microplastics

Review

Recent Insights into Microplastic Pollution and Its Effects on Soil Carbon: A Five-Year Ecosystem Review

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Abstract: The widespread presence of microplastics (MPs) is of growing concern for both the scientific community and the public. Contemporary research increasingly focuses on ecosystem transformation and global climate change. We conducted a literature review, consisting of 46 studies, to investigate the consequences of MPs' influence on the carbon cycle in different soil types across various ecosystems. MPs can affect the cycling of carbon compounds and other biogenic elements by impacting the soil microbiome, enzyme activity, plant growth, litter decomposition, and more. The majority of authors report increased CO_2 and/or CH_4 emissions in soils containing MPs. However, some studies demonstrate the opposite or a neutral result, and the outcomes can differ even within a single study depending on the soil type and/or the type, form, and size of the MPs used. Further clarification and development of our understanding regarding the impact of MPs on the carbon cycle across different ecosystems remain crucial, taking into account the inclusion of as wide a variety of MPs as possible in future research.

Keywords: microplastic; soil; carbon; greenhouse gases; soil organic carbon; emission activity

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1. Introduction

Currently, among global concerns, climate change and the pollution of the environment with novel pollutants, including plastics and microplastics (MPs), are attracting particular attention from the scientific community. Plastics have been actively used in industry and everyday life since the 1940s–50s, but studies devoted to plastic waste in the environment first appeared in the scientific literature starting in the 1970s [1,2]. However, the problem did not attract significant interest from scientists until the early 2000s, when, along with increasing pollution from large plastic waste, the accumulation of microplastics in ecosystems also became a concern. Under the influence of ultraviolet radiation, seawater, hydrolysis, soil erosion, or biological activity, large plastic waste degrades into small particles. The term "microplastics" was first used to describe such particles in the ocean in a 2004 article by Thompson et al. [3]. Currently, MPs are defined as plastic fragments <5 mm [4], and MPs themselves have been detected virtually everywhere in the environment and even in animal and human tissues [5,6]. High production rates (global annual plastic production reached 400.3 million tons in 2022 [7]), including of single-use products (approximately 50% of plastic items are tableware, bags, and packaging) [8], low recycling rates, and the long lifespan of plastics lead to the significant accumulation of the material in the environment. The lifespan of plastic products varies from less than 1 year to more than

50 years; therefore, the annual volume of plastic waste does not necessarily correlate with production within a specific time frame [6]. Environmentally unsound waste management and unauthorized dumping lead to plastic entering the environment, and due to the long decomposition time of plastics, they readily accumulate in various environmental compartments. Huge volumes of MPs end up in the soil through sewage sludge deposition and the use of compost, controlled-release fertilizers (CRFs), plant protection products using capsule suspensions (CSPs), film-coated seeds, mulching films, and others [9–11]. The use of the latter increased fourfold from 1991 to 2011 (from 0.32 to 1.25 million tons), and more than 80% of agricultural films are made of low-density polyethylene (LDPE), which is primarily used in greenhouse films [6]. The most significant plastic pollution levels in soils are found in urban and agricultural areas. However, MPs are detected even in soils of remote, non-urbanized territories, with data showing a content of 66 to 1933 units/kg of dry soil in East Antarctic soils [12].

The accumulation of MPs affects the physicochemical properties and microbiome of soil, which, in turn, can affect biogeochemical processes, including the carbon cycle, which is one of the key functions of an ecosystem [13]. Soil represents the most important global carbon reservoir on Earth (about 2300 Pg C [14]—more than the carbon in the atmosphere and phytomass combined) [15], making it a crucial link in addressing climate change issues.

The soil organic carbon (SOC) pool is the largest active terrestrial carbon pool in the biosphere, and even slight fluctuations in it can cause significant changes in the concentration of greenhouse gases in the atmosphere [16]. An increase in greenhouse gas concentrations in the atmosphere will further exacerbate climate warming. In turn, climate warming can contribute to the release of soil carbon, creating a positive feedback loop with global warming [17]. Thus, the distribution and transformation of SOC have a profound impact on the global carbon balance and climate change.

