

Impacts of Micro- and Nano-Plastics on Soil Properties and Plant Production in Agroecosystems: A Mini-Review

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Abstract

Micro- and nano-plastics (MNPs) are tiny plastic particles resulting from plastic product degradation. Soil MNPs have been identified as potential influential factors affecting various soil properties and crop biomass productivity. This mini-review provides a synthesis of recent findings concerning their effects on soil physicochemical properties, microorganisms, organic carbon content, soil nutrients, greenhouse gas emissions, soil fauna, and their impacts on plant ecophysiology, growth, and production. The results indicate that MNPs may markedly impede soil aggregation ability, increase porosity, decrease soil bulk density, enhance water retention capacity, influence soil pH and electrical conductivity, and escalate soil water evaporation. Exposure to MNPs may predominantly induce changes in soil microbial composition, reducing the diversity and complexity of microbial communities and microbial activity while enhancing soil organic carbon stability, influencing soil nutrient dynamics, and stimulating organic carbon decomposition and denitrification processes, leading to elevated soil respiration and methane emissions, and potentially decreasing soil nitrous oxide emission. Additionally, MNPs may adversely affect soil fauna, diminish seed germination rates, promote plant root growth, yet impair plant photosynthetic efficacy and biomass productivity. These findings contribute to a better understanding of the impacts and mechanistic foundations of MNPs. Future research avenues are suggested to further explore the impacts and economic implications.

Keywords

Soil Property, Micro- and Nano-Plastics, Crop Yield, Soil Microorganism, Soil Fauna, Soil Greenhouse Gas Emissions

1. Introduction

Plastics play a ubiquitous role across diverse sections globally, including packaging, construction, electronics, household items, and agriculture [1] [2]. The global plastic production amounted to 370 Mt in 2022 and is anticipated to reach 1200 Mt by 2050 [3]-[5]. As of 2015, 6300 Mt of plastic waste has been generated globally and the total amount will increase from 260 to 460 Mt annually from 2016 to 2030 [6] [7]. In the realm of agriculture, plastics are extensively utilized to meet the demands of a growing world population [2]. For example, plastic films are used for mulching, a technique involving covering soil to optimize the microclimate and retaining humidity and heat for crop growth [2] [8]. This practice has revolutionized agriculture by preventing soil erosion and weed development and increasing crop yield [9] [10]. The global market for agricultural plastic is currently at 6.6 Mt per year, with expectations of a 64% increase by 2030 [5] [10] [11]. Plastic pollution in agroecosystems is estimated to be 1.15 - 2.41 Mt yearly [12].

Larger fragments of plastics, known as macro-plastics (with an average particle size of diameter, dp, exceeding 25 mm) or meso-plastics (dp ranging from 5 to 25 mm), undergo a gradual breakdown when subjected to environmental weathering factors such as ultraviolet light, hydrolysis, and wind [5] [13] [14]. The degradation methods include physical degradation (e.g., mechanical, thermal, and photodegradation), chemical degradation (e.g., oxidation, hydrolysis, and chemical catalysis), and biological degradation (e.g., microbial, enzymatic, and plant-assisted biodegradation) [3] [5] [7] [10] [11]. The degradation process often leads to the formation of smaller fragments and particles, specifically micro-plastics (MPs, dp measuring from 1 to 5000 μm) and nano-plastics (NPs, dp measuring from 1 to 1000 nm) [5] [14] [15]. There are two categories of MPs and NPs: primary and secondary. In agricultural soils, primary sources encompass sewage sludge, coated fertilizers, agrochemicals, seed casings, and row covers [3] [5] [7]. Conversely, secondary sources involve the degradation and improper management of macro-plastics, such as mulching, greenhouse film, plastic bottles and bags, and waste plastics [5] [16] [17].

The introduction of MPs and NPs into agricultural fields raises significant concerns due to their ecotoxicity to soil organisms, including vital contributors such as earthworms [18]. The escalating environmental pollution severely threatens agroecosystems [19]-[21] that provide food, fiber, fuel, biodiversity, soil fertility and nutrient cycling, and carbon sequestration. Given the pervasive nature, varied sizes, diverse sources, different chemical compositions, and numerous interactions of MPs and NPs with biological and abiotic factors, these particles exert both direct and indirect impacts on the agroecosystems [22]. NPs, in particular, are considered potentially more hazardous than MPs, as they can permeate biological membranes [7] [23]. Recognizing the analogous impacts of MPs and NPs on soil properties and plant traits, we combine them into a unified category termed MNPs. Recent studies reveal that MNPs significantly alter the physical and chemical properties of soil, affecting the distribution of water-stable aggregates, bulk

density, porosity, water retention capacity, and pH value [17] [22]. Moreover, MNPs affect soil organic carbon and nutrients, disrupting the C, N and P cycles, influencing microbial communities, and impacting soil greenhouse gas emissions [2] [17] [24]. These particles also impact soil fauna by disturbing their digestion processes, inducing oxidative stress, and causing physical changes such as alterations in morphological characteristics, growth rate, mortality, and behavior [22]. Furthermore, MNPs alter the quality of agricultural products, as well as plant photosynthesis of plants, growth, biomass production, and crop yield [17]. As research on MNPs in agriculture advances rapidly, there is an essential need to synthesize recent findings and propose future research directions [25].

