microplastics

MDPI

Review

Nanoplastics and Microplastics in Agricultural Systems: Effects on Plants and Implications for Human Consumption

Tarcisio Wolff Leal [1], Gabriel Tochetto [2], Sayonara Vanessa de Medeiros Lima [3], Patricia Viera de Oliveira [3], Henrico Junior Schossler [4], Carlos Rafael Silva de Oliveira [3,5,*] and Afonso Henrique da Silva Júnior [3,4]

[1] Department of Environmental Engineering, Federal University of Paraná, Curitiba 81530-000, PR, Brazil; tarcisio.leal@ufpr.br
[2] Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina, Florianópolis 88040-900, SC, Brazil; gabriel.tochetto@posgrad.ufsc.br
[3] Department of Chemical and Food Engineering, Federal University of Santa Catarina, Florianópolis 88040-900, SC, Brazil; sayonara.vanessa@posgrad.ufsc.br (S.V.d.M.L.); p.v.oliveira@posgrad.ufsc.br (P.V.d.O.); afonso.silva@ufsc.br (A.H.d.S.J.)
[4] Department of Energy and Sustainability, Federal University of Santa Catarina, Araranguá 88905-120, SC, Brazil; henrico.bug@gmail.com
[5] Graduate Program in Nanoscience, Processes and Advanced Materials (PPGNPMat), Federal University of Santa Catarina, Blumenau 89036-256, SC, Brazil
* Correspondence: carlos.oliveira@ufsc.br

Abstract: Nanoplastics and microplastics in agricultural systems have raised significant concerns due to their effects on plant health and potential risks to human consumption. This review examined these pollutants' origins, behavior, and impacts in agricultural environments, emphasizing their primary contamination pathways, such as irrigation, plastic mulching, and sewage sludge application. It explored the transport, accumulation, and interactions of these particles in the soil, including their ability to adsorb other contaminants like pesticides and heavy metals. The effects on plant physiology and potential toxicity were highlighted, along with the implications for food quality and safety. Chronic exposure to these pollutants through the food chain posed notable health concerns for humans, emphasizing the urgency of addressing this issue. Research gaps, such as the toxicokinetics of nanoplastics and microplastics in plants and humans, were identified, underscoring the need for further investigation. The review also presented mitigation strategies, including improved waste management and the development of sustainable agricultural practices.

Keywords: environmental impact; plastic pollution; soil ecosystems; food safety

Academic Editor: Nicolas Kalogerakis

Received: 20 December 2024
Revised: 1 February 2025
Accepted: 3 April 2025
Published: 7 April 2025

Citation: Wolff Leal, T.; Tochetto, G.; Lima, S.V.d.M.; de Oliveira, P.V.; Schossler, H.J.; de Oliveira, C.R.S.; da Silva Júnior, A.H. Nanoplastics and Microplastics in Agricultural Systems: Effects on Plants and Implications for Human Consumption. *Microplastics* **2025**, *4*, 16. https://doi.org/10.3390/microplastics4020016

1. Introduction

Microplastics and nanoplastics (MPs and NPs, respectively) are formed through the fragmentation and degradation of larger plastic items due to environmental factors such as UV radiation, mechanical abrasion, and chemical weathering. MPs are particles ranging from 5 mm to 1 µm, while NPs are smaller, ranging from 1 µm to 1 nm [1]. These particles possess unique physicochemical characteristics, such as high surface area, hydrophobicity, and the ability to adsorb organic pollutants, heavy metals, and other contaminants from their surroundings. Their small size enables them to easily penetrate biological membranes, potentially leading to toxicological effects in aquatic and terrestrial organisms. Additionally, their persistence in the environment is heightened by their resistance to biodegradation, contributing to long-term ecological and health challenges [2].

While the presence of NPs in water, especially in oceans, has received significant attention from the scientific community, their presence in agricultural environments is a growing concern [3]. Plastics enter these systems through various pathways, including plastic mulching films, irrigation with contaminated water, and applying sewage sludge as fertilizer. Additionally, MPs and NPs can be introduced through atmospheric deposition, as plastic particles are transported by wind from urban areas and industrial zones. Wastewater treatment plants (WWTPs) are also significant contributors to the release of NPs into agricultural systems [4]. Many plastic debris particles reach WWTPs, where the treatment process fragments them into smaller particles, including NPs that are difficult to remove. These particles are often retained in sludge, which is later used as fertilizer in agricultural fields or deposited in soil. For example, it is estimated that sludge from WWTPs contains between 1000 and 183,000 plastic particles per kilogram of dry weight. This practice can introduce large quantities of MPs and NPs into agricultural soils, where they persist and interact with the environment [5].

In addition to contamination from WWTPs, agricultural practices contribute to releasing plastic particles. Plastic mulches, used extensively in agriculture to control weeds and conserve soil moisture, break down over time, releasing MPs and NPs into the soil. Furthermore, irrigation systems that rely on water contaminated with plastics contribute to the widespread distribution of these particles in farmlands [6]. The challenge is exacerbated by the difficulty of detecting and removing these particles from water and soil systems, as their small size and widespread distribution complicate their management. The ubiquity of MPs and NPs across environments is well documented, with reports of their presence not only in aquatic systems but also in the atmosphere and remote locations such as the Austrian Alps [7] and Antarctica [8]. However, the global transport of these materials still needs to be fully elucidated, particularly in the context of agricultural environments. Figure 1 illustrates the global cycling of NPs and MPs through aquatic, terrestrial, and atmospheric systems, highlighting the multiple pathways through which these contaminants reach agricultural soils. The deposition of MPs and NPs from atmospheric transport and aquatic migration underscores the complexity of their environmental distribution, making their accumulation in agricultural lands a growing concern. These particles can alter soil physicochemical properties, impact microbial communities, and potentially enter the food chain through crop uptake, raising concerns about their implications for food safety and human health. Also, one critical question is the variation in concentrations of MPs and NPs, as their distribution appears to vary widely depending on environmental factors.

Many studies indicate that plastic materials in the aquatic environment, such as in oceans, lakes, and even water for human consumption, belong to this environmental compartment [9]. Among the many plastic particles found in aquatic environments, the most frequent types are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polyethylene terephthalate (PET) [10]. One of the main transport routes for NPs is through water. It is estimated that 70–80% of plastic materials reach the oceans through rivers. Some factors may contribute to the higher incidence of NPs, such as urbanization and industrialization close to water bodies so that fresh waters concentrate and have more room to retain plastic particles.

One of the primary forms of transport of plastic particles in the sea and oceans is through fresh water, especially rivers. However, the ocean has also been used as a dump, while patches of plastic waste have been observed in the Atlantic and Pacific oceans [11]. Ter Halle et al. (2017) presented one of the first reports of NPs in the sea, detecting PE, PS, PVC, and PET with sizes ranging from 1 to 1000 nm [12]. In the case of lakes, one of the primary forms of plastic contamination is through river entry, waste disposal, and wind action. The NPs decant and settle at the bottom of the lakes; however, they may be easily resuspended and captured along with the water that will be purified.

Abrasive dust, tire wear, abrasion of synthetic clothing, construction waste, material incineration, and polymer fragmentation on a nanometer scale help to explain how plastic particles reach the atmospheric environment. Thomas and coworkers recently reported that tire particles transported from roadways to agricultural soils pose an increasing challenge in assessing microplastic contamination, which impacts soil quality and potentially affects crop uptake [13]. As stated earlier, the detection of NPs is complex, and in the case of atmospheric environments, it becomes even more complex, so there are still no reports of studies that have detected NPs in the air. However, plastic particles have already been detected in indoor environments, e.g., bedrooms, offices, corridors, and different places [14], e.g., in China, the USA and Brazil [15]. The challenge is still great, mainly because the transport of particulate materials of plastic origin, especially of nanometric order, has greater mobility than those present in the terrestrial or aquatic environment, influenced by the particles' atmospheric elevation and aerodynamic conditions.

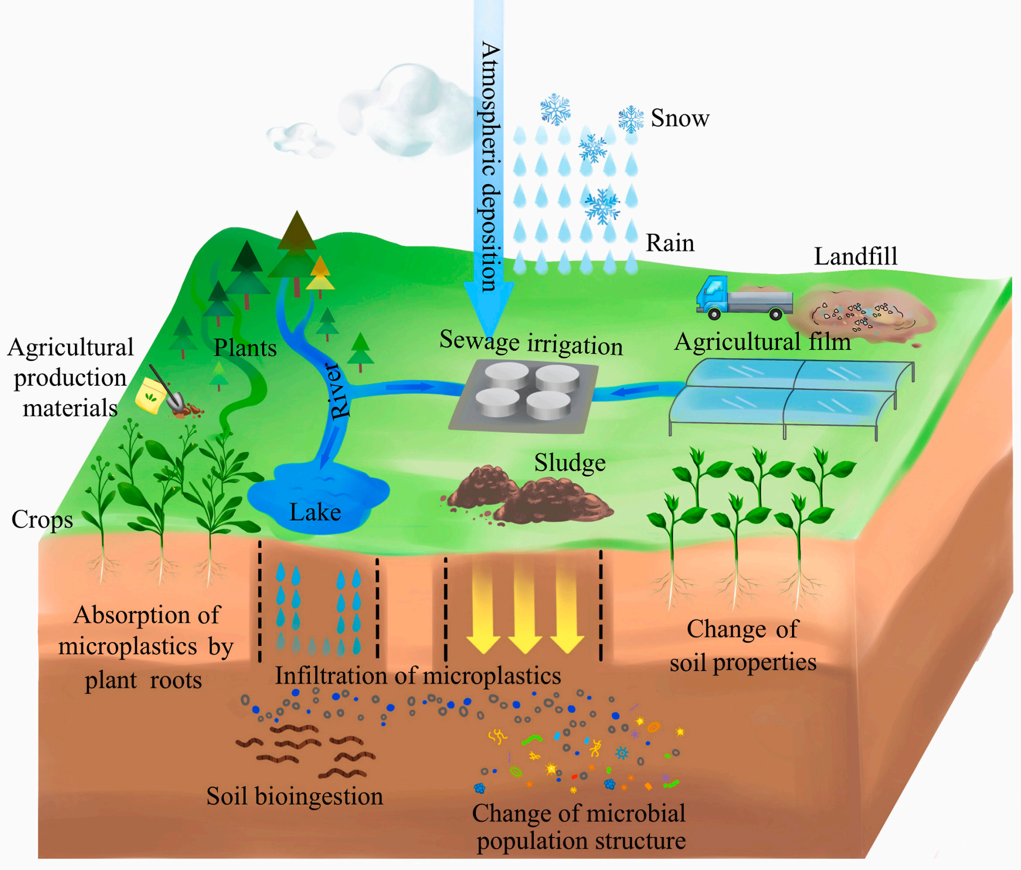

Figure 1. Representation of distribution cycle of MPs and NPs in atmospheric, aquatic and terrestrial environments. Reproduced with permission from [16].