MPs are organic polymers containing almost 90% carbon [18]. Due to degradation and leaching, they can contribute to SOC accumulation, and influence humification and the further polymerization of dissolved organic matter (DOM), thereby indirectly affecting the stability of SOC. Another way that MPs influence SOC formation is through various changes in the structure of the soil microbial community, functional gene expression, and enzyme activity [18]. It is also noted that MP pollution can complicate the accurate measurement of SOC in soil, with possible overestimations, and this increase is more intense in soils with low carbon content (<10.0 g kg^{-1}) [6].

Prior to 2020, the impact of microplastic (MP) incorporation into soils received limited research attention. However, studies conducted on loess soils in China have demonstrated significant effects on soil dissolved organic matter (DOM)—specifically, high MP amendment levels increased nutrient content within the DOM solution—and on soil enzyme activity [19]. Furthermore, research has explored the complex interactions between pesticides and MPs [20], revealing that the interaction of glyphosate with low MP concentrations negatively impacted dissolved organic carbon (DOC) dynamics, ultimately leading to a loss of bioavailable carbon.

In the past 5 years, there has been a rapid increase in the number of publications concerning the impact of MPs on the soil carbon cycle. Simultaneously, several reviews have been compiled, analyzing the effects of MPs on carbon cycling processes in soils [18], the likelihood of MPs contributing to the exacerbation of global warming [21], and the microbial mechanisms of carbon transformation in MP-contaminated soils. Furthermore, two separate reviews have been published on the accumulation of MPs in wetland systems and agricultural soils [22,23], including data on the influence of MPs on carbon.

However, there has been a lack of focus on systematizing data on the impact of MPs on processes related to the carbon cycle in different soils across various ecosystems, as soil greenhouse gas emissions are dependent on texture, soil moisture, SOC, pH, and the microbiome.

The objective of this review is to identify, consolidate, and analyze data from experimental studies and literature reviews to determine the effects of MP addition on the soil carbon cycle in different soil types.

2. Materials and Methods

The search for and selection of relevant peer-reviewed research were conducted in November 2024, using two online publication databases: PubMed and ScienceDirect. The selection was limited to data published since 2020 in English only, and included empirical or review studies that examined the link between soil microplastic contamination and the carbon cycle. Additionally, the reference lists of selected publications were analyzed.

The following keywords were used to identify relevant articles: "microplastic", "soil", "chemical properties", "physical properties", "soil organic carbon", "greenhouse gases", and "emission activity". Potentially relevant articles were read in full, and information was analyzed.

3. Results

The initial search yielded 619 publications. After the removal of duplicates and screening of titles and abstracts, 46 articles were selected (Figure 1). In order to control the quality of the search and avoid biases, the search was validated by a second researcher.