This mini-review aims to comprehensively evaluate current research on MNPs in the agroecosystems, synthesizing insights from recent studies and reviews. The primary objective is to provide an updated overview of their impact on soil properties and plant production. The key goals include: 1) assessing the effects of MNPs on soil physicochemical properties, microorganisms, soil organic carbon, nutrient cycling, greenhouse gas emissions, and soil fauna; 2) evaluating the impacts of MNPs on plant uptake, seed germination, ecophysiology, growth, and production; and 3) identifying knowledge gaps that warrant further investigation concerning the influences of MNPs on agroecosystems.

2. Impacts of MNPs on Soil Properties

The impacts of MNPs on agricultural soils are diverse and complex [26]. Soil physicochemical properties, such as soil aggregation ability, bulk density, and water retention capacity, are significantly affected by the dispersion of MNPs (Figure 1) [27]-[29]. MNPs in the soil may also disrupt soil microclimate, alter the structure and functioning of the microbial community, and affect ground-dwelling soil fauna, leading to potential adverse consequences for soil organic carbon storage, nutrient cycling, and greenhouse gas emissions in agroecosystems [29]-[31].

2.1. Soil Physicochemical Properties

Numerous studies have reported significant impacts of MNPs on various soil physicochemical properties, including aggregate stability, bulk density, porosity, specific surface area, pH, cation exchange capacity (CEC), and hydraulic characteristics [25] [26] [29] [32]. For example, Qiu *et al.* [33] reported MNPs increase soil porosity and aeration while reducing soil bulk density. Similarly, Ren *et al.* [32] noted a reduction in soil bulk density and an improvement in soil water holding capacity due to MNPs. Conducting a meta-analysis of 868 data points from 55 experimental groups, Qiu *et al.* [33] demonstrated a significant inhibitory effect of MNPs on soil aggregate stability. MNPs were found to bind to soil aggregates, diminishing the aggregation capacity of organic matter and influencing the formation and stability of the soil aggregates. Verma *et al.* [29] highlighted MNPs' influence on soil pH, emphasizing the role of exposure duration in inducing pH changes, which can be modulated by soil aeration and porosity through altering

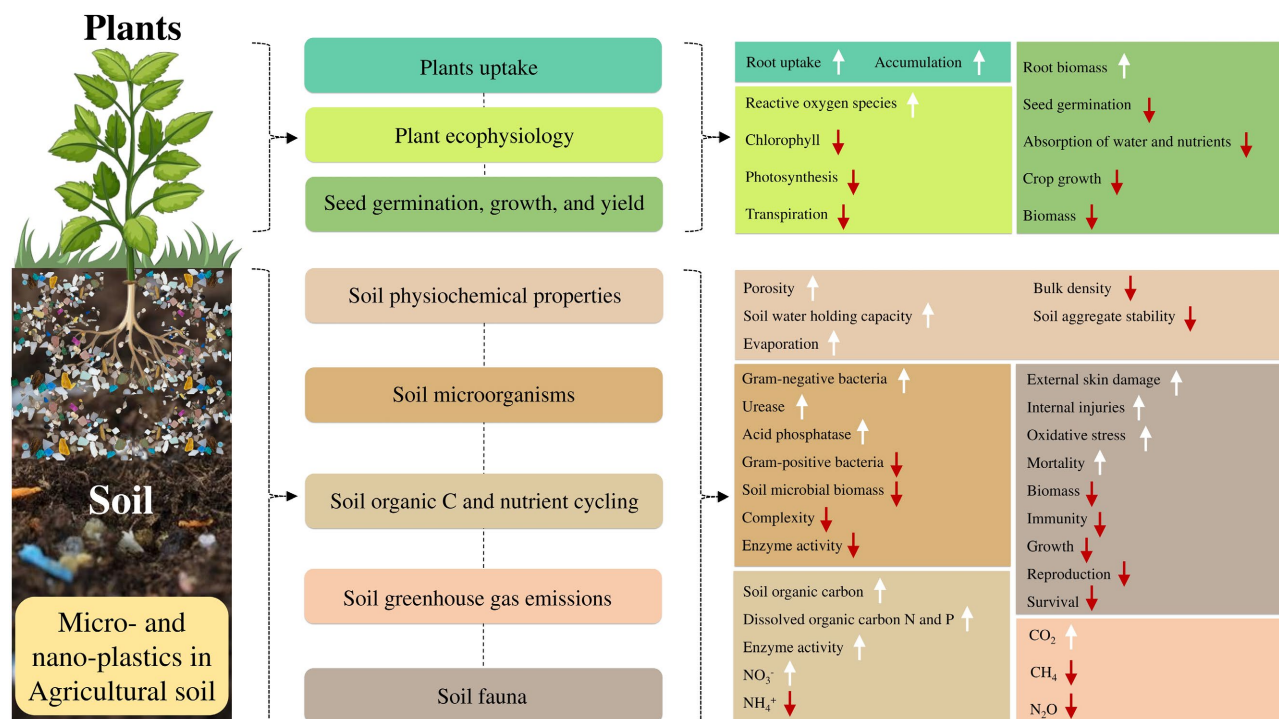


Figure 1. Impacts of micro- and nano-plastics on soil and plant properties. The upper arrow indicates increased and down arrow indicates reduced by micro- and nano-plastics.

microbial activities and gas exchange processes (e.g., CO₂ production). Soil pH could be enhanced initially but decreased over time due to leaching of chemical additives in MNPs into ground and conversion of organic N into NH₄⁺.

