and the hazardous compounds they contain are growing, especially in settings with high levels of airborne pollution. A study on the health dangers to employees at a plastic waste recycling company was carried out in Bari, Italy. Polypropylene (PP), Polyethylene (PE), and Polyvinyl Chloride (PVC) microplastic particles were found in considerable amounts in air samples taken from the plant. According to the findings, these particles also contained dangerous chemical additions like lead, phthalates, cadmium, Bisphenol A (BPA), and brominated flame retardants [60]. Serious concerns regarding the long-term health implications of breathing in microplastics were raised by the variety of symptoms that workers in this workplace described that were associated with extended exposure, including respiratory problems, hormone abnormalities, and minor neurological impairments. The study discovered that the constant mechanical handling and processing of plastic materials resulted in significantly greater indoor air concentrations of microplastics than outside ones. PP and PE were primarily associated with packaging and textiles, whilst PVC was more frequently tied to industrial, and construction uses. The types of polymers used in plastics varied according to their sources [67].

Heavy metals used in plastic coatings and stabilizers, such as lead and cadmium, were shown to present additional dangers after more chemical study. Elevated BPA and phthalate levels in urine samples from exposed workers suggested a potential endocrine disruption with consequences for metabolic and reproductive health. Persistent coughing, throat irritation, and decreased lung function symptoms of oxidative stress and pulmonary inflammation were among the common health issues that employees reported. Lung tissue fibrosis and immune system dysfunction have also been connected to inhaling fibrous microplastics like polyester and nylon. Concerns about chronic hormonal disruptions were also raised by exposure to endocrine-disrupting substances that were adsorbed onto microplastics. Chronic exposure to heavy metals, such as lead, has been linked to neurotoxic effects, including fatigue and cognitive impairment [68]. This case study demonstrates the significance of tailored mitigation techniques and proactive workplace laws in protecting the health of workers in the plastic production and recycling industries.

Case Study 4: Microplastic Pollution in the Cherating River, Malaysia

Rivers are crucial in moving plastic debris from land-based sources into marine environments, and microplastic contamination in freshwater systems is becoming more widely acknowledged as a significant environmental concern. In order to determine baseline contamination levels, a recent study on the Cherating River in Malaysia evaluated microplastic pollution at three locations along the river: upstream, midstream, and downstream in a mangrove area. The concentration of microplastics was highest in the midstream region (0.0070 ± 0.0033 particles/m^3) and lowest in the upstream site (0.0005 ± 0.0003 particles/m^3). The downstream mangrove area had the second-highest concentration (0.0051 ± 0.0053 particles/m^3) [69].

The majority of the microplastics found were fragments, mostly from brokendown plastic containers and packaging, suggesting that poor waste management and runoff, particularly from adjacent tourism operations, are major drivers of pollution. Particularly prevalent in the midstream and downstream areas were line-shaped particles, which are frequently connected to fishing gear. White pieces were the most commonly detected, and most of the particles were between 0.5 and 1.0 mm in size. This implies that a major portion of the contamination is caused by secondary microplastics, which are created as bigger plastic debris breaks down [69].

The potential for microplastics to build up in aquatic organisms and make their way into the food chain is a significant worry when they are found in river ecosystems. Moreover, these particles may serve as transporters of dangerous substances such as Polychlorinated Biphenyls (PCBs) and Polybrominated Diphenyl Ethers (PBDEs), which may intensify their detrimental impacts on wildlife and human health when consumed in seafood. These results emphasize how urgently targeted action is required (**Table 1**). Monitoring pollution trends and putting effective intervention plans into place to stop microplastic contamination in freshwater systems requires better waste management, less plastic use, and regular environmental monitoring [69].

Table 1. Toxicity effect of microplastics on human health.

