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Microplastics in Soil: Uncovering Their Hidden Chemical Implications

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ABSTRACT: This review synthesizes findings from over 100 recent studies to examine the multifaceted impacts of microplastics on soil health. Microplastics affect soil nutrient dynamics through mechanisms such as chemical leaching, nutrient adsorption, microbial shifts, and physical alterations in soil structure. Their influence varies by polymer type, particle morphology, concentration, and environmental conditions. While some microplastics may enhance nutrient retention, many contribute to nitrogen and phosphorus depletion, undermining soil fertility and agricultural productivity. Microplastics also modify soil pH in inconsistent ways, either increasing or decreasing it, thereby disrupting nutrient availability and microbial functions. The effects of microplastics on soil organic matter are equally complex. Biodegradable microplastics can stimulate microbial respiration and increase dissolved organic carbon, but they may also destabilize carbon pools, depending on the environmental context and soil conditions. Additionally, microplastics act as vectors or sinks for organic pollutants and heavy metals through diverse sorption–desorption mechanisms. Their interactions with contaminants such as pesticides, pharmaceuticals, and metals like lead, cadmium, and zinc are influenced by polymer type, surface aging, and coexisting soil constituents. Microplastics not only impair nutrient cycling but also alter microbial community composition, enzymatic activity, and pollutant degradation, raising concerns about the function of soil ecosystems and food safety. Future research should prioritize long-term, multi-factorial experiments under realistic environmental conditions. Key areas include disentangling the effects of conventional versus biodegradable microplastics, developing mechanistic models of pollutant interactions, and assessing the role of environmental parameters in mediating metal binding. Such efforts are vital for accurate risk assessments and informed mitigation strategies in terrestrial ecosystems.

KEYWORDS: Chemical leaching; metals; organic pollutants; pollutant interactions; soil nutrient; soil organic matter.

1. Introduction

Plastics play a significant role in everyday life and industrial processes due to their affordability, stability, and ease of transport, along with various other benefits [1]. In 2024, approximately 220 million tons of plastic waste were generated globally, averaging 28 kg per person. Plastic waste is expected to nearly triple worldwide by 2060, with half of all waste anticipated to end up in landfills, and less than one-fifth being recycled [2]. A major issue associated with plastic waste is the presence of microplastics, which are identified as tiny plastic particles or fragments measuring less than 5 mm in size [3]. Microplastics are categorized based on their sources: primary microplastics are created to be smaller than 5 mm, while secondary microplastics result from the breakdown of larger plastics or from primary microplastics. Among the microplastics, any fragments or particles measuring less than 100 nm are categorized as nanoplastics [4].

Lately, there has been a noticeable shift in focus regarding microplastic pollution, moving from the oceans to land-based environments [5, 6]. Studies indicate that around 80% of the plastic waste found in oceans originates from land sources [7, 8]. Consequently, soil can be considered a significant repository for microplastics, which are introduced through various mechanisms such as atmospheric deposition, the agricultural application of biosolids, irrigation with wastewater, and the use of plastic films for mulching [9, 10]. Research revealed that the average quantity of microplastics found in biosolid samples was 12,000 particles per kg of dry biosolids [11]. When biosolids were applied to soil over an extended period at low, medium, and high rates, the average concentrations of microplastics in the top 10 cm of soil were recorded at 383, 500, and 361 particles per kg, respectively. Although these concentrations were not statistically distinguishable from one another, they were significantly greater than the levels in soil that had not received biosolids amendments, which measured at 117 particles per kg [11]. Additionally, atmospheric deposition added approximately 15 particles per kg of dry soil annually. The production of microplastics occurred at a quicker rate with biodegradable mulch film, followed in succession by oxodegradable mulch film, white polyethylene (PE) mulch film, and black PE mulch film [12]. The rate of microplastic production adhered closely to Schwarzschild's law, demonstrating exponential growth with indices ranging from 1.6309 to 2.0502 in the microplastic generation model [12].

Different from soil particles that contain minerals and organic materials, microplastics possess distinct compositions and characteristics. The presence of microplastics in the soil is bound to influence its properties. Most microplastics feature a hydrophobic surface, which can affect soil water retention, pollutant movement, and nutrient availability [5, 13]. Their significant adsorption capacity can also alter the behaviors of nutrients and contaminants, especially the organic fractions, which in turn affect soil health and the toxicity of contaminants [14–16]. A growing number of studies have demonstrated that microplastics significantly influence soil characteristics [17]. While several reviews have addressed this issue, their primary focus has been on the ecological impacts, fates, occurrences, and detection methodologies of microplastics in soil [18–21]. Currently, there is a lack of comprehensive reviews that systematically outline the effects of microplastics on the chemical properties of soil. The existing relevant reviews tend to focus on limited chemical aspects [22] or on specific types of microplastics [23].

This review provides a comprehensive overview of how microplastics impact the chemical properties of soil, highlighting the key chemical consequences these particles have on the soil. It also points out existing knowledge gaps in this area and suggests avenues for future research. Understanding the chemical impacts of microplastics on soil is crucial for developing precise environmental risk assessments, creating effective soil remediation strategies, and informing policy frameworks related to plastic pollution in agricultural contexts.

2. Materials and Methods

This review adopted a narrative approach to gather, evaluate, and synthesize peer-reviewed literature pertaining to the chemical impacts of microplastics in terrestrial soil environments. A comprehensive literature search was conducted using major academic databases including Web of Science, Scopus, and ScienceDirect. The following keywords and Boolean operators were employed to obtain articles with titles containing these keywords:

- "microplastics" AND "soil" AND ("chemical impact" OR "chemical properties" OR "soil chemistry")
- "microplastics" AND ("pH" OR "pollutant" OR "organic matter" OR "nutrient") AND "soil"

The articles retrieved were screened based on the following inclusion criteria: 1) Published in English in peer-reviewed journals between 2015 and 2025; 2) Focused on how microplastics affect the chemical properties of terrestrial soil environments (primarily in the environmental science tract); and 3) Addressed interactions with organic pollutants, heavy metals, nutrients, or soil organic matter and pH. Exclusion criteria included: 1) Studies solely on aquatic or marine environments; 2) Papers focusing only on physical impacts (e.g., morphology or abundance of microplastics) without chemical context; 3) Studies on the fate and transport of microplastics in terrestrial environments; and 4) Non-peer-reviewed sources, such as preprints, opinion pieces or blog posts. The flowchart of literature screening and selection is shown in Figure 1.

