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Review

Characteristics and Migration Dynamics of Microplastics in Agricultural Soils

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Abstract: The risks brought by microplastics (MPs) to agricultural soil structure and crop growth in the agricultural system are the focus of global debate. MPs enter the soil through various routes, such as through the use of agricultural mulch and atmospheric deposition. Here, we review the research on MP pollution in the soil during the last 30 years. This review focuses on (i) the sources, types, and distribution characteristics of MPs in agricultural soils; (ii) the migration and transformation of MPs and their interactions with microorganisms, organic matter, and contaminants in agricultural soils; and (iii) the effects of environmental factors on the composition and structure of MPs in agricultural soils. This review also proposes key directions for the future research and management of MPs in the agricultural soil. We aim to provide a theoretical basis for the fine management of agricultural farmland.

Keywords: agriculture; microplastics; microorganisms; transformation; degradation

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1. Introduction

Microplastics (MPs) are particles that are less than 5 mm in at least one dimension [1–3], while nano-plastics are generally referred to as plastic particles with a size smaller than 100 nm [4]. The results of many studies have shown that the amount of MPs remaining in soil is directly proportional to the duration of mulching with plastic film [5,6]. Although nanoplastics are also widely present in soil, this review focuses on MPs [7]. For example, the average abundance of MPs in the cotton fields in Xinjiang Province was 80.30 ± 49.30 and 308.00 ± 138.10 particles/kg dry mass (dm) of soil in the farmlands with 5 and 24 years of film mulching, respectively [8]. The annual discharge of MPs into the soil through wastewater treatment plants in Europe was estimated to range from 63,000 tons to 430,000 tons, while the estimate for that in North America ranged from 44,000 tons to 300,000 tons [9,10]. Most previous studies of MPs focused on water bodies such as oceans, lakes, and rivers [8,11]. MP amount in the soil has been found more than four times higher than that in the ocean [12,13]. However, MP pollution in the soil has received much less attention from researchers [8]. Therefore, it is critical to characterize MPs in the soil and propose relevant treatment technologies.

With a large surface area to volume ratio and high hydrophobicity, MPs can adsorb many hydrophobic organic pollutants, heavy metals, and other complex pollutants [14]. After being ingested by organisms in the soil, MPs can threaten their survival and development. MPs can also be ingested by human beings through the food chain, posing potential risks to human health [15]. Despite the potential risks of MPs in the farmland, studies have found that microorganisms in the plant rhizosphere can use hydroxy-valerate copolymer (PHBV, a type of biodegradable MP) as a carbon source, thus promoting their growth and development [16]. The presence of PHBV also changed the structure of bacterial colonies at different classification levels [16]. Therefore, biodegradable plastics have the potential to optimize the ecological function of the soil and the biogeochemical cycle of carbon and other nutrients by stimulating the activity of functional microbial enzymes in the rhizosphere of crops [17]. Hence, the impact of MPs on the agroecosystem is not entirely negative. More comprehensive studies are needed to assess the impact of the complex effects of MPs with other pollutants and microorganisms in the soil ecosystem.

Currently, the international community has set the target of plastic waste treatment at a recycling rate of 35% by 2050 [18]. The EU is launching the "Plastics Strategy", aiming to reduce the use of single-use plastic bags and establish a new circular economy [19]. The "Biotechnology Innovation in Environmental Restoration" program has been set up to establish biotechnology for the biodegradation of refractory and degradable plastics (CE-Biotec-05-2019). China's Soil Pollution Prevention and Control Law, promulgated on 31 August 2018, proposes to strengthen the recycling and reuse of agricultural film waste [20]. Furthermore, efforts to clean up residual mulching film and the plastic packaging of pesticides and fertilizers, as well as political rectification, should be promoted to gradually reduce the amount of plastic waste in the farmland.

This review summarizes the global research on MPs in the agricultural soil over the last 30 years in terms of source analysis, pollution status, distribution characteristics, migration and transformation, and treatment technologies. Furthermore, key research directions are proposed to provide a theoretical foundation and guide the future research on the effects of MPs on soil ecosystems.

2. Environmental Characterization of Microplastics in Agricultural Soils

2.1. Literature Searching and Screening

In the database of the Web of Science Core Collection, we used the condition "TS = (microplastic)" to find the research on microplastics and narrowed the scope with the condition "(TS = ((soil) or (land) or (farmland))) AND TS = (microplastic)" to focus on the research on MPs in soil. A total of 8839 articles related to microplastics were obtained, while a total of 1520 articles were obtained on microplastics in soil. The annual number of articles published on MPs and MPs in soil is presented in Figure 1A. Research on MPs started in 2013, and has gradually emerged as a research hotspot in recent years. Figure 1B displays the proportion of research on MPs in the soil relative to the overall research on MPs, revealing the growing focus on MPs in the soil.