When the first surveys detected the presence of tiny plastic particles in the sea, attention was turned to the oceans. However, it is estimated that plastic contamination in the soil can be between 4 and 23 times greater [17]. However, studies to prove the occurrence of NPs in soil are rare since the determination and quantification of nanoplastic pollution in a complex matrix rich in organic matter, such as soil, still needs to be solved due to the feasibility of analytical methods. MPs and NPs are of particular concern in agricultural environments due to their interactions with soil, crops, and water systems. Their small size and ability to bind to contaminants can affect plant nutrient uptake, soil fertility, and the overall health of agricultural ecosystems. This has implications for crop productivity and food safety, as these particles may be taken up by crops and enter the human food chain [18].

NPs can reach this environment through improper disposal of plastic waste, deposition of sewage sludge, inadequate management of sanitary landfills, and transport by rainwater. The first synthetic fibers were found in soil fertilized with sewage sludge and are identified as the primary sources of plastic pollution in the terrestrial environment [18]. Studies on the quantification of nanoplastics in soil are indeed scarce. However, Wahl et al. (2021) identified the presence of PE, PP, and PVC in France, with sizes ranging from 20 to 150 nm [19]. It is already known that NPs affect the physicochemical properties of soil, as well as causing deleterious effects on microbial biomass and enzymatic activity. Studies that can identify the presence of NPs directly in plants are still rare. However, Sun et al. (2022) demonstrated that crops can absorb NPs through leaves, threatening food security [20].

This review addresses the emerging concern of NPs and MPs in agricultural systems, which needs to be more represented in the current literature. While much research has focused on their prevalence in aquatic systems and urban environments, more knowledge is needed about their impacts on soil health, plant physiology, and potential bioaccumulation in crops. Previous reviews have often concentrated on marine ecosystems or human exposure through water sources [21–23]. However, the agricultural context is particularly critical, as it directly influences food security and safety. Table 1 shows the approaches analyzed in different reviews on microplastics in soil. Contamination of agricultural soils with plastic particles poses significant risks to crop health and human consumption. For example, recent studies have demonstrated that crops can absorb MPs and NPs, which raises concerns about food safety and the potential for long-term exposure to these contaminants through diet. Furthermore, MPs and NPs affect the physicochemical properties of soil, potentially disrupting microbial communities and enzymatic activity crucial for soil fertility [24]. This review seeks to fill the knowledge gap by providing an updated synthesis of the sources, pathways, and potential impacts of MPs and NPs in agriculture. It will offer new insights into their implications for plant health, soil quality, and human consumption while also comparing the current understanding of the issue with other reviews in the literature. Understanding the behavior of these particles in agricultural systems is critical for developing strategies to mitigate their presence and protect food safety in the future.

Table 1. Comparison of topics covered in selected reviews on microplastics in soil.

Title	Approach	Reference
Environmental fate, aging, toxicity and potential remediation strategies of microplastics in soil environment: Current progress and future perspectives	The review addressed the environmental fate, aging, toxicity, and potential remediation strategies of microplastics in soil.	[25]
Micro- and nanoplastics in agricultural soils: Assessing impacts and navigating mitigation	The review addressed the contamination of agricultural soils by micro- and nanoplastics, highlighting their implications for agroecosystems and potential health risks.	[26]
Microplastics in soil aggregates: Analytical methods, occurrence patterns, impact analyses and removal approaches	The review explored microplastic contamination of soil aggregates, highlighting their relevance to soil structure and function.	[27]
Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling: A review	The review examined the impacts of microplastic pollution on soil microbial diversity and function, focusing on carbon and nutrient cycles.	[28]

Table 1. *Cont.*

Title	Approach	Reference
Nanoplastics and microplastics in agricultural systems: Effects on plants and implications for human consumption	The review discusses the contamination of agricultural systems by nanoplastics and microplastics, their sources, transport, and impacts on plant physiology and food security. It highlights the ability of plastic particles to adsorb other contaminants, the risks to human health, and the gaps in toxicokinetics in plants and humans. Furthermore, it proposes future directions and research gaps.	This work

2. Behavior and Transport in Soil

Once in the soil, nanoplastics and microplastics exhibit unique physicochemical behaviors influenced by their size, shape, chemical composition, and surface properties [29]. Their interactions with soil components, such as minerals, organic matter, and microorganisms, determine their environmental fate and potential toxicity. Due to their larger size, microplastics are generally less mobile and tend to accumulate in the upper soil layers. However, bioturbation caused by earthworms and other organisms can transport these particles deeper into the soil profile. Nanoplastics, owing to their smaller size and higher surface area-to-volume ratio, are more dynamic and can infiltrate micropores within soil aggregates, reaching subsoil layers and, potentially, groundwater systems [30]. Surface charge and hydrophobicity also play crucial roles in their interactions with soil particles. Hydrophobic plastics, such as polyethylene and polypropylene, tend to adsorb onto organic matter, while hydrophilic plastics, like polyvinyl chloride, may interact more strongly with mineral surfaces. These interactions influence the particles' persistence, bioavailability, and ecotoxicological effects. Furthermore, the weathering of microplastics through mechanical forces, UV radiation, and chemical degradation can alter their surface characteristics, forming smaller fragments or leaching additives, such as plasticizers and flame retardants [31]. These leached chemicals may exacerbate soil contamination, posing additional risks to soil biota.

Adhikari and coworkers conducted a study to quantify and characterize the accumulation of microplastics in soils subjected to prolonged application of biosolids and to evaluate the contribution of atmospheric deposition [32]. The extracted microplastics from biosolids and soil samples exhibited diverse morphologies, including fibers, films, fragments, and pellets, with fibers being the most abundant (Figure 2). The predominant fiber colors observed were blue and red, characterized by uniform thickness and shape. These morphological attributes influence the behavior and mobility of microplastics in soil, affecting their interactions with soil components and transport mechanisms. The results indicated that the application of biosolids over 23 years resulted in microplastic concentrations ranging from 360 to 500 particles$\cdot$kg^{-1} of dry soil in the 0–10 cm layers. In contrast, soils without biosolid application presented a significantly lower concentration (117 particles$\cdot$kg^{-1}). The biosolids used contained, on average, 12,200 particles$\cdot$kg^{-1} of dry material. The primary polymer classes identified in the soil were polyurethane, polyethylene terephthalate, polyamide, and polyethylene, with atmospheric deposition contributing approximately 15 particles$\cdot$kg^{-1} of dry soil per year, predominantly polyamide fibers. The results indicate that, although the application of biosolids is a significant source of microplastics for soils, atmospheric deposition also represents a considerable contribution of these contaminants.

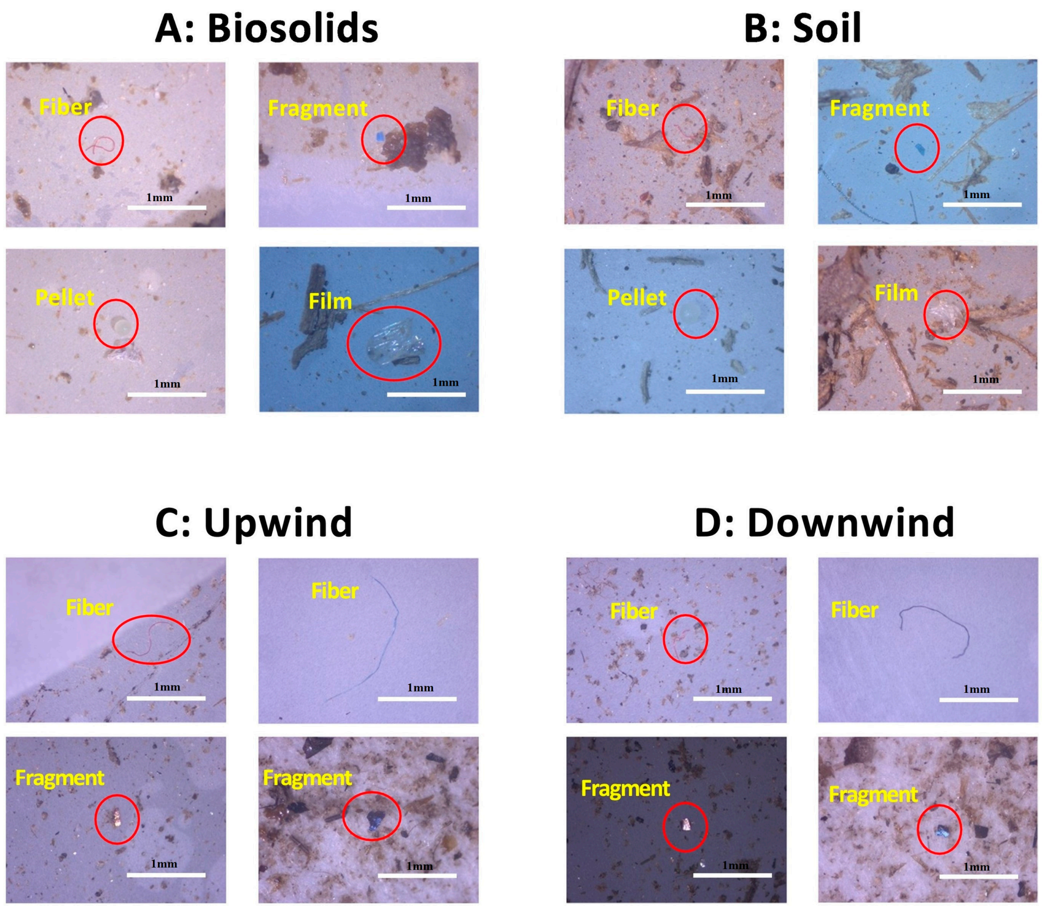

Figure 2. Microscopic images illustrating microplastics identified in biosolids, soil, and atmospheric deposition samples. Scale bars are 1 mm. Reproduced with permission from [32].

A combination of abiotic and biotic factors governs nanoplastics and microplastic transport within soil systems. Abiotic factors include water flow, soil texture, and the structural properties of the plastic particles, such as size, density, and shape. During heavy rainfall or irrigation events, microplastics can be carried along surface runoff pathways, while nanoplastics are more likely to percolate through the soil profile, potentially reaching groundwater. Soil texture significantly affects the mobility of these particles. Sandy soils, with larger pore spaces, allow for greater vertical and lateral movement of micro- and nanoplastics compared to clay-rich soils, where smaller pores and higher adsorption capacities restrict particle mobility [33]. Soil compaction and aggregation can further influence the transport pathways. Biotic factors, such as the activity of soil fauna and plant root systems, also play a pivotal role. Earthworms, for instance, can ingest microplastics and excrete them in different soil layers, facilitating their redistribution. Plant roots can uptake nanoplastics, which may translocate to aboveground tissues, raising concerns about food chain contamination. Additionally, microbial communities interact with plastic particles, forming biofilms on their surfaces [34]. These biofilms can alter the density and hydrophobicity of microplastics, affecting their movement and degradation. The behavior and transport of nanoplastics and microplastics in soil have far-reaching implications for soil health and ecosystem functioning. These particles can disrupt soil structure, alter water retention, and interfere with the nutrient cycling processes. Their interaction with soil biota, including microorganisms, earthworms, and plants, can reduce biodiversity and fundamental ecosystem services. Moreover, the potential for nanoplastics to enter the food chain through plant uptake or soil biota consumption raises concerns about human exposure and health risks [31].