Additionally, de Souza Machado *et al.* [34] observe an increase in water-holding capacity, though some studies indicated a multifaceted impact of MNPs on water holding capacity, dependent on factors such as shape, type, size, and quantity of MNPs. Tang *et al.* [26] also found that MNPs could alter the physical properties of agricultural soils, leading to variations in water-stable aggregates—either decreasing or increasing, based on the presence of organic materials. Shafea *et al.* [31] highlighted the expected alteration in soil wettability as an effect of MNPs, contingent on their chemical and physical properties, including hydrophobic surfaces, size, and shape. Furthermore, Ren *et al.* [32] reported diverse effects on soil evaporation rates, with some types of MNPs increasing soil evaporation rates, while others exhibited a slight increase. MNPs in agricultural soil induce changes in soil texture, structure, bulk density, and increase soil water evaporation [28]. Notably, the accelerated rate of soil water evaporation caused by MNPs could adversely affect soil microorganism and plant performance [29] [35]. Some other studies also reported different impacts on soil physicochemical properties (Table 1). Overall, these findings underscore the intricate relationship between MNPs and soil properties in agroecosystems, emphasizing the imperative for further research to comprehensively understand the consequences of MNPs on soil health and agricultural productivity.

Table 1. The effects of micro- and nano-plastics on soil physicochemical properties.

Soil Property/ Soil Type	Test Index	Effects	Concentration	Polymer	Influencing Factor	Reference
Vertisol Entisol Alfisol	Bulk density	Negative	0.5%w/w	PET	In the Vertisol, contamination with polyester microplastic fibers resulted in a decrease in soil bulk density and an increase in air capacity; on the contrary, in the other two studied soils (Entisol, Alfisol), no variation in soil bulk density was observed.	[88]
Vertisol		Non-significant	0, 0.1%, 0.3% w/w	PET	The field and pot experiments showed that polyester microfibrils cannot alter soil bulk density.	[89]
Nitisol		Negative	0.05%, 0.1%, 0.4% w/w		All tested particles affected soil bulk density, and the polyester fibers were observed to cause a concentration dependent response. These shifts in bulk density might be partially explained by the fact that plastics are often less dense than many natural minerals predominant in soils.	[90]
Loamy sand		Negative	0.4% w/w	PES	Under drought conditions, the decrease of soil bulk density due to microfibrils led to a better performance of <i>Hieracium</i> , which may in turn have had a detrimental allelopathic influence on <i>Festuca</i> .	[91]
Sandy		Negative	0.5%, 1%, 2% w/w	PE	The bulk density, porosity, saturated hydraulic conductivity, field capacity and soil water repellency were altered significantly in the presence of the four kinds of plastic debris, while pH, electrical conductivity and aggregate stability were not substantially affected.	[92]
Clay		Negative	0, 0.1%, 0.3%, 1.0% w/w	PET	Soil bulk density in the 1.0% PMF treatment was less ($p < 0.05$) than that in the 0%, 0.1% and 0.3% PMF treatments, while soil bulk densities among the 0%, 0.1% and 0.3% PMF treatments did not differ significantly. This result suggested that there should be a tipping-point of microplastics level in soils, when the level of microplastics in soils exceeds the threshold, soil bulk density would decrease.	[93]
		Positive	/	PA, PES, PP, PET	PP increased soil bulk density in the rhizosphere (probability > 97.5%).	[34]
Vertisol, Entisol, Alfisol	Soil aggregate stability	Positive	0.5% w/w	PET	The addition of MP interfered with the formation of macro-aggregates by altering the binding mechanism in the soil and by reducing the aggregation capacity of organic matter.	[93]
Loamy sand		Negative	0, 0.1%, 0.2%, 0.3%, 0.4% w/w	MIXED	Soil aggregation decreased by ~29% with fibers, ~25% with films, ~20% with foams, and ~27% with fragments in comparison to the control without microplastics.	[91]
Nitisol		Positive	0, 0.1%, 0.3% w/w	PET	The increased macroaggregate formation under the PMF treatments occurred only in the pot experiment but not in the field experiment. This may due in part to the fine soil used in the pot experiment.	[94]

Continued

Loamy sand		Negative	0, 0.4% w/w	PA	Plastic microfibers might eliminate the positive effect of temperature on soil aggregation and could even lead to greater losses in the percentage of WSA. [95]
Sandy silt		Negative	0, 0.1% w/w	PE	The size distribution of water stable soil aggregates was altered when microplastics were present, suggesting potential alterations of soil stability. [96]
Loamy sand		Negative	0, 0.1% w/w	PES	Polyester microfibers have the potential to alter soil structure, and these effects are at least partially mediated by soil biota.
Loamy		Negative	0.05%, 0.1%, 0.4% w/w		Soils contaminated with polyester fibers presented a significant decrease in water stable aggregates with increasing polyester concentrations, considering qualitative exposure metrics soils containing polyacrylic fibers displayed a significant decrease in water stable aggregates. [97]
Loessial	FDase	Positive	7%, 28% w/w	PVC	FDase activity decreased quickly in the first three days and increased between days 3 - 7. FDase activity remained stable between days 7 and 30. [98]
Loamy		Negative	0, 1%, 5% w/w	PVC, PE	Both PE and PVC addition inhibited fluorescein diacetate hydrolase activity and stimulated urease and acid phosphatase activities and declined the richness and diversity of the bacterial communities. More severe effects were observed in the PE treated soils compared to the PVC treated soils generally.
Loamy and sandy		Negative	2 mm × 2 mm	PP, PE	FDA activities in soils amended with fibrous PP decreased by 29% and 38% on day 14 and 29, respectively.