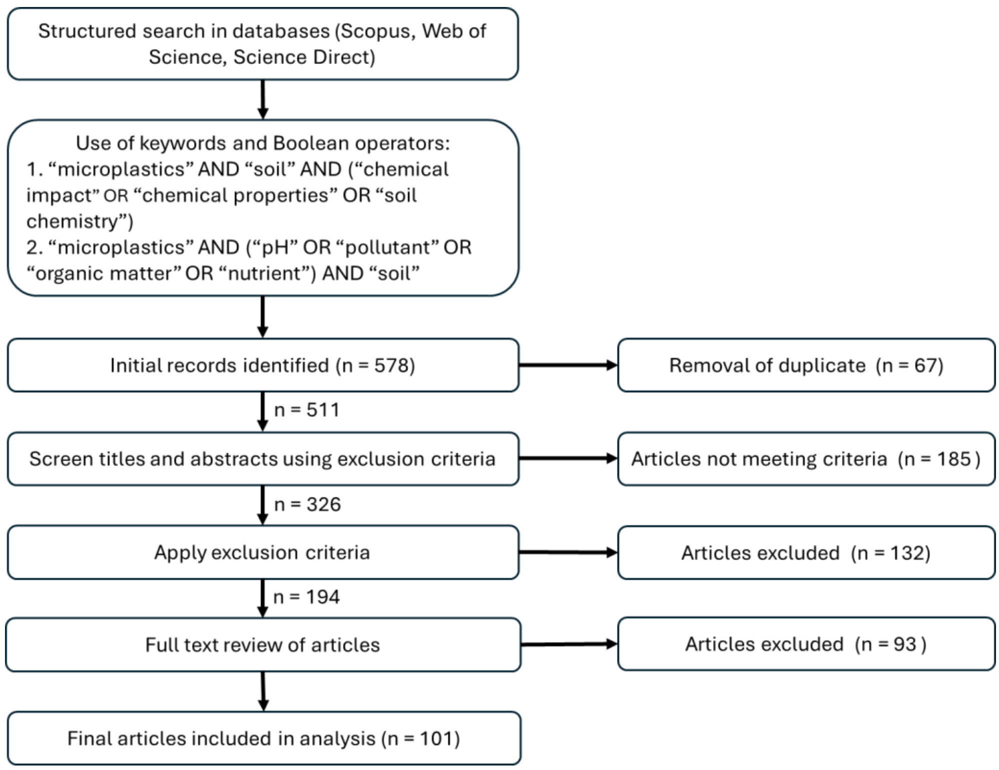

Figure 1. Flowchart showing stages of literature screening and selection.

3. Results and Discussion

3.1. Impacts on soil fertility.

The influence of microplastics on soil nutrient dynamics is complex, with outcomes ranging from beneficial to detrimental, depending on the type, concentration, and form of microplastics involved [15, 24, 25]. Nutrient depletion has been observed in several studies. For instance, when 1% (w/w) polyvinyl chloride (PVC) microplastics were introduced to rice paddy soils, available nitrogen decreased by 10–13%, and available phosphorus dropped by approximately 30% (Table 1) [15]. Similar reduction in available phosphorus was also observed with PE microplastics [26, 27], while both polystyrene (PS) and polytetrafluoroethylene (PTFE) microplastics led to declines in nitrogen and phosphorus availability (Table 1) [28]. However, other findings highlight the variability of effects; for example, 0.2% (w/w) microplastics had no measurable influence on nutrient availability in some soils (Table 1) [29]. A separate study indicated that the presence of PE and polypropylene (PP) microplastics could lead to a notable reduction in the soil available phosphate levels, dropping from 122.61 mg/l to 63.43 mg/l. Various concentrations of microplastics from biodegradable mulches influenced soil available phosphorus levels in divergent ways, with a 2.5% concentration leading to a decrease and a 1% concentration resulting in an increase in most vegetated pots. Additionally, the type of plants in the pots affected the variations in soil available phosphorus caused by microplastics [30]. Conversely, the introduction of PP microplastics was found to significantly boost the available ammonium content in the soil, increasing it from 0.94 mg/l to 1.53 mg/l (Table 1) [31]. This suggests that the impact of microplastics on various soil nutrients differs and is probably affected by the type of microplastic polymer.

Table 1. Effects of microplastics on soil fertility, particularly the nutrient levels.

Microplastic Type	Concentration and Size	Experimental Condition	Observation	Reference
PE, PVC	1% and 7% (w/w); <125 µm	56 days in Malisol and Ultisol	Nitrate levels declined.	[32]
Biodegradable mulch	0%, 1% and 2.5% (w/w); 0.2-2.5 mm	1 month in planted pots	2.5% microplastics decreased soil available phosphorus, but 1% microplastics increased it in most planted pots; 2.5% microplastics increased soil organic matter.	[30]
PE, PS, polyamide (PA), polylactic acid (PLA), polybutylene succinate (PBS), poly(3-hydroxybutyrate (PHB)	0.2% and 2% (w/w); 39-80 µm	120 days in sandy loam soil	Nitrate content declined with all 0.2% microplastic treatments, as well as with 2% PE, PS, and PA. Available phosphorus (P) content remained constant with 2% PE and PS, and 0.2% PHB; however, it decreased in other treatments.	[33]
PE	0.2% (w/w); 0.03 mm	2 months in red, paddy, and fluvo-aquic soils	No notable impacts on ammonium and Olsen P levels	[29]
PVC	0.1% and 1% (w/w); <0.9 mm	35 days in red and paddy soils	Addition of 1% PVC microplastics reduced nitrate levels in the paddy soil and affected the content of soil available P.	[15]
PLA	2% (w/w); 20-50 µm	70 days in idle paddy soil	No notable impact on inorganic P, decreased soil	[34]