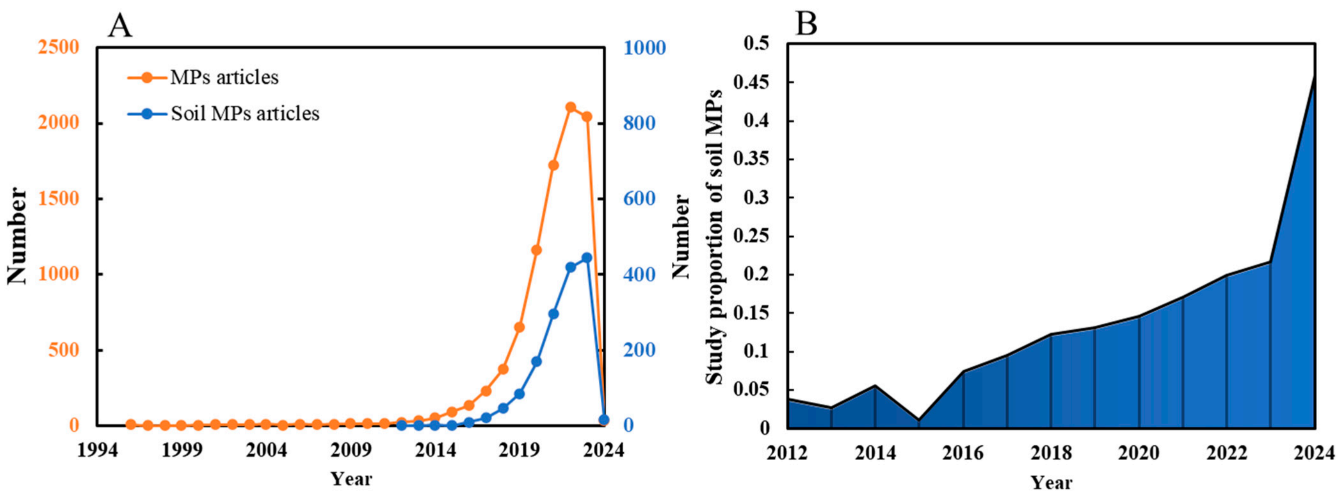

Figure 1. The number of MPs and soil MPs articles published from 1995 to 2024 ((**A**) the number of MPs articles and the number of soil MPs articles; and (**B**) proportion of soil MPs in MPs studies).

Furthermore, the retrieved publications were subjected to keyword co-occurrence analysis using the CiteSpace 6.2 R7 software (Figure 2). The most frequently occurring keywords were identified to be pollution, marine environment, sediments, particles, water, accumulation, plastics, identification, soil, and transport. This analysis highlights the complex nature and broad impact of MPs on both marine and terrestrial environments.

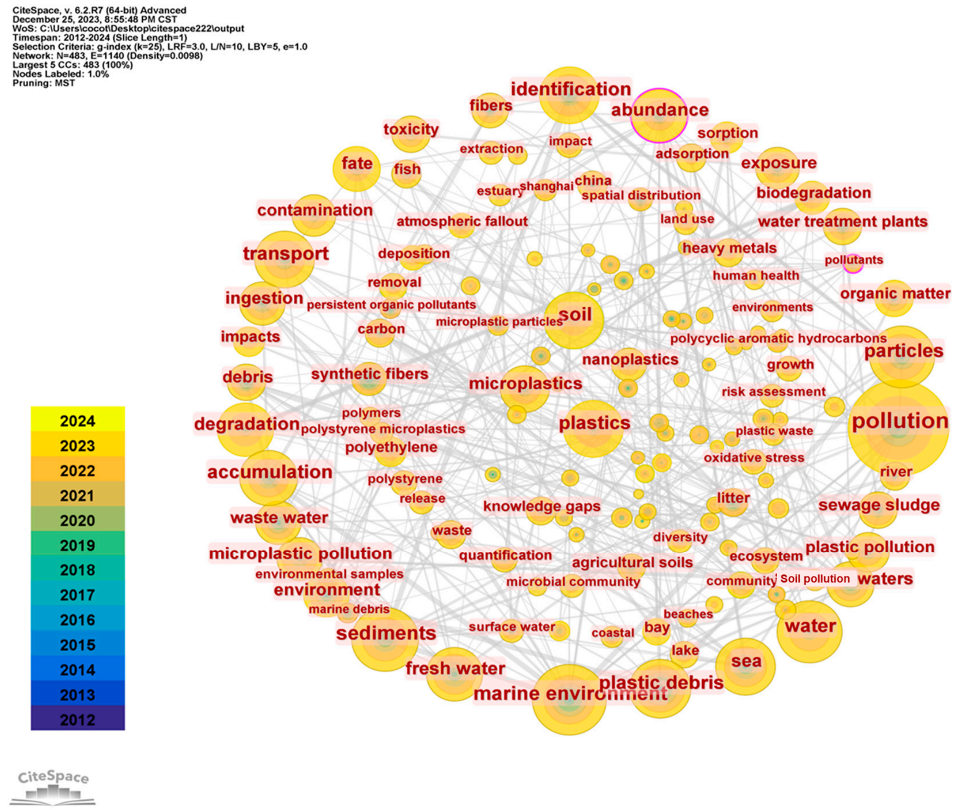

Figure 2. Keyword co-occurrence analysis of soil microplastics research from 2012 to 2024. The size of nodes and fonts is related to the number of co-occurrences.

The co-occurrence analysis of keywords reveals the focal points and trends in the research on MPs in soil. Researchers commonly focus on the impacts of MPs on soil quality and ecosystems, as well as the sources, behavior, and identification methods of MPs in soil. Additionally, attention is directed towards the accumulation and effects of MPs in the marine environment, as well as the pathways through which they enter the soil, such as through sediments or water bodies.

It is important to determine the impact of MPs on the soil ecosystem and implement corresponding management measures for the health of the environment and humans.

2.2. Sources and Types of Microplastics in Agricultural Soils

The main sources of land-based plastics include plastic greenhouses used in agricultural production, plastic mulch directly applied in the farmland, the dispersion of the domestic use of plastics (including additives in personal care products, washing machines, and the wear and tear of tires that release plastic particles), sludge, the deposition of exhaust gases from industrial production, floods, and sandstorms [21–25] (Figure 3). These plastics have become important sources of MPs in the soil because of their low recovery and susceptibility to aging and fragmentation when exposed in the environment. According to the composition, MPs consist mainly of polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). The physical and chemical characteristics of plastics that frequently occur in the soil are shown in Table 1. Agricultural films are mainly PE and PVC materials [26]. PE and PVC plastic are mostly utilized in agricultural practices. PE film has the ability to maintain a consistent temperature and a stable soil water moisture, repel pests, and inhibit the occurrence of diseases. Meanwhile, PVC plastic is commonly employed in agricultural drip irrigation systems [27,28]. According to the sources, MPs can be divided into primary and secondary MPs [26,29,30]. Primary MPs mainly originate from activities such as laundry, the use of cosmetics, and the discharge of medical wastes. In other words, cleaning products, cosmetics, sunscreen, shampoo, etc., used in our daily life, are all potential sources of MPs [31]. Secondary MPs are smaller plastic fragments resulting from the physical, chemical, and biodegradation processes of large plastic fragments [31,32].