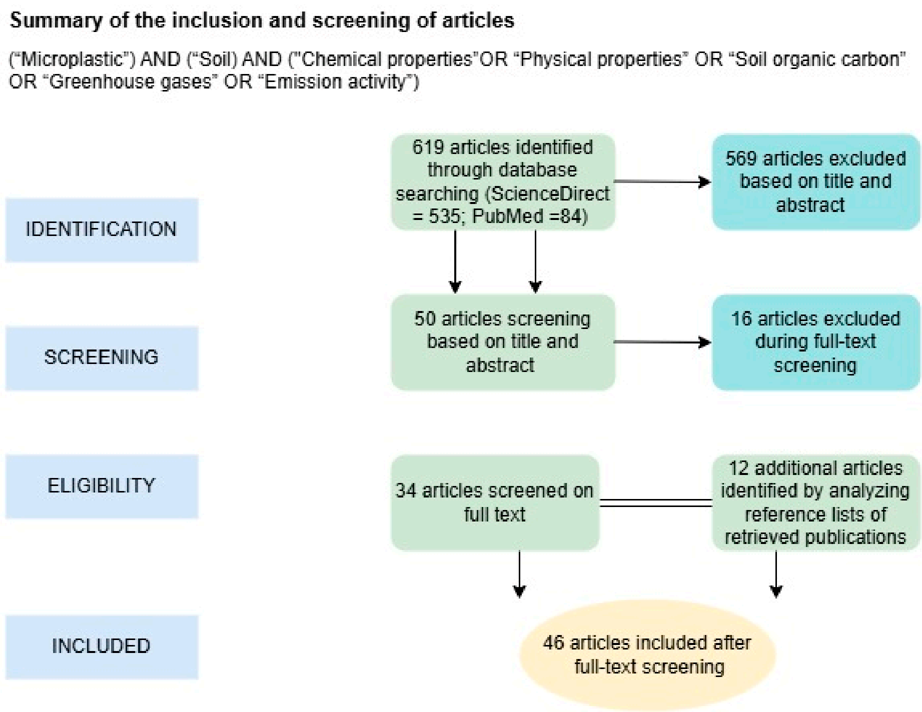

Figure 1. Flow chart of the literature screening.

The majority of authors (n = 28, 60.8%) in recent studies report increased CO_2 and/or CH_4 emissions, but in five of these studies, the effect (increase, decrease, or no change) depended on the type of MP and/or soil in soils containing MPs. However, there are also studies that have demonstrated the opposite [24,25] or a neutral result [26–29].

The mechanisms of MPs' influence on this process are receiving increasing attention. Several main research directions can be distinguished in terms of the impact on (1) vegetation cover, (2) decomposition processes, and (3) the microbiome.

3.1. Vegetation Cover

MPs can influence plant growth indirectly through their impact on the soil and rhizosphere microbiome, and the physicochemical properties of the soil [14]. There are reports of negative effects [20] of MPs on plant growth, but positive effects are more frequently observed [30–32]. The question of a dose-dependent effect of MPs on microorganisms and plants remains unresolved.

3.2. Decomposition Processes

If MPs increase plant growth independently of nutrient availability in the soil, the nutrient content in the foliage may decrease ("dilution effect"), leading to a reduced rate of decomposition. Furthermore, changes in the quality of leaf litter may result from impacts on the microbiome, for example, on the stimulation of root colonization by arbuscular mycorrhizal fungi, which have a significant influence on nutrient availability for plants. The slower decomposition of leaf litter can reduce carbon stabilization levels in soil organic matter. During the decomposition of lower-quality litter, microbes may consume nitrogen from soil organic matter to process C from the litter, thus resulting in a loss of soil C [33].

The pollution of soils and terrestrial ecosystems by MPs also affects larger representatives of the soil biota. Actively feeding living organisms may perceive MP particles as a food source, while organisms with a passive feeding type, such as filter feeders, are forced to ingest it [34]. Earthworms *(Lumbricidae)* transfer organic matter and other components to deeper soil layers, which play an important role in decomposition. The consumption of MPs by these organisms can increase their mortality and reduce their reproductive capacity [35].

3.3. Microbiome

The shift in microbial activity is associated with the following:

- Changes in the physicochemical properties of the soil (aeration, water-holding capacity, etc.). Soil microorganisms play a key role in maintaining soil structure, detoxifying pollutants, and regulating SOC turnover. Microorganisms are capable of not only converting dissolved organic matter into soil organic carbon, but also transforming labile substances into microbial biomass and its metabolites. Furthermore, most of the metabolites and residues of dead microorganisms can persist in the soil for a long period, constituting a stable pool of soil carbon;
- The direct toxic effect of substances contained within MPs, such as plasticizers, or pollutants adsorbed onto their surface (absorption of polycyclic aromatic hydrocarbons, polychlorinated biphenyls, dioxin-like chemicals, polybrominated diphenyl ethers, heavy metals, hydrophilic organic compounds like ciprofloxacin, and pharmaceuticals has been confirmed [36–38]);
- The "priming" effect upon the addition of certain types of MPs—enhancing microbial activity and subsequent potential changes in nutrient availability and dissolved organic carbon. However, the high C:N ratio of most MP types may cause nutrient immobilization and, conversely, reduce microbial activity [18].