Microplastic Type	Concentration and Size	Experimental Condition	Observation	Reference
			ammonium levels, heightened nitrate and nitrite levels.	
Polyester (PES)	0.4% (w/w); 1.23 mm	2 months in sandy loam soil	Decreased nutrient loss and enhanced nutrient retention by approximately 70%.	[25]
PS, PTFE	0.25% and 0.5% (w/w); 0.1-100 µm	Soil contaminated with arsenic (As) over a rice planting cycle	Reduced available nitrogen (N) and P levels, along with heightened available N in As-contaminated soils.	[28]
Plastic film mulch	Not available	Farmland soil with and without microplastic contamination	Lowered inorganic nitrogen levels	[35]
PP	7% and 8% (w/w); <180 µm	30 days in vegetated loess soil	Elevated levels of microplastics raised the nitrate, ammonium, and phosphate levels in soil dissolved organic matter.	[36]

In certain cases, microplastics even enhanced nutrient retention. Lozano et al. reported that PES microfibers reduced nitrate leaching by about 70%, likely due to improved soil aggregation that enhances nutrient-holding capacity (Table 1) [25]. The role of polymer composition was also evident in the study of Chen et al., where PLA microplastics under low-carbon conditions increased nitrate and nitrite levels while decreasing ammonium, suggesting an acceleration of nitrification [34]. Additionally, plasticizers such as di(2-ethylhexyl) phthalate (DEHP) in PVC microplastics may promote phosphorus solubilization or mineralization, as evidenced by increased available phosphorus at both 0.1% and 1% DEHP-PVC concentrations, while unplasticized PVC microplastics led to reductions (Figure 2) [15].

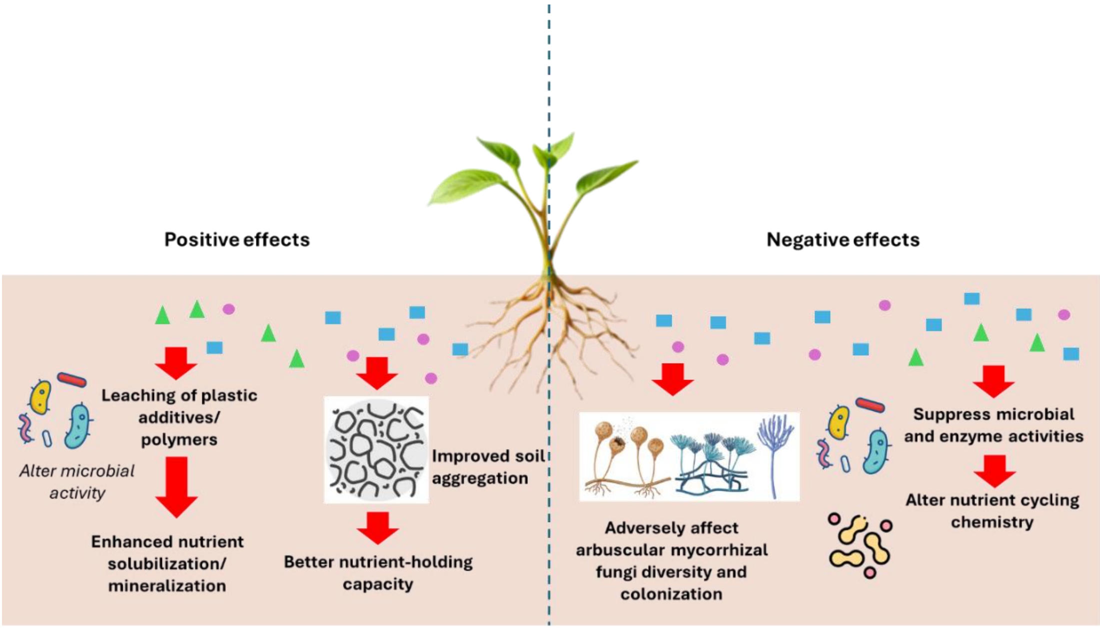

Figure 2. Effects of microplastics on soil nutrients.

Several mechanisms have been proposed to explain these divergent effects. Microplastics may serve as sources of nutrients themselves due to their chemical composition; for instance, those containing phosphorus-based antioxidants, nitrogen-rich polymers (e.g., polyacrylonitrile), or chlorine (e.g., PVC) may release these elements upon degradation (Figure

2) [13]. Additionally, aged and weathered microplastics with increased surface area and charge can adsorb soil nutrients through electrostatic interactions, altering their availability [37–39]. Microplastic surface characteristics may thus influence the retention or release of charged nutrients or metals.

Microbial mediation is another key factor. Microplastics can significantly shift microbial community structure and enzyme activity, thereby altering biogeochemical cycles (Figure 2). The availability of soil phosphorus, for example, is closely tied to microbial processes like inorganic phosphorus dissolution and organic phosphorus mineralization [40, 41]. Arbuscular mycorrhizal fungi, which facilitate phosphorus uptake, are particularly sensitive to microplastic exposure. Microplastics have been shown to affect the diversity of arbuscular mycorrhizal fungal communities and their colonization efficiency (Figure 2) [42–44]. Similarly, soil enzymes like urease and phosphatase, central to nitrogen and phosphorus cycling, can be inhibited by microplastics, leading to reduced soil organic matter and inorganic nitrogen content through the suppression of microbial gene expression and enzymatic activity (Figure 2) [35,45]. Physical changes in the soil environment further compound these effects. Improved soil aggregation linked to microplastics may enhance nutrient retention [25], while changes in porosity and aeration, especially with the addition of microfibers, can enhance oxygen diffusion and support aerobic microbial processes such as ammonia oxidation [46].