3. Interactions with Other Contaminants

MPs stand out for their high adsorption capacity, a characteristic resulting from accelerated plastic degradation caused by factors such as heat, wind, rain, and other environmental conditions [34]. These contaminants persist in the soil, where they combine with other toxic substances, impairing water permeability and compromising biogeochemical cycles that are essential for the balance of the ecosystem. Plastics such as polyethylene, polypropylene, polystyrene, and polyethylene terephthalate play distinct roles in the transport and retention of contaminants in nature [35]. Polyethylene, very common in the manufacture of packaging, is highly hydrophobic and, therefore, efficient in the adsorption of pesticides and other chemical compounds.

Sun and coworkers analyzed the sorption of the herbicide atrazine (ATZ) on biodegradable microplastics before and after microbial aging, using polylactic acid (PLA) and poly(butylene-adipate-co-terephthalate) (PBAT) as reference materials [36]. The results indicated that the sorption of ATZ on microbially aged PLA increased by 11.12% compared to unaged PLA, while the sorption on aged PBAT decreased by 4.95% compared to untreated PBAT. The fitted kinetic models indicated that the sorption best followed the pseudo-second-order model, suggesting that chemical interactions play a significant role in the process. Furthermore, structural analyses showed that microbial aging promoted biofilm formation on PLA and altered its surface properties, leading to increased ATZ sorption. At the same time, PBAT presented surface fragmentation, reducing its herbicide retention capacity. Figure 3 shows microbial aging and sorption mechanisms of PLA and PBAT. These findings highlight the impact of microbial aging on the interaction between biodegradable microplastics and organic contaminants in soil, influencing the mobility and environmental risk of atrazine.

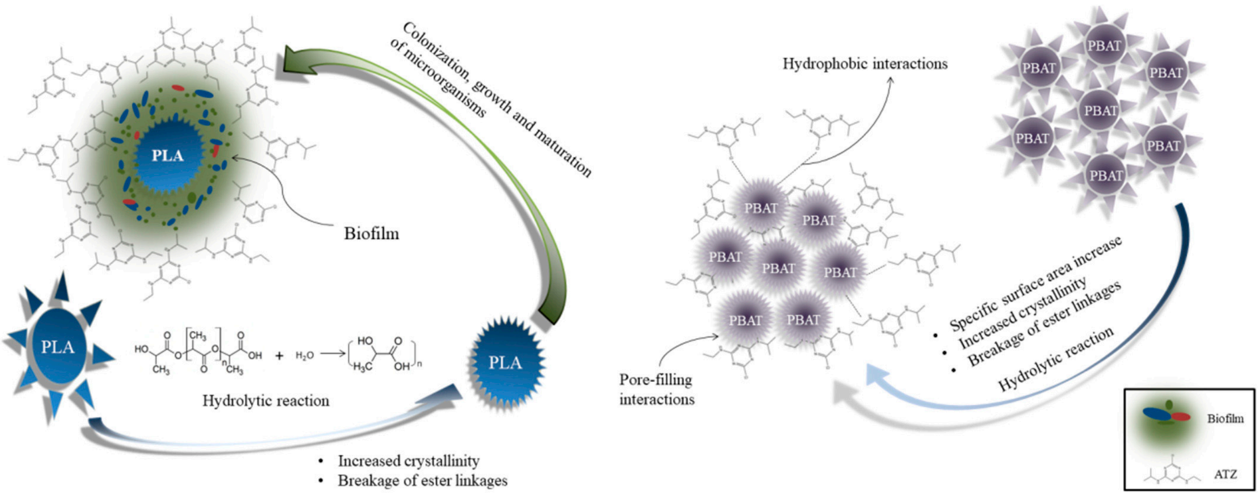

Figure 3. Microbial aging and sorption mechanisms of PLA and PBAT. Reproduced with permission from [36].

Polyethylene terephthalate, present in plastic bottles and synthetic fabrics, has shown itself to be a significant vector of heavy metals. MPs act as contaminant mediators in agricultural soils, intensifying the mobility of substances such as pesticides and toxic metals. This interaction multiplies the damage, leading to the concentration of contaminants in critical areas and increased soil toxicity [23]. Table 2 shows some advanced technologies used for soil remediation with microplastics.

Table 2. Advanced technologies used for soil remediation with microplastics.

Technique	Information	Reference
Phytoremediation	Utilizing plant species capable of absorbing, immobilizing, or even degrading microplastics present in the soil.	[37]
Bioremediation with microorganisms	Employing microorganisms that interact with microplastics, promoting their degradation or altering their properties to facilitate removal.	[38]
Advanced oxidation processes	Applying oxidizing agents directly into the soil to chemically break down the microplastic structures.	[23]
Nanoremediation	Employing nanoparticles that can bind to microplastics, facilitating their aggregation and subsequent physical removal or catalyzing their chemical degradation.	[25]
Combined remediation approaches	Combining two or more methods (for example, bioremediation followed by advanced oxidation) to remove different fractions of microplastics present in the soil.	[26,37]

MPs also interact with antibiotics, whose harmful properties to ecosystems are amplified by the presence of these plastics. Different types of MPs have varying affinities for adsorbing antibiotics, while heavy metals often compete for the same adsorption space [38]. This behavior creates a scenario of complex interactions that not only intensify contamination but also modify the bioavailability of these compounds, worsening their impacts. The effects of these interactions on plants are equally worrying. MPs can penetrate the roots, be transported internally, and trigger stress responses that affect plant growth and health. In addition, contaminants adsorbed on MPs can be released into the soil, directly impacting nutrient availability and causing combined toxic effects. In specific cases, such as the interaction between MPs, heavy metals, and organic pollutants, a synergy is observed that impairs fundamental processes such as germination and photosynthesis, affecting agricultural productivity and the sustainability of ecosystems [37]. The presence of MPs also impacts the soil microbiota, altering essential properties such as pH, porosity, and enzymatic activity. By modifying the biological balance of the soil, these plastics compromise nutrient cycles and harm plant health. In addition, the ability of NPs to cross root tissues increases the accumulation of heavy metals in plants, intensifying toxic effects and impairing plant metabolism [33].

4. Effects on Food Quality and Plants

Microplastic pollution is steadily infiltrating agricultural systems, with accumulation in soils caused by multiple sources. One of the leading causes is the widespread use of polymer-based fertilizers, both organic and synthetic. Organic fertilizers, derived from municipal solid waste, sewage sludge, and agricultural by-products, often contain significant MPs [39]. For instance, fertilizers made from these materials can contribute between 2.38 and 180 mg per kg soil, with finer particles reaching concentrations of up to 105 items$\cdot$kg^{-1} [40]. Synthetic fertilizers, especially those containing polymer coatings such as urea-formaldehyde, also play an important role in soil contamination. These results show that fertilizers play a significant role in increasing MP concentrations in agricultural soils [41]. In addition to fertilizers, the application of treated sewage sludge, used to improve soil fertility, is another significant source of MPs. Long-term sewage sludge use drastically increases the concentration of MPs in the soil. A study in Chile showed an 800% increase in MP concentration in the soil after ten years of sewage sludge application [42]. Similarly, compost derived from food waste is also a growing source of MPs in soil, with some studies reporting concentrations of thousands of particles per kilogram of compost [43].

Recently, a study investigated microplastic distribution, morphological characteristics, and polymeric composition in different land use types in a city with agricultural and mining activities, analyzing their primary sources and correlations with environmental parameters [44]. The investigation revealed that the abundance of microplastics varied significantly between different land use types, with the highest concentration being 27 times higher than the lowest recorded (Figure 4A). The highest abundance of microplastics was observed in soils of agricultural lands with facility farmland (3738 ± 2097 particles·kg^{-1}), followed by residential land (2859 ± 858 particles·kg^{-1}), traditional farmland (1894 ± 858 particles·kg^{-1}), industrial land (1604 ± 1144 particles·kg^{-1}) and grassland (635 ± 286 particles·kg^{-1}). Therefore, the abundance of microplastics in soils from agricultural lands with facility farmland (FF) showed a statistically significant difference compared to soils from traditional farmland (TF), grassland (GL), and industrial land (IL) ($p < 0.05$) (Figure 4B). The characterization of microplastics indicated that particles with a size of less than 0.1 mm represented the predominant fraction (45%), with primarily fibrous and fragmented morphologies and transparent coloration. The spectroscopic analysis identified polypropylene and polyethylene as the most abundant polymers, corresponding to 33% and 30% of the total. In addition, a significant positive correlation was observed between the abundance of microplastics and the soil organic carbon, total phosphorus, and cadmium contents. In contrast, soil pH was negatively correlated with the concentration of these particles.

Irrigation systems that utilize recycled wastewater are also a pathway for MP contamination. Studies show that soils irrigated with treated wastewater can harbor between 79 and 238 particles·kg^{-1}, while MP concentrations in the irrigation water range from 1.88 to 141 per liter [45]. Repeated irrigation introduces these particles and helps transport them deeper into the soil, amplifying their effects [46]. Plastic mulch, which is commonly used to promote plant growth, is another important factor. Made from polyethylene or polypropylene, these plastic films break down into MPs over time, especially with repeated use. This practice is associated with up to 56% of MP contamination in agricultural soils [47]. When mulch rots, it becomes a permanent source of contamination that is difficult to reverse.

Lastly, atmospheric deposition is an important pathway for MPs to enter agricultural soils. Airborne MPs from sources such as synthetic textiles or tire abrasion can travel long distances before being deposited by precipitation or snow. Studies have measured deposition rates of up to 1008 items·m^{-2}·d^{-1}, highlighting the far-reaching impact of airborne microplastic pollution [48]. The contamination of agricultural soils with MPs poses a significant risk to the functioning of soil ecosystems and the quality of the crops produced. One of the main problems is the disruption of soil microbial communities, which are crucial for maintaining soil health and fertility. MPs reduce bacterial diversity and richness, impairing important microbial functions such as nutrient cycling and organic matter decomposition [49]. As a result, soil fertility decreases, affecting plant nutrient uptake and lowering plant growth, yield, and nutrient quality. This problem is particularly pronounced in crops sensitive to soil amendments, such as wheat, broccoli, and radish sprouts, where MP contamination has been linked to alterations in phytochemical composition and yield losses [50]. Studies indicate that the concentration of microplastics in soils can reach up to 7% by weight, especially in agricultural areas that use plastic films for soil cover [51]. Plastic materials significantly affect soil structure and can reduce aggregate stability. A recent study demonstrated a reduction in aggregate stability from 1.4 mm to 1.0–1.1 mm and a decrease in macroaggregate fraction from 84% to 65–71% [52]. In addition, microplastics altered the microbial composition (54%), mainly affecting groups such as Proteobacteria, Actinobacteria, and Chloroflexi.