Note: PET (Polyethylene Terephthalate), PES (Polyester). PE (Polyethylene), PA (Polyamide), PP (Polypropylene, PVC (Polyvinyl Chloride), FDase (Fluorescein Diacetate Hydrolase Activity), MP (Microplastics), PMF (Polyester Microfiber), WSA (Water-Stable Aggregates), w/w (weight/ weight).

2.2. Soil Microorganisms

The impacts of MNPs on soil microorganisms are intricate and diverse, influencing structure and functioning of soil microbial communities, enzyme activities, and critical ecosystem processes such as element transformation, nutrient cycling, and the decomposition of soil organic matter [32] [33]. Astner *et al.* and Okeke *et al.* [5] [12] highlighted the pivotal roles of soil microorganisms, encompassing bacteria, archaea, and fungi, in various soil functions, including soil organic matter decomposition, stabilization, mediation of soil enzyme activities, and nutrient cycling. The type and concentration of MNPs exert an influence on soil microbes, leading to alteration in the richness, diversity, and functioning of microbial communities [26] [32]. Especially, MNPs increase the population of Gram-negative bacteria while decreasing Gram-positive bacterial populations. They also induce changes in arbuscular mycorrhizal fungi (AMF), impacting colonization and

composition, although the overall impact of MNPs on AMF remains inconclusive. Verma *et al.* [29] reported a significant decrease in the variety and complexity of microbial communities due to MNPs, with effects on microbial populations varying with MNP concentrations, exposure duration, and soil characteristics. MNPs may also influence microbial functional genes associated with carbon degradation, such as those encoding cellulose and chitin degradation [22] [36]. Moreover, the effects of MNPs on soil enzymes are contingent on the type of MNPs [32]. Some types enhance soil fluorescein diacetate hydrolase (FDAse) activity, while other types inhibit FDAse activity but promote the activity of urease and acid phosphatase. MNPs significantly affect soil phosphatase activity by both promoting effect and inhibitory effect on FDAse activity, depending on the type of MNPs [31]. A positive correlation is observed between soil MNP concentration, soil phosphatase, and FDAse activity, with lower MP concentrations showing no significant effect on enzyme activity [33]. Additionally, MNPs are reported to decrease general microbial activity, as measured by fluorescein diacetate hydrolysis activity [5]. High concentrations of MNPs are associated with a reduction in soil microbial biomass, enzyme activities, and functional diversity [7]. MNPs impact bacterial community composition, with different communities associated with different types of MNPs [31]. They affect microbial NH_4^+ and NO_3^- metabolism and enhance degradative activities by soil microbes. MNPs also disturb mineralization rates and affect root-colonizing symbionts [28]. Notably, MNPs contribute to a reduction in the activity of two key enzymes involved in nitrogen cycling: leucine aminopeptidase and N-acetyl-glucosaminidase [12].

To summarize, the impacts of MNPs on soil microorganisms are complex and multifaceted, affecting enzyme activities, microbial community diversity, and various microbial processes. Changes in soil physicochemical properties, such as alterations in porosity, may influence oxygen flows and impact the distribution of aerobic and anaerobic microorganisms. These alterations in microbial communities can have cascading effects on soil functions, including nutrient cycling and organic matter decomposition. The effects on soil microbial community diversity also vary based on microbial species, soil properties, the type and concentration of MPs, and environmental conditions. Further research is crucial to fully understand the mechanisms and long-term consequences of MNP interactions with soil microorganisms.

2.3. Soil Organic Carbon and Nutrient Cycling

The impact of MNPs on soil organic carbon (SOC) is multi-dimensional. Comprising approximately 80% carbon, MNPs can function as a substantial carbon source for ecosystems, accumulating over time and contributing to the increased SOC storage [12] [33] [37] [38]. Although the carbon content derived from MNPs may constitute a relatively small fraction of total SOC, these carbons are resistant to microbial decay and could lead to a notable accumulation over extended periods [12] [39]. MNPs, particularly at high concentration, significantly elevate

concentrations of dissolved organic matter (DOM), dissolved organic nitrogen (DON), dissolved organic phosphorus (DOP), PO_4^{3-} , NO_3^- , humus, and fulvic acid [32] [33] [40]. Furthermore, MNPs stimulate FDAse activity, enhance nutrient content, promote the accumulation of humic acids, and release soil nutrients, thereby affecting soil enzyme activity and soluble nutrient accumulation [41]. MNPs also indirectly impact soil microbial community structure, influencing the absorption potential of exogenous carbohydrates and amino acids [33] [42]. The organic-organic persistence hypothesis suggests that MNPs may induce a negative priming effect by diluting and adsorbing soil available DOC onto their plastic surfaces [12] [38].