In conclusion, microplastics impact soil nutrients through an array of interrelated mechanisms, including chemical leaching, nutrient adsorption, microbial alteration, and physical restructuring of the soil matrix. However, the physical and microbial effects resulting from chemical interactions between microplastics and soil are beyond the scope of this review and are not illustrated further. These effects vary by microplastic type, size, shape, concentration, and environmental context. Alterations in the availability of essential nutrients, such as nitrogen, phosphorus, and potassium, can disrupt plant growth and reduce crop yields. Nutrient depletion, such as reduced levels of available nitrogen and phosphorus, caused by PVC, PE, or PTFE microplastics [15, 28], may necessitate increased fertilizer input to maintain productivity. This not only raises economic costs for farmers but also increases the risk of nutrient runoff and eutrophication in adjacent water bodies. Despite growing evidence, current understanding remains limited, particularly regarding the behavior of soil micronutrients like Fe, Mn, Zn, and Cu. Future research should adopt longer-term, multi-factorial designs to better predict the implications of microplastics for soil fertility and plant health.

3.2. Changes in soil pH.

Soil pH is a key abiotic factor that influences various soil properties, including mineral binding, soil organic carbon dynamics, nutrient and contaminant bioavailability, and the composition and activity of microbial communities [47]. A growing body of research suggests that microplastics can alter soil pH, but the direction and magnitude of these changes vary depending on multiple factors.

Several studies reported that microplastics tend to increase soil pH. For instance, the addition of 1% and 10% (w/w) PLA and high-density polyethylene (HDPE) microplastics has been shown to elevate pH levels in soil [43]. Both 0.5% and 1.5% PLA and PP microplastics led to a consistent increase of 7.1% to 25.4% in soil pH [48]. Similarly, plastic film fragments, such as low-density polyethylene (LDPE) and biodegradable mulch films, also increased soil pH [49]. Lozano et al. found that 0.4% (w/w) PES microfibers led to an increase in pH as well [25].

However, this trend is not universal. Other studies have demonstrated neutral or even negative effects of microplastics on soil pH. For example, Boots et al. reported that HDPE microplastics significantly lowered soil pH after 30 days of exposure, whereas PLA and clothing fiber microplastics had no notable impact (Table 2) [50]. These inconsistencies can be attributed to differences in polymer composition, as various types of plastics may exert distinct and sometimes opposing effects on soil chemistry. Such variability in pH alteration can have important implications for nutrient availability, plant growth, and agricultural productivity. According to Hu et al., the average pH levels of bare soil and soil samples with vegetation subjected to microplastic treatments (7% and 28% polyethylene terephthalate (PET)) showed minor variations from the control. However, the general trend indicated a decrease, implying that PET contributes to increased soil acidity to some level, warranting further investigation [51].

Table 2. Effects of microplastics on soil pH.

Microplastic Type	Concentration and Size	Experimental Condition	Observation	Reference
PBS, PE	0.1% and 1% (w/w); 50 µm	30 days in red and brown soils	PBS treatment notably lowered pH levels in red soil, while increasing pH in brown soil.	[52]
PLA, PP	0.5% and 1.5% (w/w); approx. 50 µm	41-day microcosm	A consistent increase of 7.1% to 25.4%	[48]
PE, PS, PA, PLA, PBS, PHB	0.2% and 2% (w/w); 39-80 µm	120 days in sandy loam soil	Soil pH remained unchanged with 0.2% MPs, decreased with 2% PE and PS, and increased with 2% PLA and PHB.	[33]
PES	0.4% (w/w); 1.28 mm	2 months in sandy loam soil	Elevated soil pH	[25]
PS, PTFE	0.25 and 0.5% (w/w); 0.1-100 µm	Soil contaminated with arsenic over a rice planting cycle	Lowered soil pH	[28]
PE	0.2% (w/w); 0.03 mm	2 months in red soil	The pH of the unfertilized soil decreased, but no notable changes occurred in soil with organic fertilizer or a combination of organic and inorganic fertilizers.	[29]
		2 months in paddy soil	Higher pH levels were observed in unfertilized soil and soil fertilized with combined organic and inorganic fertilizers. Soil fertilized with inorganic fertilizer showed no effect.	
		2 months in fluvo-aquic soil	No notable variation	
PA, polycarbonate (PC), PE, PES, PET, PP, PS, polyurethane (PU)	0.4% (w/w); 1.28-2.26 mm	31 days in sandy soil	Foams and fragments raised soil pH, while films had a slight effect on it.	[53]
PE	1% (w/w); 100-150 µm	5 weeks in Ustic Cambosol	No notable variation	[54]
LDPE, bioplastic mulch films	1% (w/w); <10 mm	61 days and 139 days in sandy soil	Elevated soil pH	[49]
PLA and HDPE particles, acrylic and nylon fibers	0.1% (w/w) HDPE (102.6 µm) or PLA (65.6 µm); 0.0001% (w/w) fibers	30 days in sandy clay loam soil	HDPE reduced soil pH, while PLA and fibers did not cause significant changes.	[50]

The influence of microplastics on soil pH also appears to be dependent on concentration, particle size, shape, and exposure duration. Dong et al. observed a dose-dependent decrease in soil pH with increasing concentrations of PS and PTFE microplastics, with smaller particles exerting greater effects [28]. Zhao et al. further noted that microplastics in the form of foams and fragments caused more substantial pH increases than film or fiber-shaped microplastics. Extended exposure to PS foams and PET fragments also led to progressive increases in pH (Table 2) [53].

Environmental conditions and land management practices can further modulate microplastic effects. For instance, Lozano et al. highlighted that PES microfibers elevated soil pH more under drought conditions, suggesting an interaction with soil moisture content [25]. In agricultural soils, the accumulation of PE residues produced inconsistent pH outcomes depending on soil type and fertilization history. In one study, 0.2% (w/w) PE decreased the pH of unfertilized red soil, increased the pH of unfertilized or compound-fertilized paddy soils, and had no significant effect on fluvo-aquic soils or fertilized red and paddy soils (Table 2) [29]. However, the mechanisms by which fertilization modulates these effects remain unclear.