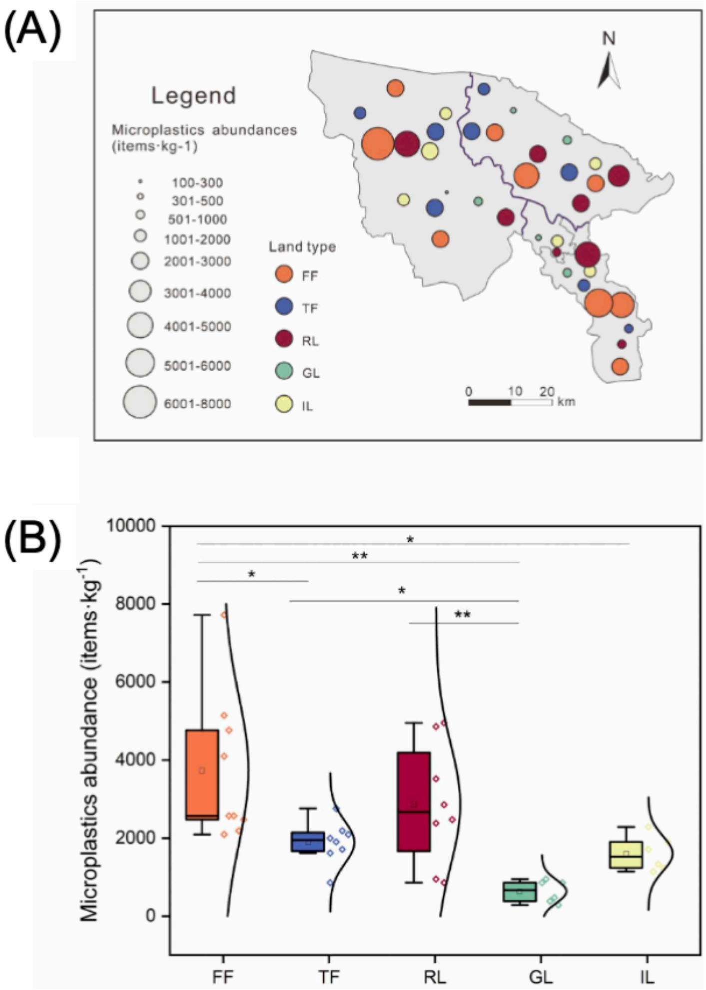

Figure 4. (**A**) Spatial distribution of microplastics in soil across five sampled site types within the study area. Circle size represents varying microplastic abundances, while different colors indicate distinct land use categories. (**B**) Variation in microplastic abundance among different land use types, with statistical significance levels: * $p < 0.05$, ** $p < 0.001$. Reproduced with permission from [44].

Liu and coworkers investigated the effects of polyethylene microplastic contamination on agricultural soil, focusing on microbial community, nutrient cycling, and ecosystem multifunctionality [53]. The results indicated that adding 5% plastic particles reduced soil water availability, dissolved carbon, and total phosphorus contents while increasing soil pH and carbon storage. Regarding carbon cycling enzymes, the activity of α/β-1,4-glucosidase and β-D-cellobiohydrolase was stimulated by 1% particle concentration, while β-1,4-glucosidase was inhibited by 5% concentration. The activity of protease and urease enzymes, associated with the nitrogen cycle, was reduced by 5% polyethylene, while that of alkaline phosphatase, associated with the phosphorus cycle, was increased. Furthermore, the soil microbial community underwent significant changes with the addition of 5% polyethylene, increasing the stability of the microbial network and reducing the limitation of dispersal (from 13.66% to 9.96%). Overall, the ecosystem's multifunctionality was improved by adding 1% polyethylene but was reduced at the 5% concentration, suggesting that excessive contamination by microplastics may compromise the ecological balance of the soil and the sustainability of agricultural systems.

In addition to their physical effects on soil structure and microbial communities, MPs also act as a vector for toxic substances. Harmful chemicals such as polycyclic aromatic hydrocarbons, heavy metals, and persistent organic pollutants are easily adsorbed on the surface of MPs [54]. These pollutants can be transported to the plant roots, accumulating in the plant tissues and entering the food chain. This process not only affects the nutritional content of plants but also poses a serious health risk to consumers, as continuous exposure to these toxic substances can lead to long-term health complications [55]. The accumulation of heavy metals and contaminants in food crops is a growing concern, especially as MPs persist in agricultural soils and interact with other pollutants. It has also been shown that exposure to MPs disrupts the metabolic processes of plants. One of the primary mechanisms by which this occurs is oxidative stress. MPs cause the formation of reactive oxygen species (ROS) in plant cells, which leads to oxidative damage to vital cell components [56]. This oxidative stress impairs the plant's antioxidant defense systems, essential for maintaining cellular health and metabolic balance. As a result, plants experience reduced biosynthesis of essential nutrients such as vitamins and minerals, which are critical to the nutritional value of crops. This metabolic disruption harms the plant's ability to grow and develop properly. It compromises the nutritional quality of the food it produces, posing an additional challenge to food security and public health.

The impact of MPs on crop productivity and quality is complex and is influenced by factors such as the size, type, and concentration of plastic particles and the crop in question. Smaller MP particles can, for example, accumulate in the pores of seeds and hinder germination and early root development [57]. This physical obstacle impairs water and nutrient uptake, reducing plant growth and yield. In addition, certain MPs, such as polyvinyl chloride, are particularly harmful to plants, as they significantly reduce photosynthesis and leaf size [58]. These effects highlight the complex interactions between MPs and agricultural systems and show how contamination can lead to diverse and far-reaching consequences for crop production and food quality. As agricultural soils become increasingly contaminated with MPs, the combined effects of reduced soil fertility, altered plant metabolism, and toxic substance bioaccumulation pose a serious challenge to global food security.

Emenike and coworkers investigated the combined effects of three types of microplastics (PE, PS, and PP) on the physiology, morphology, and biochemistry of greenhouse-grown tomatoes [59]. The results indicated that 1% of microplastics in the soil had no significant effect on plant physiological and morphological parameters, including height, number, total fruit weight, and root structure. However, an increase in photosynthetic rate (25.8%), transpiration rate (16.7%), stomata conductance (20.8%), and chlorophyll content (5.2%) was observed compared to the control, while sub-stomata CO_2 concentration was reduced by 3.23%. Regarding fruit quality, microplastics caused a significant reduction in the content of carotenoids (12.6%), flavonoids (42.3%), and total sugars (21.7%) while increasing the levels of total protein (11.1%), ascorbic acid (38.4%) and peroxidase activity (30.2%). Although microplastics did not directly compromise tomato growth and productivity, the observed biochemical impacts raise concerns about the influence of these particles on the nutritional quality of fruits and their potential effects on food safety.

Yang and coworkers investigated the effects of aged polyethylene microplastic transfer in the soil–plant system, analyzing their impact on corn physiology and microplastic migration dynamics within the plant [60]. The results demonstrated that exposure to 0.1% raw polyethylene promoted corn growth, while aged microplastics impaired its development. Analysis of microplastic distribution revealed a decreasing accumulation pattern in the sequence root > leaf > stem, with transfer rates of 1.07% from soil to root, 0.76% from root to stem, and 103.28% from stem to leaf (Figure 5). Polyethylene particles as small as 26 μm could penetrate roots and reach stems, expanding the known upper limit for plant microplastic transport. Furthermore, the release of endogenous organic matter from microplastics favored the accumulation of soil organic matter, with increases of 0.57% for 0.1% polyethylene, 1.28% for aged polyethylene, and 1.36% for 1% polyethylene, compared to the control. Exposure to polyethylene also impacted soil enzymatic activity, stimulating β-glucosidase activity by 49.1% and inhibiting nigrosin activity by 32.3% in the aged microplastic treatment. MPs' persistence in soil ecosystems means that these effects are likely to accumulate over time, continuously affecting plant health and the nutritional value of food. The far-reaching impacts of MPs on agricultural systems highlight the urgent need for strategies to curb plastic pollution and protect soil health to ensure the productivity and security of the global food supply.

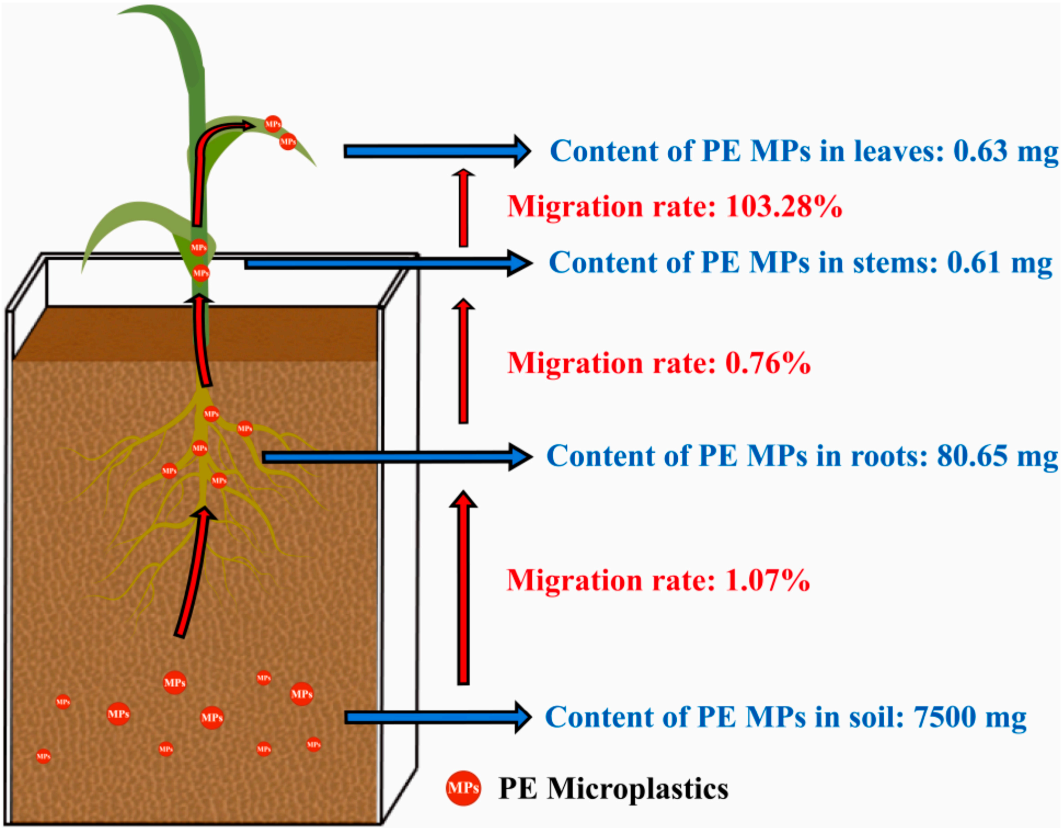

Figure 5. Microplastic transfer in soil–plant system. Reproduced with permission from [60].