Nearly a quarter of the studies (n = 8) focused on the impact of biodegradable MPs on carbon cycling and emissions. Biodegradable MPs are increasingly attracting the attention of researchers due to the large-scale use of mulching films and the growing popularity of their biodegradable alternatives. The aim of transitioning to such mulching films is to reduce plastic pollution in agricultural soils. However, the degradation of many of these films in the environment has proven to be too slow or incomplete, also resulting in MPs remaining in agricultural ecosystems.

4. Discussion

It is not entirely possible to directly compare the results of the reviewed studies, as there was significant variability in their methodologies, including the methods used for determining and evaluating the effects. Furthermore, authors selected various types of plastics, although polyethylene (PE) was used in the majority of studies using conventional plastics and polylactic acid (PLA) in those investigating the effects of biodegradable polymers.

4.1. Distribution by Soil Type

Rice paddy ecosystems attracted the attention of authors in at least four studies. Specifically, Xiao et al. (2021) [39] investigated the effect of PE MP addition on SOC decomposition in waterlogged gley soils of rice paddy ecosystems. Soils were used without MP addition, with low [0.01% w/w] and high [1% w/w] concentrations, and with the addition of rice straw and glucose. Compared to the control, the total amount of CO_2 derived from SOC in the soil with a low concentration of MPs decreased by 13.2% and 7.1% after the addition of straw and glucose, respectively. The authors concluded that low doses of polluting components of MPs promote SOM (soil organic matter) decomposition in rice soil. However, at a high concentration of MPs, SOM decomposition was lower than at a low concentration [39].

Wang et al. (2024) [40] studied the effects of three biodegradable plastic types—polybutylene adipate terephthalate (PBAT), polylactic acid (PLA), and polybutylene succinate (PBS)—on rice paddy and upland (mountain) soils. The study is notable because the authors conducted it in situ, assessing CO_2 and CH_4 emissions using a portable optical gas sensor. PBAT and PLA significantly increased CO_2 and CH_4 emissions, but PBS demonstrated the opposite result [40]. Thus, the impact of biodegradable plastics on CO_2 emissions may not be uniform.

Han et al. (2022) [41] studied the combined effects of hydrochar (HBC) and MP on CH_4 emissions in rice paddy soils. HBC is a new carbon-enriched material that serves multiple functions as a soil amendment, including reducing greenhouse gas emissions. The addition of HBC alone slightly reduced cumulative CH_4 emissions. However, the addition of PE and PP clearly stimulated an increase in the copy numbers of genes for CH_4 production (e.g., the *mcrA* gene), a decrease in the copy numbers of CH_4 oxidation genes (e.g., *pmoA*), and reduced crop yield, leading to an 83.5% increase in CH_4 emissions compared to the soil where only HBC was present. However, at the same time, no difference in the effects on CH_4 emission levels was observed between HBC and HBC combined with PP [38]. In a similar study, HBC and HBC combined with polyethylene terephthalate (PET) were added to rice paddy soils throughout the entire rice growth period. PET reduced bacterial diversity, but the combined addition of PET and HBC did not cause significant changes. At the same time, the relative abundance of some microorganisms associated with the carbon cycle (e.g., *Cyanobacteria*, *Verrucomicrobia*, and *Bacteroidetes*) changed at the phylum and class levels under all treatments. In addition, BC, PET, and their combination reduced CH_4 emissions, with the most pronounced reduction observed with the addition of HBC + PET [42]. Thus, both the potential of HBC in reducing greenhouse gas emissions and the soil response to MP addition in rice paddy ecosystems will vary significantly depending on the co-presence of different MP types.