Type of effect	Types of microplastics	Effect details on human body	Reference
Oxidative stress	Polystyrene Polyvinyl Chloride (PVC)	Excessive in Reactive Oxygen Species (ROS) production leads to DNA damage	[70]
Metabolic homeostasis	Cationic polystyrene	Deficiency in energy metabolism	[71]
Inflammation	Polystyrene (PS)	The liver is inflamed as a result of the inflammation	[72]
Cytotoxicity	Polyethylene (PE) Polystyrene (PS)	Cellular damage	[60]
Mitochondrial dysfunction	Polystyrene (PS)	Leads to mitochondrial depolarization, disrupting energy production	[73]
Bloodstream toxicity	Various microplastics travelling via blood	Leads to pulmonary hypertension, vascular occlusions, and blood cell toxicity	[74]
Carcinogenic potential	Polystyrene (PS)	Tested on human intestinal CCD-18Co and MEF cells, providing insight into potential cancer development mechanisms	[75]
Mutagenic potential	Micro plastic associated compounds (Bisphenol A and styrene oxide),	Induce genomic rearrangements and DNA structural alterations, contributing to genomic instability	[76]
Reproductive health risk	Polytetrafluoroethylene (PTFE)	Exposure linked to reduced sperm count and motility	[77]
Allergic reaction & skin irritation	Polypropylene (PP) Polyamide (PA) Polyurethane (PU)	Causes allergic skin reactions and irritation upon exposure	[78]

Continued

Respiratory issues & irritation	Polyurethane (PU) Polyethylene Terephthalate Glycol (PETG)	Leads to respiratory irritation and potential lung-related problems	[78]
Reproductive & hormonal disruption	Polyethylene Terephthalate (PET)	Affects hormone balance and may impact reproductive health	[78]
Developmental & neurological effects	Polybutylene Terephthalate (PBT)	Linked to developmental delays in children and neurological complications in adults	[78]
Cardiovascular problems	Polybutylene Terephthalate (PBT)	Associated with heart-related issues in adults	[78]

5. Regulatory Framework and Guidelines

5.1. International Regulations

In recent years, the issue of microplastic pollution has gained considerable attention from both researchers and the public. However, there remains a notable gap in the development of clear policies and governance strategies to effectively mitigate this environmental threat and reduce plastic usage, particularly in marine ecosystems. Early legislative initiatives to control land-based and marine pollution, or the direct or indirect release of materials or energy into the environment by humans that might negatively impact ecosystems, living resources, infrastructure, and human health, began in the 1970s [79] [80]. A thorough analysis of laws pertaining to plastics and microplastics revealed that several laws were created to handle plastics that are dumped in landfills. To cover all types of plastics, these laws need to be strengthened and reviewed. The lack of citizen science and co-management efforts by major players, as well as the lack of a standardized management strategy, were the main causes of the lack of community involvement in monitoring and conservation, according to a review of governance strategies for controlling MPs in marine ecosystems [81].

Additionally, action plans to address pollution from both land and water were developed by the United Nations' "Global Program of Action for the protection of the marine environment from land-based activities" [82]. Some well-known conventions and action plans were modified to address plastic pollution, even though plastics were not specifically addressed in any of the aforementioned policies and were not included in the program on persistent organic pollutants. For example, the Northwest Pacific Action Plan, the Barcelona Convention, the OSPAR Convention, and the Basel Convention amendment all specifically addressed microplastics [83].

5.2. National Guidelines

National guidelines on microplastic management refer to a set of regulatory frameworks and best practices developed by governments to address the prevention, reduction, and monitoring of microplastics in the environment. These guidelines typically include strategies for controlling plastic waste, encouraging alternatives to single-use plastics, enhancing waste management practices, and promoting research into the environmental impacts of microplastics. They may also provide standards for industries to limit the release of microplastics into ecosystems, with an emphasis on protecting marine environments and public health. These guidelines aim to create a unified approach to tackle the growing issue of microplastic pollution at the national level, ensuring consistent action and collaboration across different sectors and regions.

5.2.1. United States

Microbead-Free Waters Act of 2015: This federal law prohibits the manufacturing, packaging, and distribution of rinse-off cosmetics containing plastic microbeads, aiming to reduce microplastic pollution in aquatic environments. Although there are some initiatives and regulations to limit or eliminate intentionally added MP in consumer products (e.g., microbeads in some cosmetic products), federal, state, and local regulations for MP are essentially nonexistent in the United States, despite the fact that MP has been found in all components of our environment and in select human tissue samples (lungs and placenta). Regulations are difficult since plastic pollution and secondary MP contamination are so widespread. The vast size range of MP source particles, the numerous chemical compositions of plastics, and the addition of additives (colorants, plasticizers, etc.) to plastics further complicate the endeavor. Regulations that limit the use, reuse, recycling, and disposal of plastics are the main focus of state, local, and county regulators' efforts due to these challenges. These regulations have centered on enforcing recycling systems, taxing plastic goods, or outlawing single-use plastics (straws, bags, etc.). The states of Maine and Oregon have mandated recycling, while several states have increased their recycling efforts. Those policies try to lessen the amount of macroplastics in the environment, which will eventually lessen the amount of MP produced, even though they do not directly target MP [84]. National Strategy to Prevent Plastic Pollution: Developed by the U.S. Environmental Protection Agency (EPA), this strategy outlines objectives such as reducing pollution from plastic production, innovating material and product design, decreasing waste generation, improving waste management, enhancing capture and removal of plastic pollution, and minimizing impacts to waterways and oceans [85].