Mendes and coworkers evaluated the effects of microplastic contamination on the soil–earthworm system, investigating changes in soil enzymatic activity, survival rate, and accumulation of MPs in earthworms [61]. The results indicated that exposure to MPs significantly affected soil enzyme activity, with urease showing a reduction of up to 25% and β-glucosidase decreasing by 18% in samples with higher MP concentrations. In addition, the earthworm survival rate was reduced by up to 30% in soils contaminated with MPs, suggesting adverse effects on soil biota. Bioaccumulation of MPs in earthworms was quantified, revealing concentrations of up to 120 particles per gram of dry tissue, with a predominance of fragments smaller than 50 μm. These findings reinforce the need to monitor MP contamination in soil, considering its ecological impacts and potential risks to food chains.

5. Impacts on Human Health

MPs are a major environmental pollutant entering terrestrial and aquatic ecosystems and finding their way into the food chain. These particles are absorbed by plants and ingested by animals, including livestock, which are important food sources for humans [62]. Agricultural soils contaminated with MPs due to human activities serve as the main reservoir for transferring these particles to crops. Plastics used in agriculture, such as mulch films and plastic containers, contribute to this contamination. Consequently, people are exposed to MPs by consuming contaminated plants, water, and animal products [63]. MPs and NPs can enter the human body through dietary and environmental exposure, primarily via ingestion and inhalation [26]. These pathways are associated with air, water, and food sources. In the atmospheric environment, exposure occurs through direct inhalation and the deposition of plastic particles onto food surfaces. Figure 6 presents the estimated quantities of plastic particles in air, food, and water based on data from reported studies.

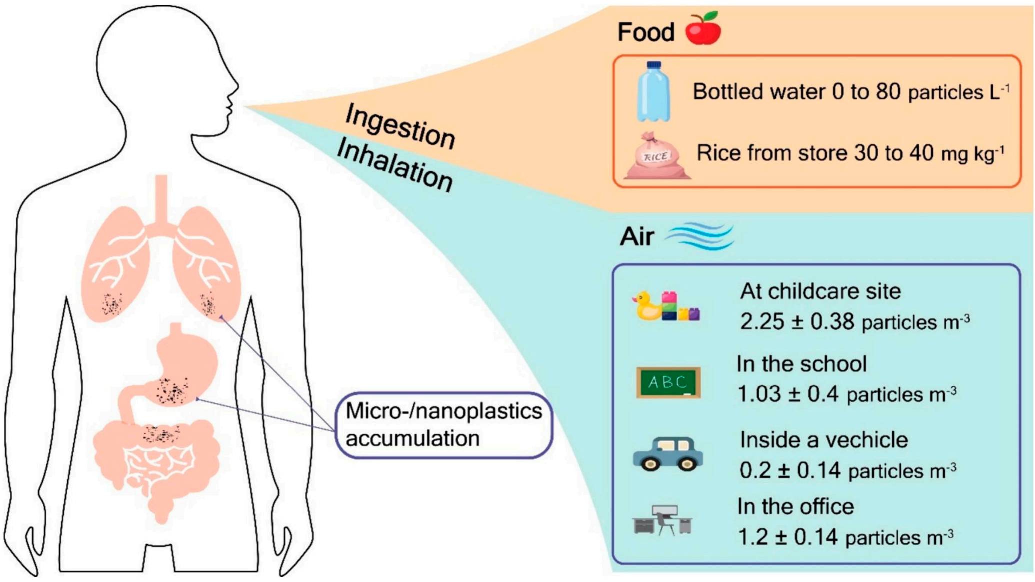

Figure 6. Estimated quantities of plastic particles in air, food, and water based on data from reported studies. Reproduced with permission from [26].

It has been found that animals, especially those used for milk, meat, and egg production, ingest MPs through their feed and water. These particles accumulate in the animals' tissues, blood, and milk, representing a direct route for human exposure through food consumption [64]. The risks associated with this exposure are exacerbated by the toxic chemicals MPs contain, including endocrine disruptors and persistent organic pollutants [65]. Ingested MPs not only serve as physical contaminants but also as carriers of harmful chemicals such as bisphenol A (BPA), which is known to interfere with hormone functions and has been linked to reproductive and metabolic disorders in humans [66].

In addition, MPs harbor microorganisms and can promote the transfer of antibiotic-resistant genes, raising concerns about food safety. Research has shown that certain pathogens, such as *Vibrio* spp., adhere to MPs and increase the likelihood of infection when people consume contaminated food [67]. MPs' ability to act as vectors for both chemical pollutants and pathogens emphasizes the significant risks posed by their presence in the food chain.

Chronic exposure to MPs through ingestion, inhalation, and skin contact poses numerous health risks. Once MPs enter the human body, they accumulate in the organs, leading to metabolic disorders, inflammation, and endocrine disruption.

Metabolic and endocrine disruption: MPs contain endocrine disrupting chemicals such as BPA, which can impair hormone function and affect the reproductive and endocrine systems. Long-term ingestion of food contaminated with MPs has been linked to endocrine disruption in humans, highlighting the potential for widespread metabolic disorders because of chronic exposure [68].

Inflammation and oxidative stress: MPs can trigger inflammatory reactions and oxidative stress as soon as they are ingested or inhaled. When MPs accumulate in the gastrointestinal tract, they physically irritate the tissue and lead to chronic inflammation. This inflammation is exacerbated by altering the gut microbiota, critical to maintaining digestive and immune health [69]. In addition, MPs increase ROS production, leading to oxidative stress that can damage tissues and organs. Research has shown that these particles can cause an imbalance in the gut microbiome, leading to increased intestinal permeability, inflammation, and diseases like endotoxemia [70].

Cardiovascular and respiratory impacts: Inhaled MPs, especially nano-sized particles, can become lodged in the respiratory system and cause oxidative stress and inflammation in the lung tissue. Studies have linked the inhalation of MPs to respiratory diseases, such as chronic obstructive pulmonary disease and cardiovascular disease [71]. There is also emerging evidence that MPs can enter the bloodstream and accumulate in blood vessels, contributing to the development of cardiovascular disease [72].

Neurotoxicity: Animal studies have shown that MPs can cross biological barriers [73]. These findings are concerning, as they indicate the possibility of neurological damage in humans from chronic exposure to MPs. Although research on neurotoxicity in humans is still limited, studies in mice have shown that MPs can accumulate in the brain and cause neuroinflammation, potentially leading to long-term cognitive and motor impairment [74]. However, due to the limited number of studies on the topic, further investigation is needed on the extent and implications of these interactions.

The presence of MPs in the food chain has far-reaching implications for public health and food safety. Food contamination, especially animal products, poses a significant risk to consumers. MPs are not only a physical contaminant but also a carrier of toxic chemicals and pathogens that can have long-lasting health consequences.

Food safety risks: Contamination of crops and livestock with MPs raises serious concerns about food safety and quality. Given MPs' ability to adsorb harmful chemicals and harbor pathogens, their presence in the food chain increases the risk of foodborne illness and chronic disease. Animal products, an important food source for many populations, are susceptible to contamination. The accumulation of MPs in animal tissues, milk, and eggs represents a direct route for human exposure, with potentially serious health consequences [63]. Ikuno and coworkers evaluated the cytotoxicity of polyethylene particles degraded by vacuum ultraviolet light, analyzing the impact of the degree of degradation on the cell viability of human alveolar adenocarcinoma cells (A549) [75]. The results demonstrated that the cytotoxicity of polyethylene increased with the level of degradation, directly correlating with the introduction of functional groups such as carbonyls and esters on the surface of the particles. Spectroscopic analysis indicated a progressive increase in the C=O/C–H ratio, ranging from 0.000 for undegraded polyethylene to 0.513 for the most degraded. The evaluation of cell viability revealed that the undegraded polyethylene did not present measurable cytotoxicity ($IC_{50} \geq 80$ g·L^{-1}). In contrast, the degraded polyethylene exhibited reduced IC_{50} values, such as 27.1 g·L^{-1} for a degradation degree of 0.156 and 12.6 g·L^{-1} for a degradation degree of 0.513, indicating greater cell toxicity. The strong negative correlation (-0.824) between PE degradation and IC_{50} suggests that chemical modification of the surface is the main factor responsible for the increased cytotoxicity.

These findings highlight the need to consider the degradation state of microplastics when evaluating their biological effects and potential risks to human health.

Public health implications: Chronic exposure to MPs is associated with several non-communicable diseases, such as metabolic syndrome, cardiovascular disease, and inflammatory diseases. The further MPs enter the food chain, the greater the risk of far-reaching effects on public health. The ingestion and inhalation of MPs and their ability to transport harmful chemicals highlight the urgent need for further research into the long-term health effects of MP exposure [62]. In addition, MPs may contribute to the rise in obesity, diabetes, and cardiovascular disease, which are already major public health concerns.

Policy and regulation: Effective policy measures are essential to mitigate the risks associated with MP contamination. Governments and regulators must introduce stricter controls on the use of plastics in agriculture, food production, and packaging to reduce food contamination with MPs [76]. Promoting sustainable alternatives to plastics and improving recycling initiatives are crucial to minimizing MP pollution. In addition, increasing public awareness of the risks associated with MP pollution can encourage consumers to make informed choices and thus reduce their exposure to these harmful particles [77]. Legislation on the contamination of agricultural soils by microplastics is still recent compared to regulations for aquatic environments. However, some countries have implemented indirect restrictions by banning single-use plastics, controlling the application of biosolids and organic compounds to agricultural soils, and regulating the use of plastic films in agriculture [78]. Measures such as banning the import and production of plastics and synthetic fabrics can reduce secondary MPs in soils, minimizing their entry through the fragmentation of plastic waste. In addition, some countries have already imposed regulations on the quality of biosolids applied to agriculture, aiming to limit the MP load present in these materials. In the European context, environmental guidelines have been discussed to restrict the use of microplastics in seed coatings and agrochemical encapsulation, given the risk of these particles persisting in the soil [78].

6. Future Perspectives and Research Gaps

The toxic effects of MPs and NPs depend on their properties and production sources, whether synthetic or natural. Synthetic plastics, such as fibers, degrade slowly, persisting as organic pollutants that harm the environment and human health. Understanding their bioaccumulation requires collaboration among ecologists, pathologists, epidemiologists, and environmental health experts.