In addition, heterogeneous results were observed in a study concerning mangrove ecosystem soils, which deposit large volumes of organic carbon due to high primary productivity and low rates of decomposition and carbon cycling. Moreover, because mangrove ecosystems are located in coastal zones, MPs enter them from both terrestrial and marine sources, which increases the level of pollution by this material. Zhou et al. (2024) demonstrated that MPs did not significantly affect the cumulative CO_2 emissions in the topsoil layer but significantly increased CO_2 release from the subsurface layer, and that the stimulating effect of biodegradable PLA on CO_2 release from the subsoil was stronger than that of PE [43]. One of the most important ecosystems regarding CO_2 sequestration is the wetland ecosystem. A review of the mechanisms of MPs' impact on this ecosystem concluded that MPs negatively affect SOC sequestration and enhance greenhouse gas emissions [32].

4.2. Distribution in Particle Size Fractions

Wang et al. 2024 observed that polypropylene (PP) and PLA increased CO_2 emissions by affecting organic carbon decomposition in different soil aggregates [40]. But although both PP and PLA contributed to increased CO_2 emissions, the effect depended on the type and concentration of PP as well as the size of soil aggregates. Changes in soil carbon stocks occurred mainly due to changes in organic carbon associated with macroaggregates. In macroaggregates, PP decreased soil organic carbon (SOC) and dissolved organic carbon (DOC). The opposite changes were observed in microaggregates, silt, and clay. PP and PLA reduced diversity and altered bacterial community structure. Microplastic-induced changes in functional genes were key drivers of their effects on carbon conversion in soil aggregates.

In their study, Yu et al., 2021 [44] observed a decrease in SOC in macroaggregates (>250 μm) and an increase in unaggregated silt and aggregated clay (<53 μm)—soil aggregates are the main depots of dissolved organic carbon (OC), and its protective mechanism is different in soil aggregates with different particle sizes. In the experiment of Ren et al., 2020 MPs at a concentration of 5% (by weight) had no significant effect on the DOC content in the short term in clay soil, and the DOC composition was related to the MP particle size: smaller particles, degraded in the environment, created a new environment for microbial life and increased the diversity of both bacterial and fungal communities in the contaminated soil [44]. In general, the transformation of the granulometric composition of fine particle fractions under the influence of microplastics is poorly studied and can be manifested in the transformation of the adhesive properties of soils, the formation of non-true microaggregates, reduction in the volume of useful pore space, and degradation of capillaries. This can directly and indirectly reduce the useful specific surface area of soil, thus destroying ecological niches of microorganisms.

The addition of aged MPs to loam disturbed the bacterial community and changed the physicochemical properties of soil, creating a favorable environment for increased microbial activity and, consequently, accelerating the decay of organic matter. However, a similar effect was not observed when pure MPs were added. This may be an indication of the effect of MPs on the physical, adhesion, colloidal, and water–air parameters of soils.

Aged MPs also yielded a higher carbon mineralization ratio than pure MPs in contaminated soils in a study on artificial soil composed of four different minerals: quartz–montmorillonite (mineral mixture), kaolinite (clay mixture), and goethite. The four model minerals increased DOC release and CO_2 emissions by altering the physicochemical properties of the MF and formed an environment for microbial growth. Increased enzyme activity was observed in all soil variants except montmorillonite, in which high CO_2 emission against the background of low enzyme activity was present due to the fact that most of the DOC was already mineralized. In general, the increased biomineralization of carbon by MP minerals is at variance with ideas about the protective role of minerals with respect to SOC.

One work was devoted to sandy loam soils, in which the effect of straw application to MP PE-contaminated soil was evaluated. The authors noted a decrease in the carbon level against the background of a significant increase in SOC in the fraction available to microorganisms [45].

Thus, the role of microplastics in soils can be multidirectional. In soils of heavy particle-size distribution, MPs can lead to the degradation of the pore environment and air capacity, also reducing water permeability and clogging pores and voids. This is far from a harmless effect, leading to a decrease in the specific surface area of the soil as a space for microbial life. In sandy loam soils, and especially in sandy soils, the accumulation of microplastic fine fractions in a certain amount can contribute to an increase in the range of ecological niches for microorganisms (Figure 2).