Several hypotheses have been proposed to explain how microplastics influence soil pH. One possibility involves the release of chemical substances during microplastic degradation. For example, Bandow et al. showed that photo-oxidized HDPE released compounds that lowered pH [55]. However, microplastics buried deeper in soil are less exposed to photo-oxidation. Another mechanism, suggested by Boots et al., involves the high surface area of microplastics, which may alter cation exchange processes and enhance proton mobility in the soil solution [50].

Microbial interactions may also play a role. Changes in microbial community structure and activity, both of which are highly pH-sensitive [17, 56], can contribute to microplastics-induced pH shifts. For instance, Rong et al. reported that LDPE microplastics altered the abundance of ammonia-oxidizing bacteria and nitrification rates, processes that can release H^+ ions and affect soil pH [57]. Biodegradable plastics like PLA theoretically should lower pH through the release of lactic acid during mineralization, yet studies have paradoxically observed pH increases following the application of PLA microplastics, possibly due to the alteration in the soil microbial community and the microbial utilization of lactic acid [33, 42].

Overall, the current understanding of how microplastics affect soil pH remains incomplete and inconsistent. Numerous studies have demonstrated that microplastics can increase or decrease soil pH, depending largely on the polymer composition. For instance, materials such as PLA, HDPE, LDPE, and PES have been shown to increase soil pH, possibly due to changes in soil aeration, microbial activity, or chemical interactions with soil components [25, 43, 49]. In contrast, some studies have reported a decrease in pH following the application of HDPE or PS microplastics [28, 50], emphasizing the heterogeneity of microplastics-induced effects. These discrepancies underscore the critical role of polymer properties, such as surface area, hydrophobicity, and chemical composition, in shaping soil responses.

The magnitude and direction of pH change also appear to be dose-dependent and influenced by particle morphology. Smaller microplastics generally exert a greater impact on pH, likely due to their larger surface area and higher reactivity. Irregular shapes, such as foams and fragments, tend to induce more significant pH shifts than films or fibers [53]. As concentration increases, particularly in the case of PS and PTFE, soil pH can decline or alter, suggesting that microplastic accumulation may pose long-term risks to soil buffering capacity and acidity regulation [28]. Further research is needed to uncover the underlying mechanisms and to assess how microplastic characteristics, soil types, and agricultural practices interact to shape pH dynamics in terrestrial ecosystems.

3.3. Impacts on organic content in soils.

Soil organic content plays a fundamental role in maintaining soil fertility, supporting plant nutrition, and sustaining microbial activity. However, the impact of microplastics on the dynamics of soil organic matter remains unclear, with studies reporting divergent results, ranging from inhibition [28, 34, 58] to enhancement [34, 36], and in some cases, no significant effects at all (Table 3) [29, 59]. These inconsistencies suggest that multiple factors modulate how microplastics influence soil organic content.

Table 3. Effects of microplastics on soil organic content.

Microplastic Type	Concentration and Size	Experimental Condition	Observation	Reference
PE, PVC	1% and 7% (w/w)	56 days in Malisol and Ultisol	The amounts of dissolved organic carbon and specific dissolved organic matter components increased.	[32]
PE, polypropylene carbonate (PPC) + PBAT	0.03% and 0.3% (w/w); 5 mm	8 weeks in grassland, farmland and facility soils	0.03 % and 0.3 % PE decreased soil organic carbon content by 7.4 % and 8.2 % in grassland, and 3.0 % and 6.0 % in the facility. Dissolved organic carbon in grassland and farmland rose by 33.1% and 38.3%, respectively, under 0.03% (PPC + PBAT) treatment.	[60]
PE, PS, PA, PLA, PBS, PHB	0.2% and 2% (w/w); 39-80 µm	120 days in sandy loam soil	0.2% and 2% PLA and 0.2% PE, PS, PA, and PBS enhanced dissolved organic carbon	[33]
PE	0.2% (w/w); 0.03 mm	2 months in red, paddy, and fluvo-aquic soils	No notable impacts on dissolved organic carbon	[29]
PE	5% (w/w); <13 µm and <150 µm	30 days in clay soil	No notable impacts on dissolved organic carbon	[59]
PLA	2% (w/w); 20-50 µm	70 days in idle paddy soil	Reduced dissolved organic carbon in soil treated with rice straw	[34]
PES	0.1% and 0.3% (w/w); 2.65 mm	75% in Nitrosol	No notable variation in total organic carbon	[61]

Soil pH, for instance, appears to be a crucial factor. One study observed that the effects of microplastics on soil organic carbon, a major component of soil organic matter, were more pronounced under alkaline conditions, with soil organic carbon levels decreasing as microplastic concentration increased [58]. Conversely, under acidic conditions, microplastics tend to age more rapidly and experience alterations in their chemical structure due to acidification. This accelerates the release of organic compounds (Figure 3) [62], which can partially offset the loss of soil organic carbon, thereby mitigating the overall decline in soil organic matter.