Nanoplastics alter soil biota’s chemical properties, impacting plants and terrestrial ecosystems [62]. Despite their relevance, studies on nanoplastic effects on plants under environmentally relevant conditions remain limited. The interaction of nanoplastics with soil pH, cation exchange capacity, and microbiota diversity determines their toxic effects. These dynamics affect soil structure and plant health, highlighting the need for comprehensive qualitative and quantitative evaluations [58]. Studies on this topic should focus on understanding how the presence of plastic particles affects microbial communities’ diversity, structure, and functionality. How can these changes influence essential biogeochemical processes, such as nutrient cycling, directly impacting soil health and productivity? Metagenomic analyses are proposed to investigate these interactions and allow for the identification of changes in genetic composition [38].

Growing concern exists regarding the entire life cycle of biodegradable mulches. This concern encompasses their operational efficiency, and a comprehensive evaluation of the environmental impacts associated with their production, application, and degradation. The objective is to ensure that the solutions implemented contribute effectively to sustainable agriculture. Intensive research on biodegradable polymers has facilitated the development of mulches that decompose rapidly without generating microplastic waste. These materials are continually optimized to retain their mechanical integrity and agronomic performance throughout their intended period of use.

MPs and NPs can cross the intestinal barrier in animals, enter the bloodstream, and accumulate in organs like the liver and kidneys, causing inflammation, oxidative stress, immune suppression, and reproductive impairments [31]. Exposure occurs via contaminated food, water, air, and skin contact [73]. These particles also raise concerns about DNA damage, neurotoxicity, and potential tumor formation, yet insufficient evidence exists regarding their long-term effects on human health [73]. Research must address particle distribution in secondary tissues, cellular pathways, and the impacts of accumulation.

Quantifying toxicokinetics is essential to understanding MPs' and NPs' health effects, especially through seafood. Differences in size, shape, and surface properties between MPs and NPs necessitate distinct ecotoxicological studies. Standardized methodologies for extracting and characterizing MPs and NPs are crucial for reliable comparisons and risk assessments. Fragmented particles present challenges in detection due to their small size and complex environmental matrices, complicating traditional risk assessment techniques.

Interactions between MPs/NPs and specific plant species represent a key area for advancing phytoremediation strategies. It is essential to identify which plant species demonstrate greater resilience or sensitivity to the presence of these contaminants in the soil, as this knowledge can guide the selection of the most effective plants for removing or immobilizing the pollutants. Investigation of these interactions should include experimental studies in situ and under controlled conditions, aiming to evaluate the capacity of different species to capture, degrade, or immobilize plastic pollutants. In this context, physiological and biochemical analyses are essential, as they allow monitoring indicators of stress, growth, nutrient absorption, and metabolic changes in plants exposed to varying concentrations of contaminants [37,38].

Analytical methods such as Fourier transform infrared spectroscopy, Raman spectroscopy, and mass spectrometry enable the identification and quantification of MPs and NPs [79]. Advanced techniques like dynamic light scattering, electron microscopy, and pyrolysis–gas chromatography–mass spectrometry enhance analysis but face challenges like sample contamination and data reliability. Ali and coworkers critically evaluated the effectiveness of hyperspectral imaging (HSI) technology in detecting and quantifying microplastics in soils, considering the influence of environmental factors such as moisture, size, and color of plastic particles [80]. The results demonstrated that near-infrared (NIR) HSI effectively identified microplastics, exhibiting a linear relationship between the concentration of these particles and their spectral responses. However, detection efficiency was reduced in clayey soils, particularly for polyethylene, and was significantly impacted by soil moisture, introducing nonlinearities in quantification. Furthermore, larger and brighter-colored plastic particles were detected with greater accuracy, while smaller and darker-colored particles presented additional challenges in spectral analysis. The findings indicated that pre-segregation of microplastics by size and color can improve the accuracy of the analysis and highlighted the need for further investigations into the interaction between soil moisture and the detectability of these particles. Expanding the use of HSI can contribute to more efficient monitoring of soil contamination by microplastics and developing mitigation strategies in environmental systems. Standardizing protocols and improving analytical precision are essential to understanding MPs' and NPs' environmental and health implications [81].

Applying machine learning to predict and interpret the impact of MPs and NPs on soil properties can provide valuable insights into their complex interactions with soil systems. Withana and coworkers reported using machine learning to predict and interpret the impact of microplastics on soil properties [82]. They highlighted the significant influence of MP characteristics on key soil parameters. MP size, type, and dosage were pivotal in altering pH, dissolved organic carbon, nitrate, ammonium, total phosphorus, and acid phosphatase enzyme activity. Among these, MP size was the dominant factor affecting acid phosphatase enzyme activity (89.3%), pH (71.6%), and dissolved organic carbon (44.5%), while MP type primarily influenced nitrate nitrogen (52.0%), and MP dosage significantly affected ammonium nitrogen (46.8%). However, further research is needed to refine predictive models and explore additional soil properties affected by MP and NP contamination. Understanding the long-term impacts of these pollutants on soil health, microbial communities, and nutrient cycling is important to develop effective mitigation strategies. Furthermore, integrating field-scale studies and multi-omics approaches can increase the accuracy of predictions and provide a more comprehensive perspective on soil–MP interactions.

Finally, establishing viable guidelines for regulating MP release in agricultural soils remains a critical research gap. Legislation to mitigate microplastic contamination of agricultural soils is still limited, but some policies indirectly address the problem. The Break Free from Plastic Pollution Act (2023) holds producers accountable for managing plastic waste in the United States. The European Union has implemented the Packaging and Packaging Waste Directive, imposing taxes on plastics to reduce their production. France has banned cosmetic products containing plastic particles under the Circular Economy Law (2020) and is seeking to regulate the release of textile fibers. Canada has proposed legislation to reduce the amount of plastic microbeads entering aquatic environments (Microbeads in Toiletries Regulations (2017) and Single-use Plastics Prohibition Regulations (2022)). The Plastic Bag Control and Management Regulations (2018) and the Wildlife Conservation and Management Act (2020) have banned single-use plastics in Kenya [78]. Therefore, while these measures reduce MPs in ecosystems, there is a need for specific regulations for agricultural soils.

7. Conclusions

Addressing the environmental and health risks MPs and NPs pose requires immediate action across multiple sectors. Despite advancements in wastewater treatment technologies, MPs and NPs remain pervasive pollutants in aquatic and terrestrial ecosystems, with limited regulatory measures targeting their presence in agricultural soils. Current research underscores the need for specific legislation, international cooperation, and standardized methodologies to enhance our understanding of their behavior, impacts, and removal. Educational campaigns and consumer awareness programs can drive behavioral changes, reducing plastic waste generation. Simultaneously, advancements in treatment technologies, such as membrane filtration and photocatalysis, hold promise for mitigating pollution. Collaborative international efforts and funding for research and innovation are essential to developing sustainable materials and improving recycling processes. Comprehensive regulations, such as those under the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) framework, highlight the importance of balancing environmental preservation, human health, and economic sustainability. Public engagement and stakeholder participation are critical in effectively shaping policies to combat microplastic pollution. Future efforts must prioritize quantitative analyses, eco-design, and innovative solutions to minimize the release of MPs and NPs, fostering a healthier environment and ensuring long-term ecological balance.

Author Contributions: Conceptualization, C.R.S.d.O. and A.H.d.S.J.; methodology, T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; validation, H.J.S., T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; formal analysis, H.J.S., T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; investigation, H.J.S., T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; data curation, T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; writing—original draft preparation, T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; writing—review and editing, H.J.S., T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J.; supervision, T.W.L., G.T., S.V.d.M.L., P.V.d.O., C.R.S.d.O. and A.H.d.S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Guo, S.; Xiao, G.; Chen, Y.; Zhang, J.; Zhang, B.; Ru, S.; Zhao, M. Unraveling the Characteristics of Microplastics in Agricultural Soils upon Long-Term Organic Fertilizer Application: A Comprehensive Study Using Diversity Indices. *Chemosphere* **2024**, *364*, 143235. [CrossRef] [PubMed]
2. de Oliveira, C.R.S.; Maestri, G.; Tochetto, G.A.; de Oliveira, J.L.; Stiegelmaier, E.; Fischer, T.V.; Immich, A.P.S. Nanoplastics: Unveiling Contamination Routes and Toxicological Implications for Human Health. *Curr. Anal. Chem.* **2024**, *20*, 175–190. [CrossRef]
3. Belli, I.M.; Cavali, M.; Garbossa, L.H.P.; Franco, D.; Bayard, R.; de Castilhos Junior, A.B. A Review of Plastic Debris in the South American Atlantic Ocean Coast—Distribution, Characteristics, Policies and Legal Aspects. *Sci. Total Environ.* **2024**, *938*, 173197. [CrossRef]
4. Mohana, A.A.; Farhad, S.M.; Haque, N.; Pramanik, B.K. Understanding the Fate of Nano-Plastics in Wastewater Treatment Plants and Their Removal Using Membrane Processes. *Chemosphere* **2021**, *284*, 131430. [CrossRef]
5. Wu, X.; Zhao, X.; Chen, R.; Liu, P.; Liang, W.; Wang, J.; Teng, M.; Wang, X.; Gao, S. Wastewater Treatment Plants Act as Essential Sources of Microplastic Formation in Aquatic Environments: A Critical Review. *Water Res.* **2022**, *221*, 118825. [CrossRef] [PubMed]
6. Junhao, C.; Xining, Z.; Xiaodong, G.; Li, Z.; Qi, H.; Siddique, K.H.M. Extraction and Identification Methods of Microplastics and Nanoplastics in Agricultural Soil: A Review. *J. Environ. Manag.* **2021**, *294*, 112997. [CrossRef]
7. Materić, D.; Ludewig, E.; Brunner, D.; Röckmann, T.; Holzinger, R. Nanoplastics Transport to the Remote, High-Altitude Alps. *Environ. Pollut.* **2021**, *288*, 117697. [CrossRef]
8. Materić, D.; Kjær, H.A.; Vallelonga, P.; Tison, J.-L.; Röckmann, T.; Holzinger, R. Nanoplastics Measurements in Northern and Southern Polar Ice. *Environ. Res.* **2022**, *208*, 112741. [CrossRef]
9. Jung, J.-W.; Kim, S.; Kim, Y.-S.; Jeong, S.; Lee, J. Tracing Microplastics from Raw Water to Drinking Water Treatment Plants in Busan, South Korea. *Sci. Total Environ.* **2022**, *825*, 154015. [CrossRef]
10. Alimi, O.S.; Farner Budarz, J.; Hernandez, L.M.; Tufenkji, N. Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport. *Environ. Sci. Technol.* **2018**, *52*, 1704–1724. [CrossRef]
11. Seuront, L.; Zardi, G.I.; Uguen, M.; Bouchet, V.M.P.; Delaeter, C.; Henry, S.; Spilmont, N.; Nicastro, K.R. A Whale of a Plastic Tale: A Plea for Interdisciplinary Studies to Tackle Micro- and Nanoplastic Pollution in the Marine Realm. *Sci. Total Environ.* **2022**, *846*, 157187. [CrossRef] [PubMed]
12. Ter Halle, A.; Jeanneau, L.; Martignac, M.; Jardé, E.; Pedrono, B.; Brach, L.; Gigault, J. Nanoplastic in the North Atlantic Subtropical Gyre. *Environ. Sci. Technol.* **2017**, *51*, 13689–13697. [CrossRef]
13. Thomas, J.; Patil, R.S.; Patil, M.; John, J. Addressing the Sustainability Conundrums and Challenges within the Polymer Value Chain. *Sustainability* **2023**, *15*, 15758. [CrossRef]
14. Zhang, Q.; Zhao, Y.; Du, F.; Cai, H.; Wang, G.; Shi, H. Microplastic Fallout in Different Indoor Environments. *Environ. Sci. Technol.* **2020**, *54*, 6530–6539. [CrossRef] [PubMed]
15. Amato-Lourenço, L.F.; dos Santos Galvão, L.; de Weger, L.A.; Hiemstra, P.S.; Vijver, M.G.; Mauad, T. An Emerging Class of Air Pollutants: Potential Effects of Microplastics to Respiratory Human Health? *Sci. Total Environ.* **2020**, *749*, 141676. [CrossRef]
16. Liu, J.; Zheng, L. Microplastic Migration and Transformation Pathways and Exposure Health Risks. *Environ. Pollut.* **2025**, *368*, 125700. [CrossRef] [PubMed]
17. Cao, J.; Yang, Q.; Jiang, J.; Dalu, T.; Kadushkin, A.; Singh, J.; Fakhrullin, R.; Wang, F.; Cai, X.; Li, R. Coronas of Micro/Nano Plastics: A Key Determinant in Their Risk Assessments. *Part. Fibre Toxicol.* **2022**, *19*, 55. [CrossRef]
18. Hurley, R.R.; Nizzetto, L. Fate and Occurrence of Micro(Nano)Plastics in Soils: Knowledge Gaps and Possible Risks. *Curr. Opin. Environ. Sci. Health* **2018**, *1*, 6–11. [CrossRef]