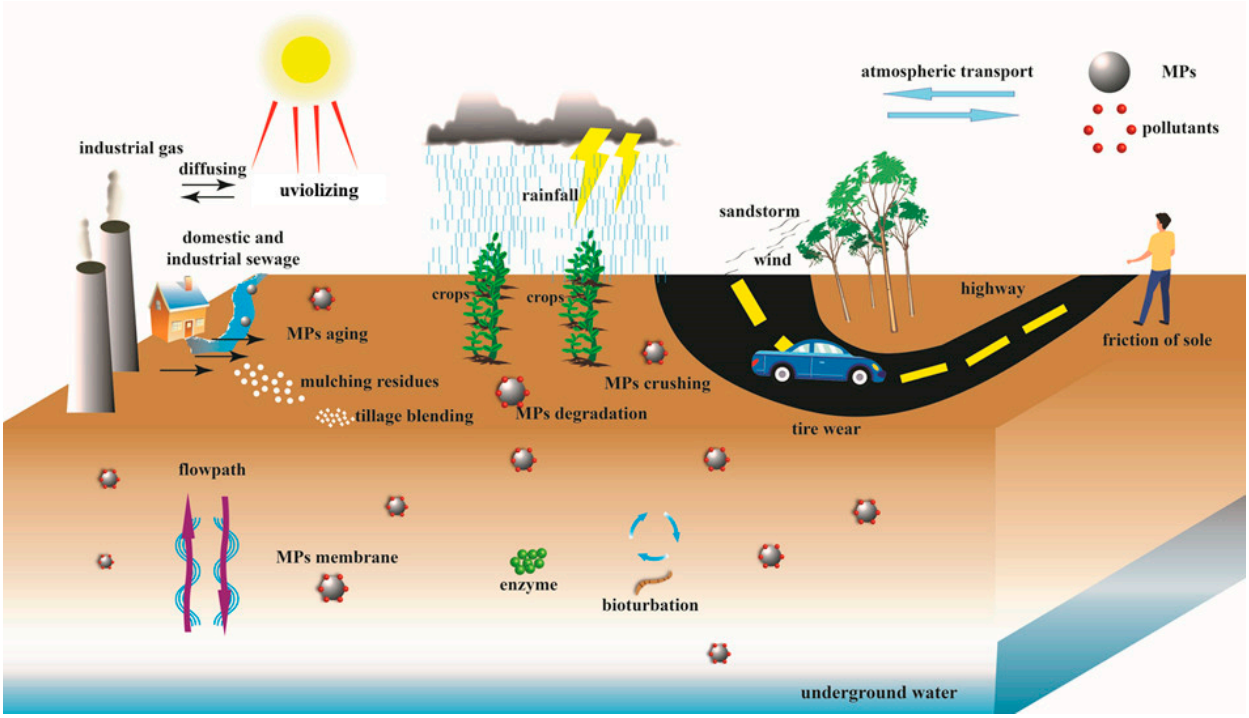

Figure 3. Main sources and migration of MPs in the soil.

Table 1. Physical and chemical properties of MPs in the soil [33–35].

Mcroplastics	Chemical Formula	Polarity	Glass Transition Temperature (°C)	Density (g/cm^3)	Resistance to UV Light	General Properties
PE	$(C_2H_4)_n$	non-polar	−110	0.92–0.97	Poor	With good water resistance, weather resistance and flexible chemical resistance
PP	$(C_3H_6)_n$	non-polar	−49 to −20	0.88–1.23	Fair	Resistance to a variety of acids and alkalis, low density, high stiffness, heat resistance and good transparency
PVC	$(C_2H_3Cl)_n$	polar	60–100	1.15–1.70	Good	Flame retardancy, resistance to acids, alkalis and most inorganic chemicals
PS	$(C_8H_8)_n$	non-polar	90	1.04–1.50	Poor	Crystal clear appearance, good impact resistance and toughness, and poor waterproofing and oxygen resistance
PET	$(C_{10}H_8O_4)_n$	polar	73–78	1.30–1.50	Fair	Light weight, aging resistance, strong impact and shatter resistant with good water retention and sealing properties.
PA6 PA66	$(C_6H_{11}NO)_n$ $(C_{12}H_{22}N_2O_2)_n$	Strongly polar	−60	1.12–1.14 1.13–1.38	Poor Fair	Toughness, good tensile strength and good wear resistance

Plastic mulch is an effective agricultural practice that regulates soil temperature, maintains soil moisture, and prevents weeds and soil erosion, as well as improves crop yields [36,37]. The consumption of plastic film is growing exponentially, with a global share of more than 3.9 million tons, and it is mainly concentrated in Asia (about 70%) and Europe (about 16%), with the largest consumer country being China [38,39]. In 2017, the total amount of agricultural plastic film in China reached 2 million tons, accounting for 90% of the global total [38,39]. The use of agricultural plastic film in China increased by 30% annually from 1991 to 2001, and it increased from 1.85×10^6 tons to 2.6×10^6 tons with an increase of 41% from 2006 to 2015 [40]. The range of residual film content in the soil of Xinjiang is from 0 to 502 kg/hm^2 (average 121.5 kg/hm^2) [41]. The average residual amount of mulching film was more than 100 kg/hm^2 in most regions of Gansu Province, eastern Inner Mongolia, and the northeast areas dominated by sandy soils [42]. In these areas, the mulch is used to reduce water evaporation because of the low rainfall and high evaporation. Farmers have a low awareness of the harm of residual film pollution. The thickness of the PE film produced by many enterprises in China is lower than the national standard of 0.008 mm, resulting in low strength and easy breakage [43]. The mulch is supposed to be removed from the field at the end of the farming period. However, only a small proportion of the mulching plastic is actually collected. For example, in the European Union, 100,000 tons of plastic are used for mulching each year, but only 32% of these is collected at the end of the farming period, with the rest incinerated or buried in the soil [44].