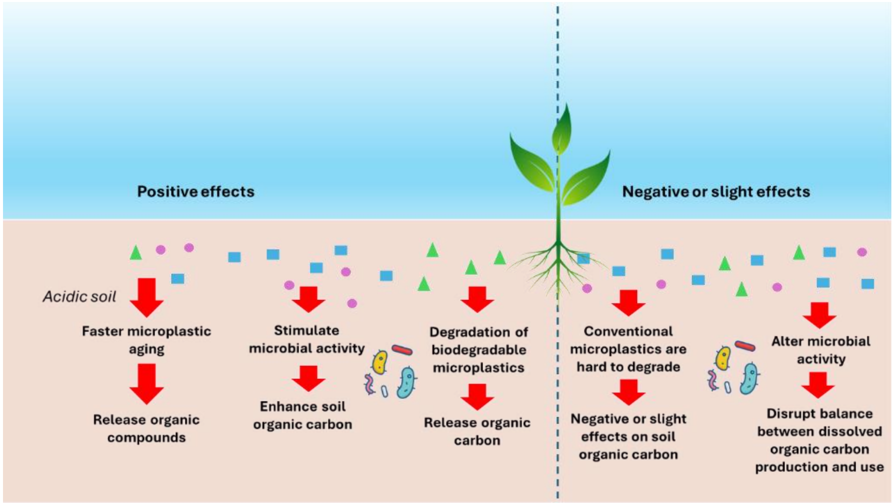

Figure 3. Effects of microplastics on soil organic carbon content.

Microbial activity is another important regulator of soil organic matter changes under microplastic exposure. Microplastics can stimulate the metabolism of certain microbial groups, potentially enhancing soil organic carbon accumulation (Figure 3). For example, Dong et al. reported a decline in soil organic matter that correlated with a reduction in the relative abundance of *Chloroflexi*, a microbial group involved in CO_2 fixation and carbon cycling [28].

Current research largely concentrates on the interaction between microplastics and soil dissolved organic matter, a mobile and reactive component of soil organic matter that plays a vital role in nutrient cycling and pollutant transport [63]. For example, PE microplastics were found to reduce soil dissolved organic carbon concentrations [26]. The impact of microplastics on dissolved organic matter appears to be driven by the balance between production and microbial mineralization (Figure 3). Liu et al. demonstrated that soils treated with 7% microplastics (w/w) experienced a slowed decomposition rate of dissolved organic matter within the first 30 days, while soils treated with 28% microplastics (w/w) showed significant increases in total dissolved nitrogen, dissolved organic nitrogen, total dissolved phosphorus, and dissolved organic phosphorus, suggesting that microplastics can mobilize and activate nutrient pools [36].

Moreover, microplastics themselves, particularly biodegradable types like PLA, can serve as sources of organic carbon (Figure 3). Soil microbes are capable of breaking down microplastics into soluble carbon forms, leading to increased dissolved organic carbon concentrations, as observed with 2% (w/w) PLA microplastic amendments [33, 34]. However, these findings are not universally consistent. Li et al. found that PE microplastic exposure did not significantly affect dissolved organic carbon levels across nine soils differing in type and fertilization history (Table 3) [29]. Similarly, Ren et al. reported that while 5% (w/w) PE microplastics did not alter dissolved organic carbon quantity, they did change its chemical composition, promoting the formation of aromatic functional groups (Table 3) [59]. Other studies noted that PLA microplastics could inhibit the formation of humic and fulvic acids when straw residue was present (Table 3) [34].

Meng et al. demonstrated that sandy soils subjected to LDPE microplastics did not exhibit notable variations in soil organic matter. However, soils treated with biodegradable microplastics experienced an initial drop, followed by an increase in soil organic matter [64]. In comparison to the control group, soil permanganate oxidizable carbon levels were significantly reduced by 0.5%, 1.0%, and 2.5% LDPE microplastic, as well as by ≥ 1.0% biodegradable microplastics at the end of treatment. LDPE microplastics did not have a significant impact on soil dissolved organic carbon or nitrogen cycling. Conversely, 2.0% and 2.5% biodegradable microplastics resulted in a substantial increase in soil dissolved organic carbon and dissolved organic nitrogen [64]. Overall, biodegradable microplastics had a more pronounced effect on soil carbon dynamics, in line with findings of Chen et al. and Feng et al., suggesting that the carbon in these microplastics is more accessible compared to conventional microplastics like LDPE [33, 34]. Furthermore, a study investigating the impact of PE and biodegradable PLA microplastics on the stability of soil organic matter revealed notable differences between Black soil and Loess soil [65]. The introduction of microplastics led to a marked increase in cumulative carbon dioxide emissions and the levels of dissolved organic carbon. Notably, the treatment involving 1% PLA resulted in a 19% to 74% rise in CO2 emissions and a 3% to 23% increase in dissolved organic carbon content at a temperature of 25 °C [65]. This confirms that different microplastic types have varying effects on soil organic matter, with biodegradable microplastics frequently enhancing the content of dissolved organic carbon.

In summary, the relationship between microplastics and soil organic matter is multifaceted, influenced by soil physicochemical properties, microplastic type and concentration, microbial responses, and climatic conditions. The greater bioavailability and degradability of biodegradable plastics render them more active in modifying soil organic matter pools, yet this also raises questions about their long-term impact on soil carbon stability and ecosystem health. Given the central role of soil organic matter in soil health and crop productivity, further research is needed to elucidate the complex interactions between the dynamics of soil organic matter and microplastic pollution, particularly concerning plant–soil–microbe relationships.

3.4. Interactions with organic pollutants.

Microplastics significantly influence the environmental fate and bioavailability of organic pollutants through sorption and desorption processes [66]. As synthetic organic polymers with inherently hydrophobic surfaces, microplastics exhibit a strong affinity for various organic compounds. These include pesticides [67, 68], antibiotics [69, 70], polycyclic aromatic hydrocarbons (PAHs) [71], polychlorinated biphenyls [72, 73], and pharmaceuticals and personal care products [74]. Adsorption typically occurs through mechanisms such as surface sorption, hydrophobic partitioning, and pore filling [75]. The extent of pollutant adsorption by microplastics is influenced by a combination of material-specific properties, such as polymer composition, surface morphology, binding energy, and contaminant characteristics, including molecular weight, polarity, and solubility. Environmental parameters, such as pH, ionic strength, temperature, and the presence of dissolved organic matter, also play critical roles in modulating these interactions [76, 77].