19. Wahl, A.; Le Juge, C.; Davranche, M.; El Hadri, H.; Grassl, B.; Reynaud, S.; Gigault, J. Nanoplastic Occurrence in a Soil Amended with Plastic Debris. *Chemosphere* **2021**, *262*, 127784. [CrossRef]
20. Sun, H.; Lei, C.; Yuan, Y.; Xu, J.; Han, M. Nanoplastic Impacts on the Foliar Uptake, Metabolism and Phytotoxicity of Phthalate Esters in Corn (*Zea Mays* L.) Plants. *Chemosphere* **2022**, *304*, 135309. [CrossRef]
21. Kokilathasan, N.; Dittrich, M. Nanoplastics: Detection and Impacts in Aquatic Environments—A Review. *Sci. Total Environ.* **2022**, *849*, 157852. [CrossRef] [PubMed]
22. Ricardo, I.A.; Alberto, E.A.; Silva Júnior, A.H.; Macuvele, D.L.P.; Padoin, N.; Soares, C.; Gracher Riella, H.; Starling, M.C.V.M.; Trovó, A.G. A Critical Review on Microplastics, Interaction with Organic and Inorganic Pollutants, Impacts and Effectiveness of Advanced Oxidation Processes Applied for Their Removal from Aqueous Matrices. *Chem. Eng. J.* **2021**, *424*, 130282. [CrossRef]
23. de Oliveira, C.R.S.; da Silva Júnior, A.H.; Mulinari, J.; Ferreira, A.J.S.; da Silva, A. Fibrous Microplastics Released from Textiles: Occurrence, Fate, and Remediation Strategies. *J. Contam. Hydrol.* **2023**, *256*, 104169. [CrossRef]
24. Awet, T.T.; Kohl, Y.; Meier, F.; Straskraba, S.; Grün, A.-L.; Ruf, T.; Jost, C.; Drexel, R.; Tunc, E.; Emmerling, C. Effects of Polystyrene Nanoparticles on the Microbiota and Functional Diversity of Enzymes in Soil. *Environ. Sci. Eur.* **2018**, *30*, 11. [CrossRef]
25. Ali, N.; Liu, W.; Zeb, A.; Shi, R.; Lian, Y.; Wang, Q.; Wang, J.; Li, J.; Zheng, Z.; Liu, J.; et al. Environmental Fate, Aging, Toxicity and Potential Remediation Strategies of Microplastics in Soil Environment: Current Progress and Future Perspectives. *Sci. Total Environ.* **2024**, *906*, 167785. [CrossRef]
26. Seo, Y.; Zhou, Z.; Lai, Y.; Chen, G.; Pembleton, K.; Wang, S.; He, J.; Song, P. Micro- and Nanoplastics in Agricultural Soils: Assessing Impacts and Navigating Mitigation. *Sci. Total Environ.* **2024**, *931*, 172951. [CrossRef]
27. Liu, B.; Shen, Z.; Zhou, Q.; Hu, L.; Zeng, G.; Wang, X.; Zhang, M.; Zhang, D.; Pan, X. Microplastics in Soil Aggregates: Analytical Methods, Occurrence Patterns, Impact Analyses and Removal Approaches. *TrAC Trends Anal. Chem.* **2024**, *178*, 117855. [CrossRef]
28. Aralappanavar, V.K.; Mukhopadhyay, R.; Yu, Y.; Liu, J.; Bhatnagar, A.; Praveena, S.M.; Li, Y.; Paller, M.; Adyel, T.M.; Rinklebe, J.; et al. Effects of Microplastics on Soil Microorganisms and Microbial Functions in Nutrients and Carbon Cycling—A Review. *Sci. Total Environ.* **2024**, *924*, 171435. [CrossRef]
29. Yu, L.; Zhang, J.; Liu, Y.; Chen, L.; Tao, S.; Liu, W. Distribution Characteristics of Microplastics in Agricultural Soils from the Largest Vegetable Production Base in China. *Sci. Total Environ.* **2021**, *756*, 143860. [CrossRef]
30. Tian, L.; Jinjin, C.; Ji, R.; Ma, Y.; Yu, X. Microplastics in Agricultural Soils: Sources, Effects, and Their Fate. *Curr. Opin. Environ. Sci. Health* **2022**, *25*, 100311. [CrossRef]
31. Yang, X.; Zhang, Z.; Guo, X. Impact of Soil Structure and Texture on Occurrence of Microplastics in Agricultural Soils of Karst Areas. *Sci. Total Environ.* **2023**, *902*, 166189. [CrossRef]
32. Adhikari, K.; Pearce, C.I.; Sanguinet, K.A.; Bary, A.I.; Chowdhury, I.; Eggleston, I.; Xing, B.; Flury, M. Accumulation of Microplastics in Soil after Long-Term Application of Biosolids and Atmospheric Deposition. *Sci. Total Environ.* **2024**, *912*, 168883. [CrossRef]
33. Jia, W.; Karapetrova, A.; Zhang, M.; Xu, L.; Li, K.; Huang, M.; Wang, J.; Huang, Y. Automated Identification and Quantification of Invisible Microplastics in Agricultural Soils. *Sci. Total Environ.* **2022**, *844*, 156853. [CrossRef]
34. Tang, K.H.D. Microplastics in Agricultural Soils in China: Sources, Impacts and Solutions. *Environ. Pollut.* **2023**, *322*, 121235. [CrossRef] [PubMed]
35. Pham, D.N.; Clark, L.; Li, M. Microplastics as Hubs Enriching Antibiotic-Resistant Bacteria and Pathogens in Municipal Activated Sludge. *J. Hazard. Mater. Lett.* **2021**, *2*, 100014. [CrossRef]
36. Sun, S.; Yang, X.; Xu, L.; Zhang, J.; Wang, Y.; Zhou, Z. Atrazine Sorption on Biodegradable Microplastics: Significance of Microbial Aging. *Sci. Total Environ.* **2023**, *862*, 160904. [CrossRef] [PubMed]
37. da Silva Júnior, A.H.; de Oliveira, C.R.S.; Leal, T.W.; Mapossa, A.B.; Fiates, J.; Ulson de Souza, A.A.; Ulson de Souza, S.M.d.A.G.; da Silva, A. Organochlorine Pesticides Remediation Techniques: Technological Perspective and Opportunities. *J. Hazard. Mater. Lett.* **2024**, *5*, 100098. [CrossRef]
38. da Silva Júnior, A.H.; Mulinari, J.; de Oliveira, P.V.; de Oliveira, C.R.S.; Reichert Júnior, F.W. Impacts of Metallic Nanoparticles Application on the Agricultural Soils Microbiota. *J. Hazard. Mater. Adv.* **2022**, *7*, 100103. [CrossRef]
39. Nguyen, M.K.; Lin, C.; Hoang, H.G.; Sanderson, P.; Dang, B.T.; Bui, X.T.; Nguyen, N.S.H.; Vo, D.-V.N.; Tran, H.T. Evaluate the Role of Biochar during the Organic Waste Composting Process: A Critical Review. *Chemosphere* **2022**, *299*, 134488. [CrossRef]
40. Bläsing, M.; Amelung, W. Plastics in Soil: Analytical Methods and Possible Sources. *Sci. Total Environ.* **2018**, *612*, 422–435. [CrossRef]
41. Weithmann, N.; Möller, J.N.; Löder, M.G.J.; Piehl, S.; Laforsch, C.; Freitag, R. Organic Fertilizer as a Vehicle for the Entry of Microplastic into the Environment. *Sci. Adv.* **2018**, *4*, eaap8060. [CrossRef] [PubMed]
42. Corradini, F.; Meza, P.; Eguiluz, R.; Casado, F.; Huerta-Lwanga, E.; Geissen, V. Evidence of Microplastic Accumulation in Agricultural Soils from Sewage Sludge Disposal. *Sci. Total Environ.* **2019**, *671*, 411–420. [CrossRef]
43. Scopetani, C.; Chelazzi, D.; Cincinelli, A.; Martellini, T.; Leiniö, V.; Pellinen, J. Hazardous Contaminants in Plastics Contained in Compost and Agricultural Soil. *Chemosphere* **2022**, *293*, 133645. [CrossRef]