The nitrogen cycle, crucial for ecosystem productivity and stability, undergoes significant alternations due to MNPs [12] [22] [43] [44]. MNPs reduce soil organic matter (SOM) and inorganic N (NH_4^+ and NO_3^-) [22] and tend to accumulate higher quantities of dissolved carbon, nitrogen, and phosphorus in the soil solution, driven by increased extracellular enzyme activity [12] [40]. MNPs also influence the hydrolysis of nitrogen, as demonstrated by elevated urease activity [12] [45]. Additionally, MNPs significantly increase soil C:N ratio and enhance nutrient content in DOM, including humic and fulvic acids [24] [29]. This improved DOM quality stimulates soil enzymatic activity, potentially enhancing nutrient availability for plants [25] [40]. Nevertheless, MNPs can also reduce soil fertility, alter microbial community functions, and disrupt the C, N and P cycles [46] [47]. Different studies present varying outcomes, with some indicating a reduction in soil NO_3^- -N (10% - 13%) and phosphorus (approx. 30%) contents [26] [48], while others suggest better nutrient retention and reduced nitrate leaching [49]. The influence of MNPs on soil carbon and nitrogen cycles varies depending on factors such as MNP types, concentrations, sizes, exposure times, soil pH, and SOM content [50]. Different MNPs also exhibit varying effects on soil enzymatic properties and microbial activity. Consequently, more studies are needed to unravel the mechanistic pathways through which MNPs impact soil carbon and nitrogen cycling.

2.4. Soil Greenhouse Gas Emissions

To comprehensively understand the direct impact of MNPs on climate change, investigations have delved into their influence on greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission [12]. Studies by Zhao *et al.* and Lozano and Rillig [51] [52] affirm that MNPs contribute to an increase in soil respiration. MNPs have been observed to create peak soil respiration several days after introduction [53] [54]. The interaction between carbon and nutrient cycling undergoes alteration due to MNPs, resulting in substantial increases in CO_2 fluxes [12] [41] [55]. Gao *et al.* [56] reported a 28.67% increase in soil CO_2 emission attributable to MNPs. Daily CO_2 flux in soil treated with MNPs was seven to eight times higher than that in the control [7] [22]. Similar enhancements of CO_2 emissions have been reported in other studies [22] [54]

[57] [58].

The increase in soil CO₂ emission could be due to that MNPs create an environment conducive to both aerobic and anaerobic metabolisms of microorganisms that contributed to CO₂ production [50] [54]. Soil microbial communities, integral to carbon and nitrogen cycles, play a pivotal role in this process, as MNPs enhance soil enzyme activity, promoting soil respiration [22] [59]. First, soil MNPs can increase soil enzymatic activities, such as glucosidase, cellobiohydrolase, and xylosidase, which in turn foster soil CO₂ emissions [54] [60]. Wang *et al.* [58] reveal that these enzymes decompose dense organic compounds, including cellulose and xylan, into smaller compounds that are more easily absorbed by soil microorganisms, leading to the release of CO₂ into the atmosphere. Additionally, MNPs contribute to the abundance of carbon-cycling microbes and their functional genes (e.g., those encoding hemicellulose (*abfA*) and lignin (*mnp*) degradation), which stimulate CO₂ emissions [54] [60]. Second, MNPs enhance soil aeration by improving soil porosity and air circulation, which reduce soil bulk density and decrease water-stable aggregates—factors that collectively promote soil CO₂ emission [38] [54] [61]. Kim *et al.* [57] also demonstrated that MNPs expand soil pores, thereby facilitating the release of CO₂ produced during soil respiration.

Much like the direct impact on CO₂ emissions, the increase of CH₄ emissions under MNPs can be attributed to at least two specific mechanisms: 1) Soil MNPs induce the bacterial degradation of the MNP material, particularly by microorganisms such as *Burkholderia sp.*, leading to the release of CH₄ from the soil [54] [61]. Li *et al.* [62] reported that MNPs stimulate *Burkholderia sp.* to degrade MNPs and subsequently release CH₄. However, the ability of soil bacteria and methanogens to degrade MNPs and emit CH₄ is contingent on the type of MNPs, as some MNPs may reduce CH₄ emissions from the soil [54]. For instance, Wang *et al.* [58] found that MNPs can decrease CH₄ emissions by inducing oxidative stress, damaging microbial cells, and inhibiting microbial activity, thereby suppressing methanogenesis in the microbial community responsible for CH₄ emissions. 2) MNPs increase soil microporosity and aeration, thereby promoting CH₄ production during soil carbon decomposition and elevating CH₄ emissions into the atmosphere [49] [54]. Given the varying impact of different types of MNPs on CH₄ emissions, further research is necessary to explore this complex relationship.