Sewage and sludge discharge is also one of the important sources of MPs in the soil environment globally. For example, Tagg et al. detected an MP concentration of 14.6 g/L in German soil, which was due to the high content of MPs in sewage sludge [45]. According to a Norwegian survey, 500 billions of MPs were released into the environment every year through sludge from sewage treatment plants [46]. Moreover, 32.4% of MPs from Canadian wastewater treatment plants were suspected to enter the soil ecosystem [47].

2.3. Distribution of Microplastics in Agricultural Soils

Large amounts of MPs have been detected in soil worldwide. In Switzerland, about 90% of the soil in the floodplain areas contained MPs, with a maximum concentration of 593 g/kg [24]. The average MPs content in the soil at the industrial sites in Australia was 23 g/kg dm [48]. MPs in the sediments of Koshi River (a typical alpine river in the Himalayas on the border between China and Indonesia) were inversely proportional to the altitude, with a range of concentration as 31–85 items/kg dry weight [49]. The abundance of MPs in the shore was twice as high as in the center of the river [50]. In the arid and semi-arid areas, relatively large amounts of MPs were observed in soils near watersheds and industrial and agricultural sites [51].

MPs in soil migrate through different processes, including leaching, bioturbation, and mechanical perturbation [52]. Some studies have shown that the fields of cereal crops (such as wheat and rice) contain a large proportion of large-size (1–5 mm) fibrous MPs, while woodland (e.g., orchard and forest) contained a larger proportion of smaller-size MPs (0.02–0.2 mm) [30]. Biological processes contributed to the horizontal and vertical redistribution of MPs in the soil. In these processes, MPs can be ingested and selectively discharged by soil protists, such as earthworms and collembola [53,54]. The pore structure of soil and disturbance of soil organisms such as earthworms help MPs to migrate deep underground and even reach the groundwater layer [53,55]. Choi et al.'s study showed that the abundance of MPs in farmland soils varied with tillage type, with the highest abundance in orchards, followed by dryland greenhouses, and paddy fields. This is probably related to the use of agricultural film and instruments, as orchards tend to have less runoff and soil erosion but more physical disturbances than other agricultural lands (e.g., tillage and soil stirring) [56,57].

3. Migration and Effects of Microplastics in Agricultural Soils

3.1. Migration of Microplastics in Agricultural Soils

MP particles on the surface of the soil could enter underground with human activities. Tillage methods affect the distribution of MPs in the soil layer [58]. Traditional tillage promotes the transfer of MPs to the deep soil layer, while shallow tillage, rotary tillage, and harrowing lead to the migration of MPs to the tilled layer [58]. The migration of MPs in the soil is influenced by the electrolytes, pH, and humic acid, etc. [59–61]. Cations with smaller ionic radii have larger hydration radii, which reduces the effect of the charge screening and steric obstruction deposition and decreases the retention of MPs in porous media; that is, the migration efficiency of MPs is increased [50,60,62]. The interaction of MPs with dissolved organic matter (DOM) in the soil also inevitably affects the migration of MPs in various ways and complicates the environmental characteristics of MPs [63]. In the soil, saturated goethite (GT), DOM, and nano-plastics (50 nm) can form GT-DOM-nanocomposite, which leads to the co-deposition of nano-plastics and DOM and blocks the migration of nano-plastics [64]. When the pH of soil solution is close to neutral, MPs interact with fulvic acid (FA) through H-bond and n-π EDA (electron donor/acceptor), which promotes the mobility of MPs in the soil [65]. The surface morphology and structural characteristics of MPs undergo changes with aging. For instance, after aging under ultraviolet, MPs exhibit embrittlement, irregular shape, increased roughness, and an alteration in surface hydrophobicity, which consequently influences the adsorption, migration, and microbial colonization in the soil [66]. The aging process is typically accompanied by chemical reactions, resulting in the formation of oxygen-containing groups such as –OH, –C=O, COOH, and C=C on the surface of MPs [67]. Additionally, the molecular weight of the polymer also undergoes changes during aging. For example, following O_3 treatment, the average molecular weight of PS decreases from 24.8 kg/mol to 18.4 kg/mol, while the weight-average molecular weight of PS decreases from 168.1 kg/mol to 121.2 kg/mol [68]. Currently, the CI and O/C values are frequently employed to assess the degree of MP aging. CI refers to the absorbance ratio of the carbonyl peak to the reference peak in the FTIR spectrum, whereas O/C represents the ratio of oxygen to carbon on the polymer surface as characterized by X-ray photoelectron spectroscopy (XPS). Therefore, the migration of MPs is also closely related to these hydrophilic heavy metals. The presence of humic acids and the heterogeneity of functional groups on the surface restrict the transport of MPs [69]. MPs in the soil mainly migrate with wind erosion, surface runoff, biological processes, and agricultural activities (Yu et al. 2019). Biological processes could accelerate both the horizontal and vertical migration of MPs in the soil. The depth of earthworm (*Lumbricus terrestris*) burrows can be more than 30 cm, which is a potential way for MPs to enter the deep soil layer with preferential flow [70–72].