The presence of microplastics in soil can substantially alter the mobility and distribution of organic pollutants. For instance, Hüffer et al. observed that PE microplastics reduced the soil's ability to retain herbicides like atrazine and 4-(2,4-dichlorophenoxy) butyric acid, effectively lowering their sorption coefficients and overall soil retention [78]. This "dilution effect" implies that microplastics can displace native sorbents in the soil, enhancing pollutant mobility [79]. Research has shown that the presence of microplastics often leads to a reduction in pesticide bioavailability, primarily due to their ability to adsorb these chemicals. This adsorption process is significantly affected by the pesticide's hydrophobicity, commonly measured by the log K_{ow} value, as well as the type and surface area of the microplastics involved. Pesticides with higher log K_{ow} values tend to bind more strongly to microplastics, resulting in decreased availability in the environment. Moreover, weathered or aged microplastics typically possess larger surface areas, enhancing their capacity to adsorb pesticides and further limiting their bioavailability [80].

However, contrasting findings illustrate the complexity of microplastic–pollutant interactions. Chen et al. found that PE microplastics retained more triclosan than both PS microplastics and natural soil, and that this pollutant was also more readily desorbed from PE [81]. Similarly, Sun et al. demonstrated that microplastics could increase the exchangeable fraction while decreasing the water-soluble fraction of tetracycline, thus delaying its degradation [82]. Xu et al. further highlighted that microplastics reduced the soil sorption of polar compounds like diazepam while enhancing the retention of nonpolar contaminants like phenanthrene, reflecting the differential affinity of microplastics for various organic compounds [83].

Microplastics can function as vectors for transporting organic contaminants, with potentially synergistic toxic effects on soil organisms. Whether microplastics enhance or mitigate pollutant toxicity largely depends on the relative affinity of the pollutant for the soil versus the microplastic surface [84]. In some cases, pre-contaminated microplastics have been shown to increase the bioaccumulation of hydrophobic organic compounds (HOCs) in biota. Conversely, introducing clean microplastics into HOC-contaminated soils may lower bioaccumulation due to competitive adsorption [84].

The toxicity of microplastics can also be exacerbated by the pollutants they carry. For instance, Xu et al. reported that PES microplastics reduced phenanthrene-degrading bacteria in earthworm guts, leading to increased pollutant accumulation [85]. Xiang et al. found that sulfamethoxazole adsorbed onto PS microplastics disrupted gut microbiota and antibiotic resistance gene profiles in collembolans [86]. Additives leached from microplastics, such as plasticizers and flame retardants, further contribute to their toxicity, as shown in nematode assays [56]. Additionally, PAHs embedded in tire wear particles have been found to disrupt microbial communities in soil and the gut microbiota of worms [87]. Despite these findings, research has disproportionately focused on soil fauna, with limited attention given to plants and microbes, warranting broader ecological studies.

Microplastics may also influence the degradation of organic pollutants by modifying their bioavailability and altering soil microbial dynamics. Although most current insights stem from aquatic systems, some soil studies have begun to reveal similar effects. Yang et al. observed no significant change in glyphosate degradation in the presence of PP microplastics over a 30-day incubation, though microbial enzymatic activities were affected at high microplastic concentrations [88]. In contrast, a 35-day microcosm experiment indicated that PE microplastics inhibited ciprofloxacin degradation, potentially due to a decline in microbial diversity [54].

Given that microplastics can alter soil physical and chemical properties, as well as microbial community composition, they likely influence the degradation rates of many organic pollutants, especially those that are less persistent. These disruptions may, in turn, affect pollutant toxicity and the risk of bioaccumulation in crops, raising concerns over food safety.

To fully understand the implications of microplastics in terrestrial systems, more empirical research is needed, particularly field-based experiments that examine how microplastics affect the behavior, persistence, and toxicity of organic pollutants in soil. Special attention should be paid to interactions involving plant uptake and microbial community responses, which remain underexplored but are essential for holistic risk assessment and management strategies in agroecosystems.

3.3. Interactions with metals.

Microplastics have increasingly been recognized not only as pollutants themselves but also as carriers for heavy metals in the soil environment. Numerous studies have demonstrated that microplastics can sorb various metal ions, including cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), cobalt (Co), chromium (Cr), and nickel (Ni), facilitating their mobility and potential bioavailability in terrestrial systems [37, 38, 89–91]. However, the degree to which microplastics adsorb metals varies considerably, depending on the polymer type and physical-chemical characteristics of both the microplastics and the metals.

For instance, PE and PVC microplastics have demonstrated a high affinity for Pb, Cr, and Zn, while PET exhibits limited adsorption capacity [90]. Similarly, Pb tends to bind more strongly to microplastics than Cu or Cd, a trend attributed to electrostatic attractions between Pb ions and the microplastic surface [38]. The adsorption efficiency is significantly influenced by microplastics-specific factors, such as particle size, porosity, surface morphology, and the degree of environmental aging [37, 90, 92]. Generally, smaller microplastics with higher surface-area-to-volume ratios exhibit stronger adsorption capacities [93]. Additionally, aged microplastics, due to roughened surfaces and the formation of oxygen-containing functional groups, offer more binding sites for metal ions, thus enhancing metal sorption [37, 91, 94].

The underlying mechanisms governing metal sorption to microplastics include both physical and chemical interactions. Physical mechanisms involve nonspecific van der Waals or hydrophobic interactions with the microplastic surface [95], while chemical mechanisms typically include electrostatic interactions, surface complexation with carboxyl or hydroxyl groups (particularly on aged microplastics), or ligand exchange [38, 90, 96].

Importantly, when microplastics are introduced into soils, they alter the natural sorption and speciation behavior of heavy metals. Compared to complex soil matrices, microplastics have simpler structures and typically lower sorption capacities. As a result, metals adsorbed onto microplastics are often more easily released back into the environment [16, 95]. For example, the addition of 10% PE microplastics to soil increased diethylenetriaminepentaacetic acid-extractable concentrations of Zn and Pb [95], suggesting enhanced metal mobility. Similarly, coexisting microplastics were shown to increase extractable Cd levels in soil [97]. Furthermore, in simulated earthworm gut environments, Zn desorption from microplastics reached 40–60%, compared to only 2–15% in soil [89], indicating a potential increase in metal bioavailability to soil fauna.