The impact of MNPs on soil N₂O emissions is multifaceted and involves various mechanisms. MNPs exert a diminishing effect on N₂O emissions, altering the abundance of microbes responsible for N₂O emission [54] [58]. Rillig *et al.* [38] provided unequivocal evidence that MNPs influence the dynamics and strength of N₂O emission. They found that MNPs might mitigate the enhancement of N₂O emissions caused by extensive nitrogen fertilization. In a meta-analysis, Su *et al.* [63] synthesized 60 published works, revealing that MNPs increase N₂O emission by 140.6%, nitrate reductase activities by 4.8%, denitrification rates by 17.8%, and the number of genes responsible for denitrification activity rose by 10.6%. The

increase in soil N₂O emissions by MNPs may be attributed to two main reasons [54]. First, MNPs enhance the abundance of soil nitrification functional genes, leading to increased NH₄⁺ and NO₃⁻ contents and N₂O emissions [54] [56] [63]. Second, soil MNPs increase N₂O emission by boosting the abundance of the functional gene *nirK*, which encodes nitrite reductase and promotes the nitrite reduction process during denitrification [64]. Functional microorganisms with the *amoA* marker gene are crucial in the denitrification process [36] [63], while ammonium-oxidizing microorganisms, also with the *amoA* marker gene, play a key role in the initial step of the nitrification process [54]. Changes in the copy numbers of *amoA* and *nirS* caused by MNPs are found to be similar to changes in the amounts of NH₄⁺ and NO₃⁻ [42] [63]. However, the different reactions of these genes make it challenging to discern the precise impact on N₂O emissions, as demonstrated by various meta-analyses [56] [61]. Su *et al.* [63] also showed that MNPs could increase N₂O emissions, likely due to enhanced denitrification.

2.5. Soil Fauna

MNPs in agroecosystems exert substantial impacts on soil fauna, resulting in potential physical and chemical damages [12]. Soil faunas are susceptible to the effects of MNPs, which can persist in their intestines, influencing crucial intestinal microbiota responsible for organic matter utilization and soil element cycling. Due to their small size, MNP particles are likely ingested by soil meso- and microfauna, serving as a potential entry point for MNPs into ground-dwelling animals [25]. MNPs can inflict physical and biochemical harm on soil fauna, leading to external skin damage, internal injuries, and disruption of lipid, osmotic, and carbohydrate metabolisms. Moreover, the detrimental effects are not solely due to MNPs but also involve poisonous substances adsorbed on MNPs, such as persistent organic pollutants (POPs) [25]. For instance, MNPs impact energy distribution, induce changes in intestinal microbial communities, cause oxidative stress, and influence various behaviors in soil-dwelling animals [65].

The impact of MNPs on soil fauna varies based on concentration, emphasizing the importance of accurately quantifying MNPs in soils [22]. Earthworms, nematodes, land snails, and soil microarthropods are studied groups, each exhibiting distinct responses to MNP contamination [25]. Responses include changes in behavior, mobility, feeding, growth, reproduction rates, and alterations in gut microbial communities. Nematodes, collembolans, earthworms, and termites show various responses to MNPs exposure, such as survival inhibition, growth alterations, and histological changes [22]. Additionally, MNPs adversely affect soil microfauna, impacting motility, growth, metabolism, reproduction, mortality, and gut microbiome [5].

The dispersion of MNPs to deeper soil layers affects earthworm health, contributing to groundwater contamination [28]. MNPs can cause histopathological damage and immune system responses, with some MNPs reducing earthworm biomass and others inducing oxidative stress and energy metabolism changes [12]

[65]. MNPs induce oxidative stress, neurotoxicity, cellular damage, impaired immunity, inhibited growth, and exoskeletal damage in earthworms [26]. High concentrations of MNPs also result in higher mortality and retarded growth of earthworms, impacting soil aeration, structure, and nutrient recycling.

Different MNPs affect nematodes, springtails, and microarthropods, leading to decreased mobility, altered reproduction rates, and changes in bacterial diversity in their gut [65]. Microarthropods like springtails and mites can transport MNPs through soil via locomotion, and MNPs reduce oxidative stress ability in snails, leading to lipid peroxidation and gastrointestinal injury [22]. High concentrations of MNPs contribute to significant toxicological effects on soil microfauna, affecting reproduction and survival [5]. Springtails' avoidance rates are increased, reproduction is suppressed, and bacterial diversity in their gut is reduced due to MNPs, while MNPs also interfere with mineral metabolisms, growth, and reproduction [26]. Soil-dwelling vertebrates like mice exhibit metabolic and digestive system effects due to MNP exposure [25]. Different particle sizes of MNPs induce gut microbiota dysbiosis, intestinal barrier dysfunction, and metabolic disorders in mice, emphasizing the diverse impacts on different soil fauna [12]. Briefly put, MNPs exert complex and sometimes detrimental impacts on various soil fauna, affecting behaviors, reproductive rates, microbial communities, and overall soil ecosystem health.

3. Impacts of MNPs on Terrestrial Plants

Plants intricately interact with soil physicochemical properties, microbial communities, nutrient content, and fauna. These soil attributes, in turn, play pivotal roles in regulating plant growth, development, and resistance against pathogens, ultimately influencing productivity and yield (Figure 1) [66] [67]. Given the profound effects of MNPs on soil physical, chemical, and biological characteristics, they can potentially exert detrimental effects on crop ecophysiology, growth, and overall productivity [26]. MNPs have been shown to exhibit direct toxicity towards root structures, leading to decreased soil fertility and nutrient depletion, thereby impairing nutrient uptake and plant growth [28]. Moreover, the impacts of MNPs on crops in agricultural soils manifests in various ways, although some effects remain inconclusive [26]. From the standpoint of agricultural production, MNPs generally have a negative influence on crop productivity [16] [68] [69], although certain instances of beneficial effects on plants growth have also been documented [25].