Heavy rainfall, high temperature, strong ultraviolet radiation, and windy weather make plastic residues more fragile and difficult to recycle from farmland soils. Regions with high temperature may face a great threat from MPs. MPs in the farmland of Hainan Island, China, ranged from 2800 to 82,500 particles/kg and showed a significant positive correlation with the temperature [73]. The distribution of MPs in the farmland soil is also affected by many factors, such as soil texture, planting time, and irrigation methods. Soil texture affects the migration and accumulation of MPs in the soil, which is related to the distribution and continuity of soil pores. The coarse soil presents a fast penetration rate; that is, the fine soil helps to retain the water. [74–77]. The abundance of MPs in sandy loam was significantly higher than that in silty loam or loam based on the international classification standard [78]. Long-term mulch application and irrigation during planting practice can cause MPs to accumulate in the soil [11]. Some studies have shown that irrigation methods can also affect the accumulation of MPs in the soil. Surface sprinkler irrigation has the lowest water utilization rate, followed by sprinkler irrigation and drip irrigation [79]. As a result, we speculated that MPs input into the soil through irrigation present in an increasing order as follows: surface irrigation, sprinkler irrigation, and drip irrigation.

Different types of plastics exhibit varying functional groups and polarities, affecting their adsorption behavior in the soil. For instance, PS displayed a notably strong adsorption capacity for toluene due to the strong π-π interaction between them [80]. Similarly, PA, which contains an amide group (a proton donor group), can form hydrogen bonds with the carbonyl group (a proton acceptor group), thereby enhancing the adsorption of PA to organic matter [34]. Consequently, the adsorption capacity of PA for hormones, drugs, pesticides, and other organic matter surpasses that of PE [81]. Non-polar plastics such as PE, PP, and PS demonstrate significant hydrophobicity, thus exhibiting stronger adsorption capacity for hydrophobic organics like 17β-estradiol compared to polar plastics [82].

3.2. Effects of Microplastics on Agricultural Ecosystems

The residues of mulch including MPs reduce the soil permeability, inhibit water and nutrient uptake by roots, and suppress soil microbial activity, thus negatively impacting the yield and quality of crops and soil sustainability [83] (Figure 4). For example, the annual mulch residue weight factor (the weight ratio of mulch residue to the total applied mulch) in the Hetao irrigation area in the Yellow River Basin was as high as 38.10% [84]. MPs can disrupt soil aggregates, which is critical for water penetration, water retention, aeration, and the fertility of soil [85–89]. The effects of MPs on plants were mainly manifested in the direct effects on plant growth and root microbial communities. Root-colonized microorganisms usually include nitrogen fixers, pathogens, mycorrhizal fungi N-fixers, pathogens, and mycorrhizal fungi [90]. Root colonization symbionts often have positive effects on plant diversity [91,92]. MPs change the soil structure, which affects the microbial communities, further affecting mineralization rates and colonizing symbionts, and even reducing plant diversity [93,94]. MPs in the soil may be absorbed by the roots and transported to the stem and the fruit, with transpiration being the main driving force [95]. MPs in the air may also enter the stomata of the leaves and then transfer through the vasculature to other parts of the plant [96,97]. NPs with smaller particle sizes have been detected in the nucleus, suggesting a risk of NPs to the nuclear membrane and chromosome function [98,99]. Degraded soil quality by MPs also limits space for roots and soil fauna, reduces aerobic processes that are important for plant nutrition, and favors anaerobic microbial processes that lead to methane and nitrous oxide production [100]. MPs are normally hydrophobic, inert, and persistent, and thus they are relatively stable and persist in the environment for a long time [101]. Most MPs are negatively charged, and metal cations in the environment can be attached to MPs via electrostatic binding [102]. At the same time, MPs have a high surface area and strong binding affinity, which enables them to interact extensively with the surrounding materials. These surrounding substances can form eco-coronas and biocoronas on the plastic surface, and the surface corona can affect the transport, absorption, distribution, biotransformation, and toxicity of MPs [103]. The corona formed on the surface of MPs can stay in the soil for a long time and interact with biological molecules such as proteins and lipids in the organisms (Figure 5). By virtue of their small size, MPs can penetrate the cells or break the cell wall of organisms, enrich in the organisms, and lead to cytotoxicity, thus affecting the survival of organisms [104–106].

The substances released from MPs, such as polyurethane, polyvinyl chloride, and acrylate-butadiene copolymers, also cause ecological risks to the soil ecosystem [62]. In addition, additives (i.e., bisphenol A and phthalate), most of which are endocrine disruptors, are usually added in the production process of plastics [93]. These environmental endocrine disruptors released from the plastic also pose a threat to the ecosystems and even human health. MPs have been found in the gut, lungs, blood, brain, and breast milk of humans [107,108]. MPs may also be able to penetrate cell membranes, the blood–brain barrier, and the placental barrier of mammals [105,109]. The 300 nm and 50 nm plastic granules increased the accumulation of oxytetracycline (OTC) in zebrafish liver by 33.8% and 44.5%, respectively [110]. In fact, most compounds added to plastics, such as plasticizers, stabilizers, and pigments, are harmful to the endocrine system [108,111]. Fragmented polyester MPs in soils are likely to adsorb organic chemicals and pathogens [60,112], whereas polycarbonate MPs undergo aging under UV exposure and chafe, releasing monomeric bisphenol A and other intermediates, such as hydroxylated, carboxylated, and carbonylated products [113–115].