5.2.2. European Union

Restriction of Microplastics in Products: The European Commission has initiated steps to restrict intentionally added microplastics in products, including developing labeling, standardization, certification, and regulatory measures to address both intentional and unintentional release of microplastics. Concern over microplastics effects on the environment has grown, according to the European Commission. Through the EU's Scientific Advice Mechanism, the Group of Chief Scientific Advisors of the European Commission commissioned a thorough analysis of the scientific data regarding microplastic pollution in April 2018 [86]. In 2019, the Commission received a Scientific Opinion based on the SAPEA report, which will be used to determine whether European policy changes should be suggested to reduce microplastic contamination [87]. The European Chemicals Agency (ECHA) suggested limiting purposefully added microplastics in January 2019 [88]. 10% of the world's total, or about 150,000 tons of microplastics annually, are produced in the European Union. With considerable regional variation in the amount of microplastic produced per capita, this amounts to 200 grams per person per year [89] [90].

Mandatory standards for the recycling and waste reduction of important products, such as plastic packaging, are outlined in the European Commission's Circular Economy Action Plan. The plan begins the process of limiting the amount of microplastics that are added to items. It requires actions to capture more microplastics throughout a product's lifecycle. For instance, the proposal would look at various policies that try to lower the amount of secondary microplastics released from textiles and tires [91].

5.2.3. India

Advocacy for Microbead Ban: Researchers in India are advocating for a ban on microbeads in personal care products due to their environmental impact. Currently, there is no specific regulation for microbeads in India, but there are plastic waste management rules in place [92].

5.2.4. Japan

The Japanese government enacted a bill on June 15, 2018, aiming to reduce pollution and microplastic generation, particularly in aquatic settings. This measure, which was introduced by the Environment Ministry and approved by the Upper House unanimously, is the first to be passed in Japan with the express goal of lowering the production of microplastics, particularly in the personal care sector, which includes items like toothpaste and face wash. This law is an update to earlier legislation that addressed the removal of plastic marine trash. It also emphasizes raising public awareness and educating people about recycling and plastic trash. Additionally, the Environment Ministry has put out several suggestions for ways to track the amount of microplastic in the water. But the law doesn't outline any sanctions for companies that keep producing goods that contain microplastics.

5.3. Recommendations for Policy Makers

Micro- and Nano-Plastics (MNPs) pose a complex and potentially devastating environmental threat, according to burgeoning research. In spite of the fact that the full extent of these particles' ecological and human health effects is not yet known, immediate and decisive action is required. Developing and implementing comprehensive and evidence-based strategies is one of the most important roles policymakers play in mitigating the risks associated with MNPs. The prevention of contamination, monitoring and assessment, and remediation efforts must be integrated into a multi-pronged approach [93] [94].

5.3.1. Source Reduction and Responsibility

To combat MNP pollution, policies should focus on source reduction, targeting the largest sources of MNPs. These include Personal care products, cosmetics, and detergents that must be banned from intentionally containing microplastics. The ban should be extended to other applications (for example, controlled-release fertilizers) and alternatives promoted. Develop and adopt biodegradable and compostable plastics that meet rigorous standards and decompose effectively. The development of extended producer responsibility schemes, which hold producers accountable for plastic products' lifecycles, including their design, manufacture, disposal, and waste management, is necessary. Encourage recycled plastics, improve durability and repairability, and promote innovative recycling technologies. Creating incentives for producers to reduce waste and encourage sustainable practices would reduce taxpayer burdens [95].

5.3.2. Monitor and Assess Using Standardized Protocols

Research and infrastructure must be invested in to better understand the scope and impacts of MNP pollution. Current research lacks standardized protocols, preventing accurate risk assessments and hindering data comparability. The use of validated and harmonized methods to identify MNPs should be mandated in environmental matrices (water, soil, air, biota). It is critical to establish long-term monitoring programs in vulnerable areas, such as coastal zones, agricultural land, and drinking water sources, to assess MNP distribution, concentration, and fate. MNP exposure at environmentally relevant concentrations has significant chronic health effects. In order to protect human health and ecosystems, policymakers must prioritize funding for research into toxicity mechanisms, exposure pathways, and long-term consequences. It is critical to conduct *in vitro* and *in vivo* studies along with epidemiological studies [96].