44. Hu, J.; Zhang, L.; Zhang, W.; Muhammad, I.; Yin, C.; Zhu, Y.; Li, C.; Zheng, L. Significant Influence of Land Use Types and Anthropogenic Activities on the Distribution of Microplastics in Soil: A Case from a Typical Mining-Agricultural City. *J. Hazard. Mater.* **2024**, *477*, 135253. [CrossRef]
45. Boughattas, I.; Hattab, S.; Zitouni, N.; Mkhinini, M.; Missawi, O.; Bousserrhine, N.; Banni, M. Assessing the Presence of Microplastic Particles in Tunisian Agriculture Soils and Their Potential Toxicity Effects Using Eisenia Andrei as Bioindicator. *Sci. Total Environ.* **2021**, *796*, 148959. [CrossRef]
46. Zhao, Z.; Zhao, K.; Zhang, T.; Xu, Y.; Chen, R.; Xue, S.; Liu, M.; Tang, D.; Yang, X.; Giessen, V. Irrigation-Facilitated Low-Density Polyethylene Microplastic Vertical Transport along Soil Profile: An Empirical Model Developed by Column Experiment. *Ecotoxicol. Environ. Saf.* **2022**, *247*, 114232. [CrossRef] [PubMed]
47. Li, S.; Ding, F.; Flury, M.; Wang, Z.; Xu, L.; Li, S.; Jones, D.L.; Wang, J. Macro- and Microplastic Accumulation in Soil after 32 Years of Plastic Film Mulching. *Environ. Pollut.* **2022**, *300*, 118945. [CrossRef] [PubMed]
48. Yu, H.; Shao, J.; Jia, H.; Gang, D.; Ma, B.; Hu, C. Characteristics and Influencing Factors of Microplastics in Snow in the Inner Mongolia Plateau, China. *Engineering* **2024**, *37*, 69–77. [CrossRef]
49. Bradney, L.; Wijesekara, H.; Palansooriya, K.N.; Obadamudalige, N.; Bolan, N.S.; Ok, Y.S.; Rinklebe, J.; Kim, K.-H.; Kirkham, M.B. Particulate Plastics as a Vector for Toxic Trace-Element Uptake by Aquatic and Terrestrial Organisms and Human Health Risk. *Environ. Int.* **2019**, *131*, 104937. [CrossRef]
50. Qi, Y.; Yang, X.; Pelaez, A.M.; Huerta Lwanga, E.; Beriot, N.; Gertsen, H.; Garbeva, P.; Geissen, V. Macro- and Micro- Plastics in Soil-Plant System: Effects of Plastic Mulch Film Residues on Wheat (*Triticum aestivum*) Growth. *Sci. Total Environ.* **2018**, *645*, 1048–1056. [CrossRef]
51. Fuller, S.; Gautam, A. A Procedure for Measuring Microplastics Using Pressurized Fluid Extraction. *Environ. Sci. Technol.* **2016**, *50*, 5774–5780. [CrossRef] [PubMed]
52. Han, L.; Chen, L.; Feng, Y.; Kuzyakov, Y.; Chen, Q.; Zhang, S.; Chao, L.; Cai, Y.; Ma, C.; Sun, K.; et al. Microplastics Alter Soil Structure and Microbial Community Composition. *Environ. Int.* **2024**, *185*, 108508. [CrossRef] [PubMed]
53. Liu, Z.; Wen, J.; Liu, Z.; Wei, H.; Zhang, J. Polyethylene Microplastics Alter Soil Microbial Community Assembly and Ecosystem Multifunctionality. *Environ. Int.* **2024**, *183*, 108360. [CrossRef]
54. Abbasi, S.; Moore, F.; Keshavarzi, B. PET-Microplastics as a Vector for Polycyclic Aromatic Hydrocarbons in a Simulated Plant Rhizosphere Zone. *Environ. Technol. Innov.* **2021**, *21*, 101370. [CrossRef]
55. Athulya, P.A.; Waychal, Y.; Rodriguez-Seijo, A.; Devalla, S.; Doss, C.G.P.; Chandrasekaran, N. Microplastic Interactions in the Agroecosystems: Methodological Advances and Limitations in Quantifying Microplastics from Agricultural Soil. *Environ. Geochem. Health* **2024**, *46*, 85. [CrossRef]
56. Wang, W.; Yuan, W.; Xu, E.G.; Li, L.; Zhang, H.; Yang, Y. Uptake, Translocation, and Biological Impacts of Micro(Nano)Plastics in Terrestrial Plants: Progress and Prospects. *Environ. Res.* **2022**, *203*, 111867. [CrossRef] [PubMed]
57. Bosker, T.; Bouwman, L.J.; Brun, N.R.; Behrens, P.; Vijver, M.G. Microplastics Accumulate on Pores in Seed Capsule and Delay Germination and Root Growth of the Terrestrial Vascular Plant Lepidium Sativum. *Chemosphere* **2019**, *226*, 774–781. [CrossRef]
58. Colzi, I.; Renna, L.; Bianchi, E.; Castellani, M.B.; Coppi, A.; Pignattelli, S.; Loppi, S.; Gonnelli, C. Impact of Microplastics on Growth, Photosynthesis and Essential Elements in *Cucurbita pepo* L. *J. Hazard. Mater.* **2022**, *423*, 127238. [CrossRef]
59. Emenike, C.; Adelugba, A.; MacDonald, M.; Asiedu, S.K.; Ofoe, R.; Abbey, L. A Combined Effect of Mixed Multi-Microplastic Types on Growth and Yield of Tomato. *Microplastics* **2025**, *4*, 5. [CrossRef]
60. Yang, S.; Zhang, Y.; Chen, Y.; Zeng, Y.; Yan, X.; Tang, X.; Pu, S. Studies on the Transfer Effect of Aged Polyethylene Microplastics in Soil-Plant System. *Chemosphere* **2024**, *349*, 141001. [CrossRef]
61. Mendes, L.A.; Beiras, R.; Domínguez, J. Earthworm (*Eisenia andrei*)-Mediated Degradation of Commercial Compostable Bags and Potential Toxic Effects. *Microplastics* **2024**, *3*, 322–338. [CrossRef]
62. Chang, X.; Fang, Y.; Wang, Y.; Wang, F.; Shang, L.; Zhong, R. Microplastic Pollution in Soils, Plants, and Animals: A Review of Distributions, Effects and Potential Mechanisms. *Sci. Total Environ.* **2022**, *850*, 157857. [CrossRef] [PubMed]
63. Rose, P.K.; Yadav, S.; Kataria, N.; Khoo, K.S. Microplastics and Nanoplastics in the Terrestrial Food Chain: Uptake, Translocation, Trophic Transfer, Ecotoxicology, and Human Health Risk. *TrAC Trends Anal. Chem.* **2023**, *167*, 117249. [CrossRef]
64. Iqbal, B.; Zhao, T.; Yin, W.; Zhao, X.; Xie, Q.; Khan, K.Y.; Zhao, X.; Nazar, M.; Li, G.; Du, D. Impacts of Soil Microplastics on Crops: A Review. *Appl. Soil Ecol.* **2023**, *181*, 104680. [CrossRef]
65. 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. Source, Migration and Toxicology of Microplastics in Soil. *Environ. Int.* **2020**, *137*, 105263. [CrossRef]
66. Campanale, C.; Massarelli, C.; Savino, I.; Locaputo, V.; Uricchio, V.F. A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on Human Health. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1212. [CrossRef]
67. Beans, C. Are Microplastics Spreading Infectious Disease? *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2311253120. [CrossRef]
68. Li, Y.; Tao, L.; Wang, Q.; Wang, F.; Li, G.; Song, M. Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. *Environ. Health* **2023**, *1*, 249–257. [CrossRef]

69. Yang, X.; Man, Y.B.; Wong, M.H.; Owen, R.B.; Chow, K.L. Environmental Health Impacts of Microplastics Exposure on Structural Organization Levels in the Human Body. *Sci. Total Environ.* **2022**, *825*, 154025. [CrossRef]
70. Forte, M.; Iachetta, G.; Tussellino, M.; Carotenuto, R.; Prisco, M.; De Falco, M.; Laforgia, V.; Valiante, S. Polystyrene Nanoparticles Internalization in Human Gastric Adenocarcinoma Cells. *Toxicol. Vitr.* **2016**, *31*, 126–136. [CrossRef]
71. Prata, J.C. Airborne Microplastics: Consequences to Human Health? *Environ. Pollut.* **2018**, *234*, 115–126. [CrossRef] [PubMed]
72. Marfella, R.; Prattichizzo, F.; Sardu, C.; Fulgenzi, G.; Graciotti, L.; Spadoni, T.; D'Onofrio, N.; Scisciola, L.; La Grotta, R.; Frigé, C.; et al. Microplastics and Nanoplastics in Atheromas and Cardiovascular Events. *N. Engl. J. Med.* **2024**, *390*, 900–910. [CrossRef]
73. Shan, S.; Zhang, Y.; Zhao, H.; Zeng, T.; Zhao, X. Polystyrene Nanoplastics Penetrate across the Blood-Brain Barrier and Induce Activation of Microglia in the Brain of Mice. *Chemosphere* **2022**, *298*, 134261. [CrossRef] [PubMed]
74. Jin, H.; Yang, C.; Jiang, C.; Li, L.; Pan, M.; Li, D.; Han, X.; Ding, J. Evaluation of Neurotoxicity in BALB/c Mice Following Chronic Exposure to Polystyrene Microplastics. *Environ. Health Perspect.* **2022**, *130*, 107002. [CrossRef]
75. Ikuno, Y.; Tsujino, H.; Haga, Y.; Asahara, H.; Higashisaka, K.; Tsutsumi, Y. Impact of Degradation of Polyethylene Particles on Their Cytotoxicity. *Microplastics* **2023**, *2*, 192–201. [CrossRef]
76. de Oliveira, P.V.; da Silva Júnior, A.H.; de Oliveira, C.R.S.; Assumpção, C.F.; Ogeda, C.H. Kombucha Benefits, Risks and Regulatory Frameworks: A Review. *Food Chem. Adv.* **2023**, *2*, 100288. [CrossRef]
77. Mamun, T.I. From Feed to Food: Unveiling the Widespread Impact of Microplastics on Animal and Human Health. *New Microbes New Infect.* **2024**, *62*, 101461. [CrossRef]
78. Adelugba, A.; Emenike, C. Comparative Review of Instrumental Techniques and Methods for the Analysis of Microplastics in Agricultural Matrices. *Microplastics* **2023**, *3*, 1–21. [CrossRef]
79. Adhikari, S.; Kelkar, V.; Kumar, R.; Halden, R.U. Methods and Challenges in the Detection of Microplastics and Nanoplastics: A Mini-review. *Polym. Int.* **2022**, *71*, 543–551. [CrossRef]
80. Ali, M.A.; Lyu, X.; Ersan, M.S.; Xiao, F. Critical Evaluation of Hyperspectral Imaging Technology for Detection and Quantification of Microplastics in Soil. *J. Hazard. Mater.* **2024**, *476*, 135041. [CrossRef]
81. de Oliveira, C.R.S.; da Silva Júnior, A.H.; Mulinari, J.; Immich, A.P.S. Textile Re-Engineering: Eco-Responsible Solutions for a More Sustainable Industry. *Sustain. Prod. Consum.* **2021**, *28*, 1232–1248. [CrossRef]
82. Withana, P.A.; Li, J.; Senadheera, S.S.; Fan, C.; Wang, Y.; Ok, Y.S. Machine Learning Prediction and Interpretation of the Impact of Microplastics on Soil Properties. *Environ. Pollut.* **2024**, *341*, 122833. [CrossRef] [PubMed]