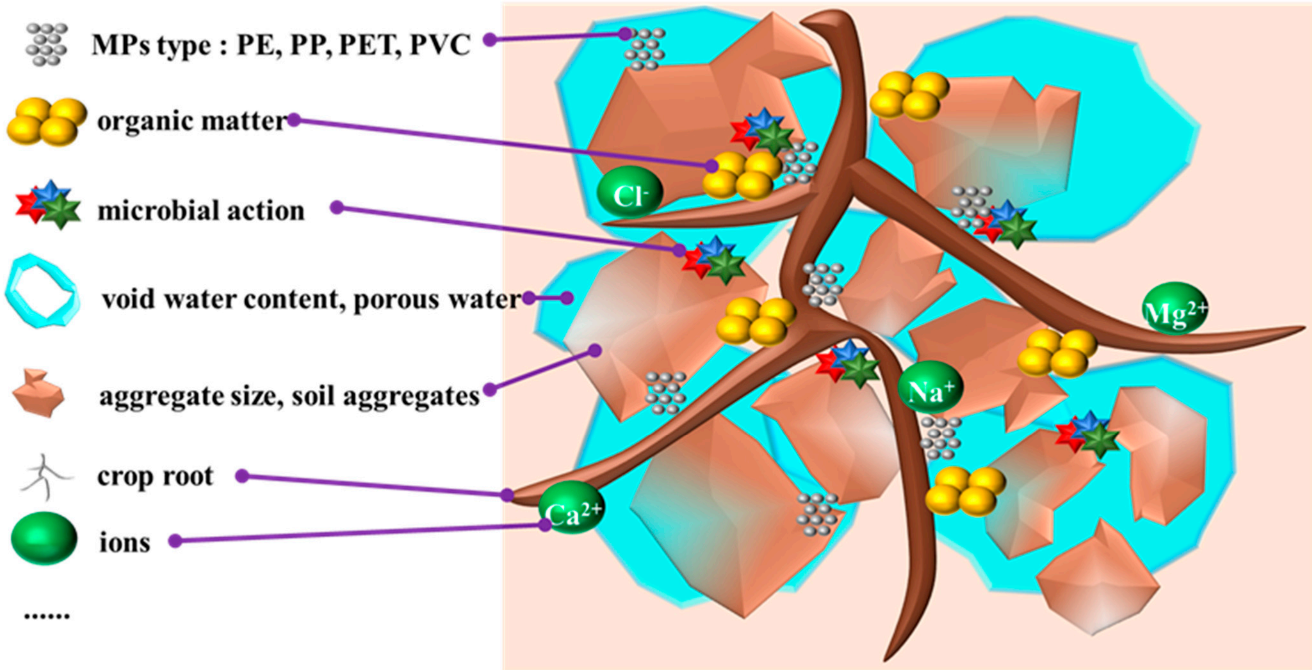

Figure 4. Complex interactions of plant roots and microplastics with other substances in soil. (Soil MPs interact with plant roots, organic matter, and nutrients in the soil).

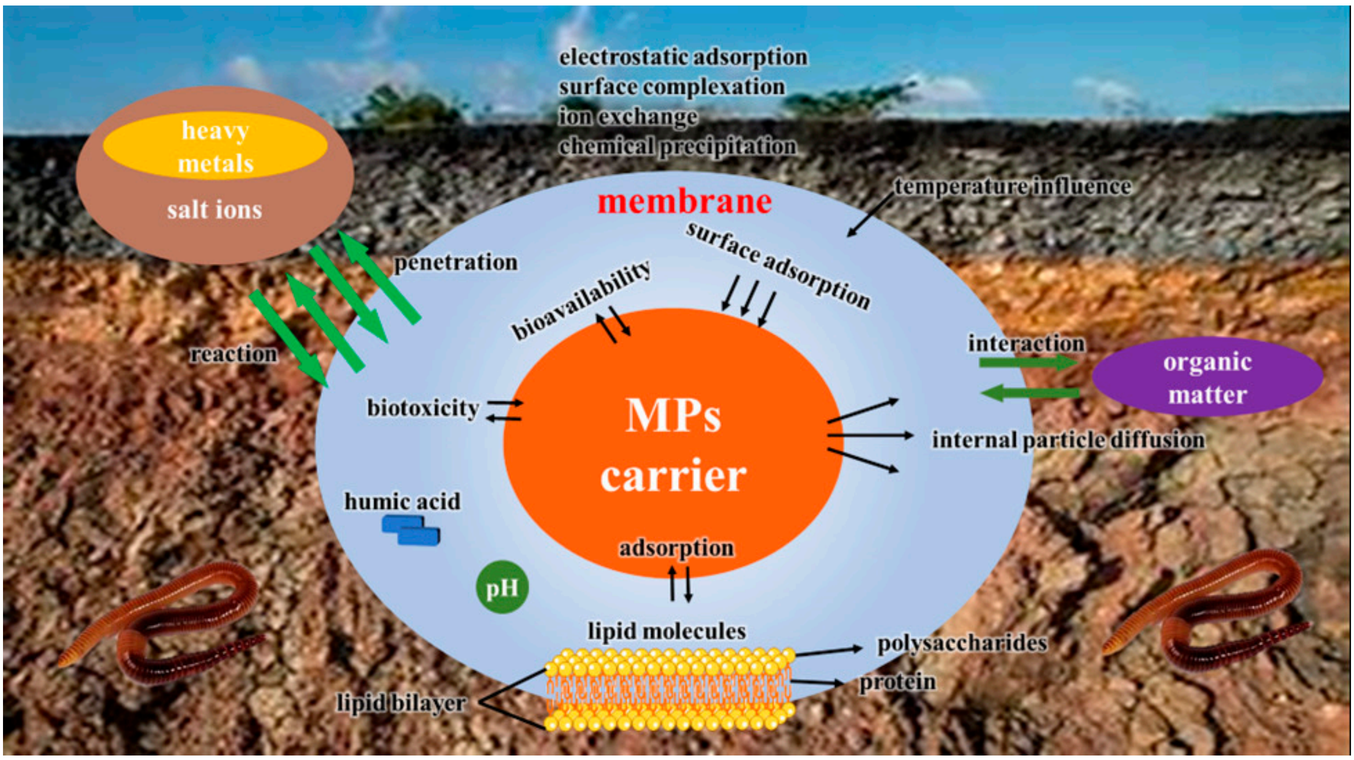

Figure 5. Microscopic interactions of microplastics with other substances in the soil.