Nevertheless, some research presents contradictory findings. For instance, PE microplastics have been reported to reduce metal bioavailability by promoting the transformation of metals from easily available forms to more stable, organic-bound fractions. This can occur through both direct metal adsorption and indirect modification of soil properties, such as decreased pH and dissolved organic carbon [26]. These transformations are metal-specific and depend on microplastic concentration, particle size, and interaction with the soil matrix.

Microplastic effects are also strongly modulated by environmental and material-specific variables. For example, biodegradable plastics like poly(butylene adipate-co-terephthalate) (PBAT) degrade more readily in the environment than PE, enhancing their surface reactivity and metal adsorption capacity [24]. Additionally, polyamide-6 and polymethyl methacrylate (PMMA) exhibited greater Cu^{2+} adsorption than PE, PET, PS, and PVC [98]. Adsorption of Cd was negatively affected by larger particle sizes, higher salinity, and increased microplastic concentration but was enhanced at higher pH and with the presence of humic substances [16, 95]. Coexisting ions such as Ca^{2+} and Mg^{2+} can compete for binding sites on microplastics, reducing metal adsorption, while organic acids like citric and oxalic acids can further suppress metal uptake by microplastics [98].

Beyond altering metal mobility, the co-presence of microplastics and heavy metals exacerbates ecological risks. Their combined toxicity has been shown to disrupt soil microbial communities, reduce biodiversity, and impair critical biogeochemical processes [92, 99]. In Pb/Zn-contaminated soils, the presence of 2% microplastics significantly increased Pb availability and was associated with decreased bacterial diversity and shifts in dominant genera [33]. Co-exposure to PES microfibers and Cd was also found to disturb key microbial taxa involved in nitrogen and carbon cycling [100]. Moreover, increased metal availability caused by microplastics can lead to greater bioaccumulation in plants and soil organisms, potentially amplifying health risks across the food web [101].

Overall, the interaction between microplastics and heavy metals is not uniform but governed by a suite of factors, including polymer type, particle morphology, and environmental aging. Aged microplastics, in particular, with their increased surface area and functional group formation, have demonstrated enhanced adsorption potential. This has significant implications for long-term contamination scenarios, as microplastics degrade and persist in soils over time. The mechanisms driving metal adsorption onto microplastics, ranging from weak van der Waals forces to stronger chemical complexation, highlight the diverse pathways through which microplastics can influence metal fate. These mechanisms are metal-specific and further complicated by soil characteristics and coexisting ions. For instance, the presence of Ca^{2+} or organic acids can reduce metal adsorption by competing for binding sites or altering the physicochemical environment around the microplastics. The co-presence of microplastics and heavy metals poses compounded toxicity risks to soil microbial communities and fauna, and underscores the importance of including microplastics in risk assessment frameworks for soil pollution. Thus, future research should concentrate on extensive field studies to evaluate the behavior of aged microplastics in realistic soil environments and develop a framework for better assessing the risks posed by microplastics to soil health.

4. Conclusions

Microplastics significantly impact soil nutrient dynamics, pollutant behavior, and overall soil health through a range of complex mechanisms. These include chemical leaching, nutrient adsorption, microbial shifts, and changes in soil structure. While some microplastics may temporarily enhance nutrient retention, many contribute to nitrogen and phosphorus depletion, threatening soil fertility and crop productivity. Microplastics also influence soil pH in inconsistent ways, causing either increases or decreases, depending on polymer type, particle size, concentration, and exposure time. Such pH shifts can alter nutrient availability, microbial activity, and plant growth, underscoring the sensitivity of soil systems to plastic contamination. The effects of microplastics on soil organic matter are equally variable. Some plastics reduce total soil organic matter, while others increase dissolved organic carbon and nutrient mobility. Biodegradable plastics, in particular, can stimulate microbial respiration and carbon release, yet they may destabilize long-term carbon pools. These outcomes depend heavily on microplastic type, microbial responses, and soil chemistry. Additionally, microplastics alter the fate and bioavailability of organic pollutants such as pesticides, pharmaceuticals, and PAHs. Acting as both vectors and sinks, they interact with contaminants through sorption–desorption processes influenced by polymer properties, environmental aging, and pollutant characteristics. These interactions can enhance or reduce toxicity and bioavailability, affecting degradation rates and accumulation in soil organisms. Furthermore, microplastics serve as carriers for heavy metals like Pb, Cd, Zn, and Cu. Aged and smaller particles have higher adsorption capacities due to increased surface area and functional groups. These metals may become more mobile and bioavailable, compounding ecological risks. Co-contamination with heavy metals and microplastics disrupts microbial communities, impairs nutrient cycling, and increases health risks through food chain transfer, highlighting the urgent need for integrated soil pollution assessments. Future research should prioritize long-term, multi-factorial experiments that simulate realistic environmental conditions and incorporate diverse microplastic types, including both conventional and biodegradable variants. A key focus should be on elucidating the mechanisms by which microplastics alter soil pH across different soil types and land use systems, as these changes have cascading effects on nutrient availability and microbial activity. Comparative studies examining how various microplastic types and aging states influence the decomposition, stabilization, and sequestration of soil organic matter under different management practices are also essential. Furthermore, mechanistic investigations are needed to clarify how environmental parameters, such as pH, organic matter, and coexisting ions, modulate the adsorption and desorption of heavy metals and organic pollutants on microplastic surfaces. The development of predictive models that integrate microplastic aging, sorption kinetics, and soil physicochemical properties will be crucial for assessing cumulative ecological risks, particularly in agricultural systems. Ultimately, advancing our understanding of these complex interactions will support more accurate risk assessments and guide mitigation strategies for microplastic contamination in terrestrial ecosystems.

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Author Contribution

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Competing Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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