3.1. Plant Uptake

Plant species exhibit variability in their uptake, translocation, and accumulation of MNPs, owing to a spectrum of anatomical and physiological distinctions [7]. Unlike NPs, MPs typically struggle to penetrate plant tissues directly, and due to that, they are frequently unable to enter plant tissues directly as their substantial size hinders them from traversing plant cell walls [12]. Nonetheless, studies have

observed that vascular plants can absorb and retain larger quantities of MNPs [12] [70]. The growth of plants may be impacted by the direct absorption of MNPs from soils, followed by transportation through the entire plant via the vascular system [1] [25]. Furthermore, miniscule plastic particles may even infiltrate plants through foliar uptake through stomata [25] [71]. Depending on their size and composition, MNPs can infiltrate seeds, roots, stems, leaves, fruits, and plant cells. Bandmann *et al.* [72] demonstrated the uptake of MNPs by plants, observing fluorescent polystyrene (PS) nanoparticles being absorbed by tobacco. Recent research has revealed that numerous plant species are capable of absorbing MNPs of various sizes and types [12]. Various mechanisms have been postulated for the root uptake of MNPs, particularly NPs: 1) transport through intracellular pore space via the apoplastic pathway (passive diffusion), 2) movement into cells through plasmodesmata via the symplastic pathway (osmotic uptake), 3) incorporation into cells through membrane deformation via endocytosis pathway, and 4) entry through cracks in cell structures at lateral roots emergence sites (crack-entry pathway) [5] [30] [73].

3.2. Plant Ecophysiology

MNPs have been shown to exert significant effects on the photosynthetic and antioxidant systems of plants [22] [74]. Chlorophyll, as a pivotal component in plant photosynthesis, varies in chlorophyll a/b values under adverse conditions, often serving as a mechanism of self-protection for plants against environmental stressors [22] [75]. Notably, MNPs have been found to negatively influence chlorophyll development in plant leaves, thereby, potentially impeding the photosynthesis process [9] [12] [75]. Sun *et al.* [42] corroborate these findings, demonstrating that MNPs can reduce photosynthetic efficiency and chlorophyll content in various plant species, including acorn squash and maize. Jin *et al.* [22] found that MNPs decreased photosynthesis, respiration, and transpiration of crops by 9.1%, 34.44%, and 14.74%, respectively, whereas growth rate and vigor were not significantly affected by MNPs. Moreover, MNPs have been implicated in affecting biochemical enzymes, the antioxidant system, electrolyte leakage, and inducing oxidative damage in plants [71] [29] [42]. For example, Lian *et al.* [27] found that MNPs significantly disrupt the photosynthetic system of *Arabidopsis* and further compounded by the interference caused by degradation products of adipic acid, phthalic acid, and butanediol [12]. The decreased chlorophyll production might be caused by the accumulation of reactive oxygen species (ROS) in chloroplasts [12]. Additionally, MNPs have been shown to inhibit plant growth, alter root traits, reduce root biomass, interfere with photosynthesis, and induce genotoxicity [29] [76] [77].

Furthermore, the specific impacts of MNPs on terrestrial plants vary depending on the plant species and the type of MNPs involved [12]. While MNPs have been observed to decrease photosynthetic pigment content in certain plants like lettuce and common beans [22], they have been found to increase photosynthetic

pigments in alfalfa [22]. Dose-dependent hormesis effects have also been noted, with wheat's photosynthetic rate showing enhancement at low doses but inhibition at higher doses [12]. Additionally, MNPs influence metabolic pathways in terrestrial plants, with metabolite concentrations decreasing with increasing exposure doses in rice [12]. MNPs induce oxidative bursts and cell damage in rice roots and Arabidopsis, as well as increase reactive oxygen species levels and oxidative stress responses in garden cress [5]. Overall, adsorption and accumulation of MNPs by plants in soil can impede plant growth, disrupt photosynthesis, and trigger various physiological, biochemical, and genotoxic effects [33] [34] [71].

3.3. Plant Seed Germination, Growth, Production, and Yield

Seed germination may be impeded by MNPs adhering to the surface of seeds and physically obstructing pores, and thereby resulting in delayed germination [12] [78]. Brief exposure to MNPs can significantly reduce seed germination rates. This decreased germination rate has been attributed to physical obstruction of the seed pores and root hairs by MNPs [12]. MNPs have been observed to inhibit both wheat seed germination and wheat bud length at low concentrations while promoting germination at high concentrations [65]. Although MNPs do not affect the germination rate of mung bean seeds, they significantly reduce the root length, bud length, and fresh weight of the seedlings [12] [41]. Furthermore, MNPs can attach to the surface of seeds and seedling roots, inhibiting water absorption and respiration, thus influencing seed and bud development [12] [27] [41] [79].

MNPs can be absorbed by plants through their roots and subsequently transported to other parts of the plant, potentially influencing plant development [19] [65] [80]. MNPs have been observed to bind to plant roots, altering their characteristics and impeding the absorption of water and nutrients [29]. Studies indicate that MNPs with smaller particle sizes tend to have more pronounced negative effects on plants [8] [29]. Through mechanisms such as modifying the state of cell membranes and intracellular molecules and inducing oxidative stress, MNPs can penetrate plant tissues and cause damage [29]. MNPs also induce notable changes in root traits, such as root length, root mean diameter, total root area, and root tissue density, along with above-ground biomass, with variations observed among different food crops [22]. Furthermore, MNPs may accumulate in the interspace tissues of plant roots and migrate to other parts such as leaves, stems, flowers, and fruits [29]. Interestingly, research by Meng *et al.* [81] revealed that the addition of certain MNPs to sandy soil does not affect the shoot, root, or bean biomass of common bean while another type of MNPs dramatically reduces bean shoot, root, and biomass. Similarly, Tong *et al.* [82] found an increase in the above-ground biomass but a decrease in the below-ground rice biomass [5]. Several other studies found that MNPs improve plant nutrient content and water supply and increase the root biomass [33] [34] [39] [49]. Using a meta-analysis, Qiu *et al.* [33] revealed that MNPs have a significantly promoting effect on plant root biomass.