MPs may also interfere with the pollination of local food crops by affecting the expression of certain genes of pollinators such as bees [116]. The influenced gene expression has been shown to be related to oxidative damage, detoxification, and immunity [116]. When the abundance of MPs is high, the growth and reproduction of other soil organisms, such as earthworms, is greatly affected [117]. MPs can accumulate in the body of earthworms, affecting the immune system and reproduction of earthworms, thus decreasing soil fertility and inhibiting crop growth [53,54]. MPs could also be brought downward by earthworms and pose a great risk to the groundwater [53,118,119]. MPs smaller than 0.1 μm could be translocated to the leaves, which can reduce the chlorophyll content in the leaves and the plant biomass [120]. MPs can also accumulate in the roots and result in a decrease in superoxide dismutase activity in the roots [120]. The phytotoxicity of MPs could also delay seed germination, affect the absorption and migration of MPs in the stems and leaves, hinder plant growth, inhibit photosynthesis, interfere with nutrient metabolism, cause oxidative damage, and produce genetic toxicity [121].

However, in addition to the damage caused to living organisms, the environmental effects of MPs require a comprehensive assessment. Yang et al. studied the interaction of MPs with the antibiotic sulfamethazine (SMT) in wastewater during ultraviolet disinfection. The study showed that the photosensitization of quinones and aromatic structures in the MP-DOM structure accelerated the photodegradation of SMT in a certain concentration range [122]. The bioavailability of pollutants could be reduced by MPs because of adsorption, creating a "cleaning effect" [123]. MPs may reduce the number of major consumers in the soil ecosystem, benefiting the microalgae populations [124]. MPs may also benefit some species, such as *Halobates sericeus*, by acting as substrates for microbial growth [125,126]. Yan et al. found that MPs affected the availability of phosphorus in rice and red soil by differentiating the microbial communities [127]. Li et al. also found that PP, PE, PS, PES, and PVC plastics with the abundance of 1000~10,000 particle/L promoted the denitrification of activated sludge, and PVC inhibited the emission of N_2O produced during the nitrification process [128]. Further research is needed to study the effects of MPs on the geochemical cycle of nitrogen and phosphorus in the soil. And it is necessary for professionals with diverse backgrounds such as biologists, chemists, and economists to fully assess the direct and indirect effects of MPs on a broad scale on the ecosystem and the society.

4. Biodegradation of Microplastics in Agricultural Soils

As an emerging type of persistent organic pollutants, MPs are generally difficult to be degraded by microorganisms in the environment [129]. However, most mulch materials that contain low-density PE are resistant to degradation [3], and biodegradable plastics have not been widely used because of their high cost [130,131]. Studies have been conducted on biodegradable plastics by microbes and microbial enzymes. PCL (polycaprolactone) and PBAT (Poly (butylene adipate-co-terephthalate)) are commonly used biobased biodegradable plastics. PBAT can be employed for the production of agricultural mulch films, while PCL can be used for agricultural product packaging [132]. *Penicillium oxalicum* DSYD05-1 depolymerase has a broad range of substrate specificity, and the strain can completely degrade PCL films within 9 days at 28 °C [133]. The degradation rate of PBAT by *thermomonospora fusca* strains could reach 99% at 55 °C within 22 days [134]. An FTIR analysis of aging polylactic acid showed an extra wide peak threshold ranging from 3000 to 3500 cm^{-1}, which indicated that the ester bond of PLA was hydrolyzed and fractured to form carboxyl and hydroxyl groups. It could then be further degraded by microorganisms into H_2O and CO_2 [48].

Biodegradation has relatively little impact on the native soil ecosystem compared to other treatment methods, so it has great potential to treat the pollution of MPs in the soil [135]. In 2017, two strains, *Bacillus cereus* and *Bacillus formans*, were isolated from mangrove sediments in Peninsular Malaysia and were shown to have the potential to degrade PP MPs [136]. Currently, more and more bacteria that can degrade PE plastic, including *Bacillus*, *Staphylococcus*, *Pseudomonas*, *Achromatobacteria*, *Chomonas*, *Delfteia*, and *Stenotrophomonas*, have been reported to occur in terrestrial environments [137,138]. When the domestication propagation technology of microorganisms with the potential of degrading MPs is mature, the efficiency of degrading MPs will be greatly improved. At the same time, microorganisms with a high efficiency of MP degradation can be combined and cultured to form enzymes that can degrade MPs (Figure 6). However, further research is needed to determine whether these artificial microbial communities have adverse effects on microbial communities in native ecosystems. At present, few studies have been focused on the microorganism degradation of MPs, but with the development of microbial culture technology, biodegradation with microorganisms will be a mainstream degradation technology for MPs in the future.