5.3.3. Improve Waste Management and Encourage the Circular Economy

Pollution caused by MNP is largely due to inefficient waste management systems. Prevention measures should be aimed at developing countries. In developing countries, where waste management is often inadequate, invest in robust waste collection and sorting infrastructure. Encourage recycling participation and responsible waste disposal through public awareness campaigns. MNPs cannot be eliminated from wastewater treatment plants using conventional technologies. Develop advanced treatment technologies to remove MNPs from wastewater effluents, such as membrane filtration and enhanced sedimentation. Promoting policies for reusing, repairing, and reusing plastic products, which reduce the need for virgin plastics and minimize waste. By creating markets for recycled plastic and incentivizing recycling product design, we can achieve this [97] [98].

Policymakers must collaborate internationally and share information to combat MNP pollution. Support international agreements that reduce plastic pollution and promote waste management improvements. The aim is to accelerate research and development of effective mitigation strategies by making it easier for countries to exchange information and expertise. Encourage developing countries to develop sustainable plastic management practices and manage plastic waste effectively [99]. Education and Promotion of Responsible Consumption: Policy makers must raise public awareness about MNP pollution in order to encourage responsible consumption. Promote sustainable consumption choices by educating the public about single-use plastics, supporting sustainability-oriented brands, and disposing of waste properly. Encourage citizens to monitor and collect MNP pollution data, creating a sense of ownership and accountability. Provide future generations with information about plastic management and make informed consumption decisions [100].

5.4. Insights into Microplastic Behavior in Ecosystems

In order to assess their environmental impacts, it is imperative to understand how microplastics behave in ecosystems. The aggregation and fragmentation processes of microplastics, their interactions with contaminants, and the long-term ecological effects on food webs have been the focus of recent studies.

5.4.1. Studies on Aggregation and Fragmentation Processes

As a result of UV radiation, temperature, and mechanical stress, microplastics aggregate and fragment in environmental settings. For modeling microplastic fate and transport, it is imperative to understand these processes, according to a study published in Environmental Science & Technology. The degradation of microplastics takes place when larger plastics break down into smaller fragments, which can then be degraded into water-soluble organics when exposed to UV light [101]. Microplastics are affected by this process in different environmental compartments, resulting in their persistence and distribution.

5.4.2. Research into Interactions between Microplastics and Contaminants

Heavy metals and pesticides can interact with microplastics to alter toxicity and environmental persistence. A study published in Environmental Science & Technology Letters revealed that microplastics aggregate contaminants like chromium, changing their oxidation state and increasing their toxicity. In addition to enhancing the aggregation of chromium when UV filters are present, microplastics can also inhibit the growth of microalgae by converting them into a toxic form [102]. Considering these interactions, it is evident how intricately microplastics play a role in the transport and toxicity of contaminants.

5.4.3. Assessment of Long-Term Ecological Impacts on Terrestrial and Aquatic Food Webs

There is considerable concern about the long-term impact of microplastics on food webs. The transfer of microplastics among terrestrial and aquatic food webs was examined in a study published in Environmental Science & Technology, emphasizing the importance of understanding microplastic ingestion and egestion rates [103]. A combination of microplastics and contaminants used in food can lead to biomagnification and bioaccumulation of pollutants at multiple trophic levels. Microplastics are not only harmful to wildlife but can also have harmful effects on human health [104].

6. Future Perspectives

6.1. Emerging Technologies in Microplastics Research

Emerging technologies have played a crucial role in advancing our understanding and mitigation of microplastics, since they continue to pose significant health and environmental challenges. Machine learning-based detection methods, new materials for removing microplastics, and real-time sensing methods are some of the latest innovations. As a result of Machine Learning (ML) and Artificial Intelligence (AI), microplastic detection is becoming faster, more accurate, and more efficient. In contrast to traditional methods, the Plastic Net model identifies microplastics with over 95% accuracy by using deep learning. A large amount of data can be analyzed using these technologies, algorithms can be trained to recognize patterns associated with microplastics, and detection processes can be automated, reducing the need for manual labor and human error [10]. The development of innovative materials, such as biodegradable foams, is required to efficiently remove microplastics from water sources. One recent breakthrough describes a foam made of chitin and cellulose that can remove 99.9% of microplastics from water and can be disposed of after use [104]. A less microplastic-polluted aquatic environment may be achieved with the use of such materials.