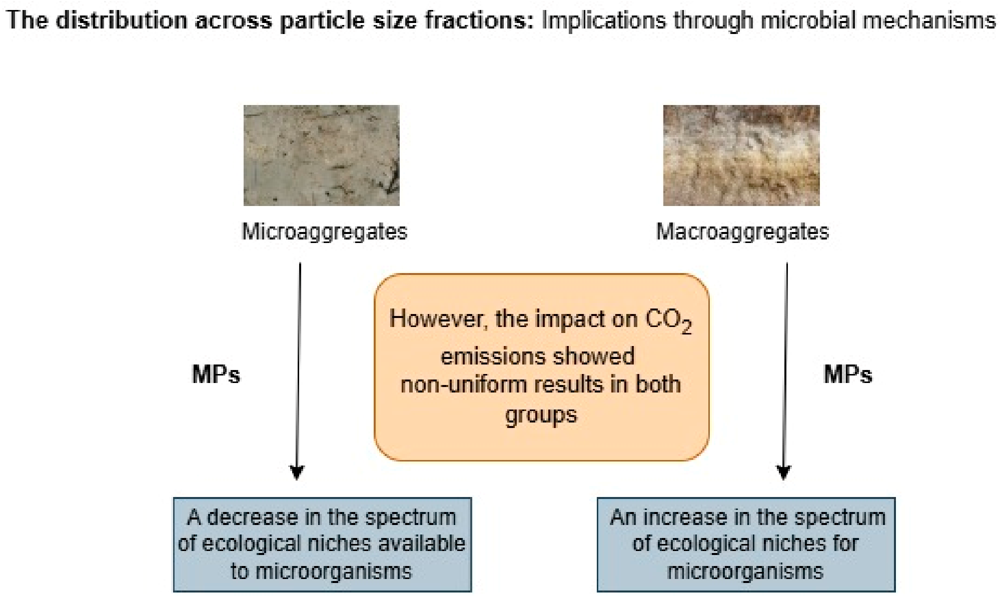

Figure 2. Influence of MPs through microbial mechanisms.

The data obtained on the presence or absence of an emission response to the addition of microplastics to various soil types [18–24,26–29,39–69] only indicate a short-term metabolic response, which depends on both the quality of the SOM itself and the oligotrophic–copiotrophic status of the microbiome of a particular soil. One of the tasks of modern soil ecology is to calculate the volumetric capacity of the soil in relation to microplastics—analogous to carbon capacity. This function of the soil can be considered a depository ecosystem service in relation to the overall health of ecosystems, although for the soil itself, this is more of a negative function, or anti-service, leading to the formation of delayed and accumulated chemical and physicochemical damage to soils [18].

5. Conclusions

A comparable and detailed study of the effects of MP presence and accumulation in soils is problematic: on the one hand, due to the impressive diversity of MP types and modifications (including those related to the size, nature, and aging of particles) and forms (fibers, particles, granules, etc.) which act differently, and on the other hand, due to the diversity of effects manifesting in different soil ecosystems. There is a very limited number of studies that examined the same type of soil, and even when 2–4 studies are available in which experiments based on soils from comparable ecosystems were conducted, the type and/or form of MP used, the concentration of polymer added, the temperature regime, the duration of the experiment, and other factors generally do not coincide. Given the growing volumes of soil pollution with this material, it remains crucial to (1) further clarify and develop our understanding of the impact of MPs on the carbon cycle in various ecosystems, (2) standardize methods for quantifying MPs and the carbon derived specifically from them in soils, (3) standardize approaches to conducting experiments, while the target MP concentrations for these should be based not only on current levels of pollution but also on future, expected higher levels, and (4) include as wide a variety of MPs as possible in future research.

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Abbreviations

MPs	Microplastics
OC	Organic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
OC	Organic carbon
DOM	Dissolved organic matter
CRFs	Controlled-release fertilizers
CSPs	Capsule suspensions
LDPE	Low-density polyethylene
PE	Polyethylene
PLA	Polylactic acid
PBAT	PBAT
PBS	Polybutylene succinate
PP	Polypropylene
PET	Polyethylene terephthalate
HBC	Hydrochar

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