Soil MNPs have been found to directly damage crop growth at early stages by

physical blockage of the pores in the in roots [25] [83]. MNPs can affect wheat plant growth throughout its vegetation and reproduction growth stages [24] [65]. Additionally, MNPs can significantly alter spring onion biomass, tissue elemental composition, and increase roots and bulb biomass [5] [34]. While some studies show increased short growth in crops like carrots [49], others report limitations in biomass accumulation in maize, decrease shoot growth, and reduce overall biomass of *Arabidopsis* [28] [32]. Plants under MNPs also grew smaller and have poor nutritional value [28] [42]. Furthermore, MNPs can negatively affect crop production by delaying fruit production and reducing fruit, shoot, and root indexes [28] [31] [50]. But Qi *et al.* [24] showed that MNPs enhance wheat growth, increase plant carbon and nitrogen contents, and biomass. The effects of MNPs on crop traits can vary depending on factors such as MNP type, concentration, size, exposure time, soil pH, and SOM content [50]. Different results have been found, for example, exposure to 1% and 1% - 5% MNPs reduces crop morphological traits by 4.83% - 6.25%, whereas exposure to 5% - 10% MNPs shows no significant effect on crop morphological traits. In general, MNPs tend to decrease commonly measured agronomic parameters such as plant height, biomass, root length, diameter, and seed germination rate [25]. However, the specific impacts may vary depending on the plant species and environmental conditions [76] [84].

4. Conclusion and Future Research

The global attention towards the escalating use of plastics and the consequential impacts of their byproducts, MNPs, on soil ecosystems is evident in research [7] [54]. This comprehensive review systematically summarized the impacts and potential mechanisms underlying the influence of MNPs on soil properties, biota, greenhouse gas emissions, and plant growth and production. The findings underscore the capacity of MNPs to manipulate critical biological processes, influence microbial activity, enhance greenhouse gas emissions from soil, inflict harm upon soil fauna, and restrain plant growth (Figure 1) [54]. This review also identifies gaps in knowledge from various studies on the effects of MNPs on agroecosystems, emphasizing the need for further investigation and research. Researchers need to pay additional attention and address the following issues as highlighted in recent literature [25] [65].

First, future research needs to employ realistic research conditions to mirror actual environmental scenarios, as numerous studies have illustrated those factors such as particle sizes, concentrations, and field conditions, including soil types, agroecosystems, or ecoregions, could significantly influence the impacts of MNPs. To ensure meaningful and applicable research, it is crucial to set research conditions closer to the real natural settings. Factors such as particle size, concentration, and exposure events of MNPs in soil under natural conditions should be simulated, and long-term simulation experiments of MNPs in outdoor environments using standardized methodology are recommended to facilitate the exploration of meaningful insights [12] [22] [25].

Second, more studies should be conducted to expand geographical scope. The research history in this domain is relatively short, and most studies are recent and concentrated in a few countries, notably China [25]. The importance of expanding the geographical scope and diversifying study areas is underscored to gain a more comprehensive understanding of the impacts of MNPs on agroecosystems [25]. There is a recognized necessity to extend research efforts, particularly in examining the long-term impacts of MNPs under standard agricultural practices, signifying the importance of broadening both temporal and spatial perspectives [10].

Lastly, contradictory results need to be solved and more research should be conducted to fill data gaps. The limited number of studies, particularly on the impacts of MNPs on plants and soil, has resulted in considerable uncertainty [7]. Previous studies have reported conflicting results. For example, Wang *et al.* and Zhang *et al.* [58] [61] showed that MNPs triggered a reduction rather than an increase in greenhouse gas emissions from soils reported in some other studies. Future study should include various types of agricultural soils, incorporating different cropping systems and varying climates, to assess the impacts of MNPs on soil and plants, and whether soil MNPs may contribute to climate change mitigation by promoting a decrease in soil greenhouse gas emissions [12] [54].

The study of the effects of MNPs on soil and plant productivity is not only crucial for understanding ecological impacts but also intersects with broader economic considerations related to plastics or MNPs. As plastic production continues to rise globally, concerns over the environmental fate of plastic waste and its breakdown products, like MNPs, have prompted regulatory scrutiny and industry responses [1]. Efforts to mitigate plastic pollution encompass measures such as recycling, waste management strategies, and the development of biodegradable alternatives [85]. However, challenges persist in effectively managing plastic waste throughout its lifecycle, from production and consumption to disposal and environmental impact [86] [87]. Addressing these challenges requires a holistic approach that integrates scientific research, policy interventions, and innovative technologies to minimize the ecological footprint of plastics and MNPs. Moreover, understanding the economic implications of plastic pollution and its associated environmental and health costs can inform decision-making processes and drive sustainable solutions across the plastic applications.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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