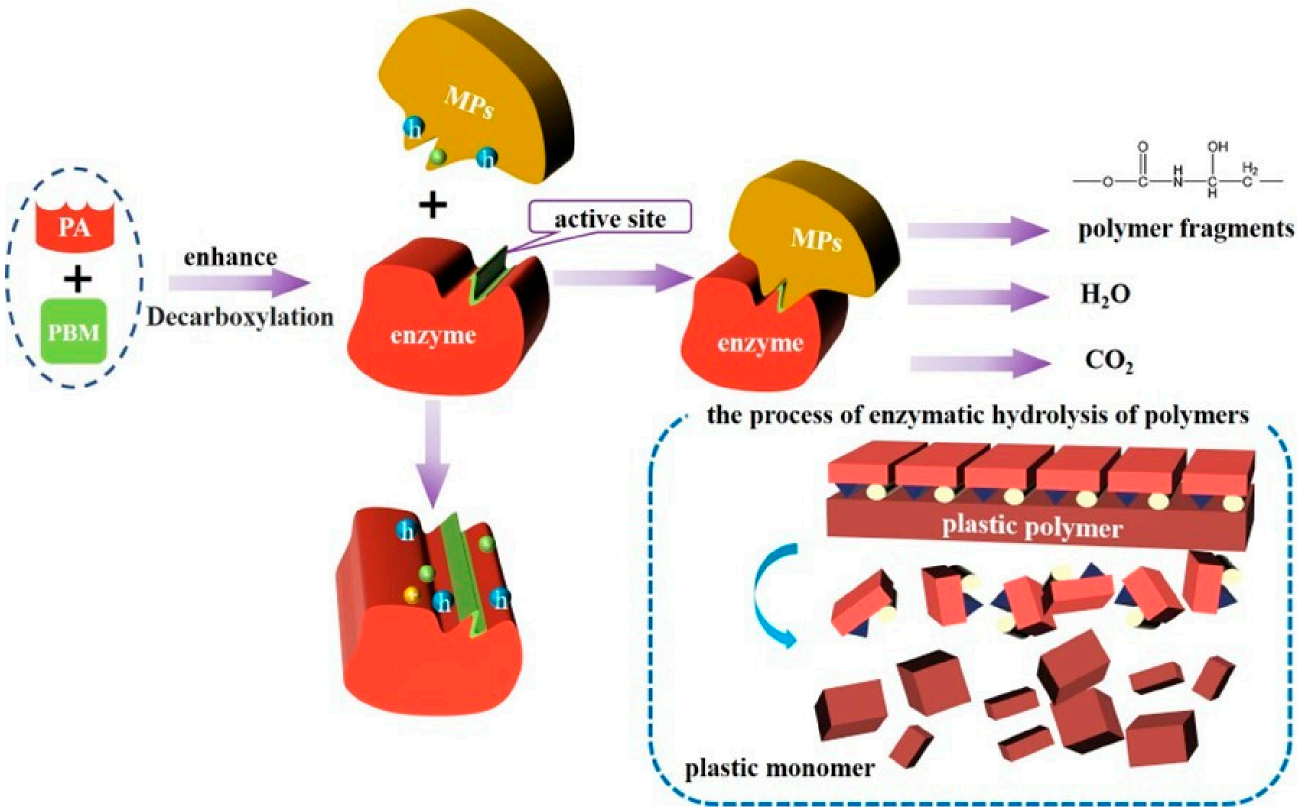

Figure 6. Schematic diagram of enzymatic degradation mechanism of PA MPs. (PBM: polymer binding module. PA: polyamidase. h: active site.).

In addition to microorganisms, isolated microbial enzymes can also be used to degrade MPs [139]. The biodegradation of MPs by microbial enzymes proceeds in two steps: enzymes are absorbed onto the surface of MPs through the surface-binding domain, which does not degrade the monomers of MPs; and the ester bond of MPs is hydrolyzed [140]. Also, enzymes can decompose complex plastic polymers into carbon dioxide, water, and other small molecule polymers, making MPs a source of carbon for microbial metabolism [141] (Figure 6).

As noted in the abovementioned discussion, overall, MPs present more risks than benefits in the soil. While the introduction of biodegradable MPs into farmland soils can increase the carbon source for biodegradation, non-degradable MPs need to be treated further. In the future, targeted microorganisms (such as bacteria, fungi, and archaea) and microbial enzymes can be used for the treatment and removal of residual MPs in the soil, which has a broad prospect and requires in-depth research and continuous exploration.

5. Conclusions

The presence of MPs in farmland soils leads to detrimental consequences by disrupting soil structure, reducing soil permeability, and impeding water and nutrient absorption by plant roots. Additionally, MPs can disturb microbial communities, causing an imbalance in the soil ecosystem and reducing biodiversity. MPs can also infiltrate plant tissues, posing risks to plant growth. Moreover, MPs release toxic compounds and endocrine disruptors, posing potential threats not only to soil ecosystems but also to human health.

To mitigate the impact of MPs pollution and foster sustainable agricultural development, it is crucial to understand the properties and environmental behaviors of MPs and to implement necessary strategies. For example, the following approaches can be considered: strengthening farmland management practices, reducing the excessive use of plastic films, exploring alternative materials, improving wastewater and sludge treatment processes, enhancing environmental awareness, and promoting scientific research cooperation. Particularly, biodegradation is considered a promising approach to address MP pollution. Certain microbial strains and enzymes can effectively degrade biodegradable plastics like PCL, PBAT, and PLA. Furthermore, the cultivation and utilization of artificial microbial communities demonstrate potential for enhancing the degradation efficiency of MPs. However, further research is needed to tackle the challenges posed by non-biodegradable MPs and explore alternative treatment methods.

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Data Availability Statement: The datasets used (or analyzed) during the current study are available from the corresponding author on reasonable request.

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

Abbreviations

CI	Carbonyl Index
DOM	Dissolved Organic Matter
EDA	Electron Donor-Acceptor
EU	European Union
FA	Fluviac Acid
FTIR	Fourier Transform Infrared Spectroscopy
GT	Goethite
NPs	Nanoplastics
MPs	Microplastics
O/C	Oxygen to Carbon Ratio
OTC	Oxytetracycline
PAHs	Polycyclic Aromatic Hydrocarbons
PBAT	Poly (butylene adipate-co-terephthalate)
PCL	Polycaprolactone
PE	Polyethylene
PHBV	Poly(-3-hydroxybutyrate-co-3-hydroxyvalerate)
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
ROS	Reactive Oxygen Species
SOC	Soil Organic Carbon
SMT	Sulfamethazine
XPS	X-ray Photoelectron Spectroscopy

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