In order to reduce microplastic pollution in aquatic environments, such materials can offer promising solutions. Real-time sensing technologies are becoming increasingly important for detecting microplastic particles in real time. An example of this is the Microplastic Detection sensor developed by Woods Hole Oceanographic Institution. It distinguishes plastic particles from non-plastic particles in liquid samples using impedance spectroscopy, delivering quick and accurate results without contamination of the sample [10]. As a result, low-cost, real-time sensors for monitoring the environment could be made from this technology.

6.2. Research Needs

Several research needs have been identified to advance our understanding and mitigation of microplastic pollution, which continues to pose considerable environmental and health challenges.

A significant amount of information about microplastic exposure pathways and levels remains lacking, particularly in terms of human health impacts. In particular, the European Commission has emphasized the need for information concerning microplastic contamination in the environment and on humans [18]. A priority is also to understand the chronic health effects of microplastics. Epidemiological studies and long-term studies are needed in this regard [105].

Detecting and characterizing microplastics requires more reliable, fast, and automated analytical techniques. It is common for current methods to lack interlaboratory validation, and published data lacks quality control measures. In order to advance microplastic research, harmonized characterization methods must be developed and advanced analytical equipment must be made more accessible. Increasing funding and enhancing interdisciplinary collaboration is essential for addressing microplastic research gaps. By collaborating with researchers from different fields and institutions, standardized protocols can be developed and specialized equipment can be made more accessible. The increased funding will enable researchers to explore new methods and technologies for analyzing microplastics and mitigating their impacts [106].

6.3. Potential Solutions

Microplastic pollution must be mitigated through innovative technology and methodologies that can effectively remove microplastics from a variety of environmental matrices. Recent advancements in technology and methodologies offer promising approaches to addressing this problem. Microplastics can be removed from water with the help of pulsing ultrasound waves, developed by researchers. As microplastics move differently in response to sound waves, this technology enables them to be separated and removed efficiently. According to real water samples, the device removed more than 70% of small microplastics and 82% of large ones, demonstrating its significant effectiveness [107].

Researchers are exploring nanomaterials for their potential to remove microplastics from wastewater. These materials are highly adsorbent and reusable, making them promising tools for remediating microplastics. Nanomaterials have significant potential for use in this context, according to a recent review by ACS, which emphasizes the need for further research to optimize their use [108]. In order to remove microplastics and microfibers from laundry wastewater, microbubble-enhanced flotation has been developed. By using this method, over 98% of microplastics and 95% of surfactants can be removed, making industrial-scale treatment more cost-effective and environmentally friendly [109]. The removal of microplastics from wastewater has also been investigated using natural materials and biological methods, such as food-grade plant extracts from okra and aloe, both of which are non-toxic and eco-friendly [110].

7. Conclusion

Microplastics and nanoplastics pose environmental problems that extend beyond geographical and ecological borders. The use and misuse of plastics can have serious consequences for air, water, soil, and food. In this review, we examine the complex pathways by which MPs and NPs accumulate in organisms, travel through the environment, and interact with other pollutants. There have been numerous studies confirming these particles in a variety of matrixes. Bioaccumulation and toxicity are the high risks associated with them. There is a growing awareness of microplastic pollution, but regulatory responses remain fragmented and reactive. In spite of significant steps taken by regions like the European Union, others are still developing standardized monitoring protocols and mitigation strategies for microplastic pollution. Harmonized regulations, international cooperation, and public-private partnerships are essential to building robust control and remediation frameworks. A number of emerging technologies, including biosensors, machine learning tools for detection, and sustainable materials, are providing promising alternatives to combat this pollution. Research findings must be translated into actionable policies through continued investment, interdisciplinary collaboration, and open communication with stakeholders in order to be translated into actionable policies. In order to improve scientific knowledge, consistency in data collection, long-term ecological research, and inclusive regulatory mechanisms are urgently needed. The challenges posed by microplastics and nanoplastics cannot be ignored; they have to be addressed in order for sustainable development and environmental sustainability to be achieved.

Conflicts of Interest

The authors declare no conflicts of interest.

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