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Microplastics alter soil carbon cycling: Effects on carbon storage, CO_2 and CH_4 emission and microbial community

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Abstract

Microplastics (MPs) are carbon-rich polymers that are ubiquitous in the environment. With the increase of plastic production, microplastic pollution may be exacerbated and result in significant changes in microbial communities and biogeochemical processes such as carbon cycling, eventually impacting greenhouse gas emission and carbon storage in terrestrial ecosystems. However, current research on the effect of MPs on soil carbon cycling is still limited, and there is a lack of systematic review of the scattered information obtained from previous studies. Accordingly, this review provides a systematic overview of the current knowledge on the effects of MPs on soil carbon cycling and gives future research suggestions. Emerging evidence indicates that MPs could affect soil carbon stability and CO_2 and CH_4 emission by modifying soil physicochemical and microbiological properties; though biodegradable MPs often exhibit a greater effect than nonbiodegradable ones, the specific effects are highly dependent on plastic type, size and concentration. The specific mechanisms of MPs' impact on soil carbon cycles remain elusive, which are discussed mainly from the perspective of microbial changes, including microbial biomass, microbial community composition, and key enzymes and functional genes associated with carbon metabolism. Further research is needed to elucidate whether MPs have a positive priming effect on soil carbon decomposition and the biotic and abiotic mechanisms involved. This review paper helps researchers gain a clearer picture of how and through which way MPs impact carbon cycling in soil ecosystems.

Impact statement

Microplastics (MPs) may have a profound impact on soil carbon stocks and global climate change by interfering with soil carbon cycling. This review paper systematically summarizes the current state of knowledge about the impacts of MPs on soil carbon cycles and the underpinning mechanisms. The effects of biodegradable and nonbiodegradable MPs are compared, and the influence of MPs property and soil conditions is analyzed. Key enzymes and functional genes involved in carbon metabolism that are affected by MPs are properly summarized. Knowledge gaps are identified, which can provide insights for follow-up research.

Introduction

As the production and consumption of plastics increase, plastic wastes become ubiquitous in the environment, posing harm to humans, other organisms, and the ecosystem (Karbalaei et al., 2018; Akdogan and Guven, 2019; Li et al., 2021b; Dissanayake et al., 2022). These plastic wastes can be broken down into small pieces under the action of physical, chemical, or biological forces, with those ≤5 mm defined as MPs (Thompson et al., 2004). Compared to the aquatic environment which has been extensively studied during the last decade, soil as another important, long-term sink for MPs is gaining increasing attention recently (Yang et al., 2021). The presence of MPs in soil can alter the degradation of organic matter and biogeochemical cycling (Riveros et al., 2022), but now, our understanding of the impacts of MPs on soil functions is still limited. In the context of promoting "carbon peak" and "carbon neutrality" strategies by many countries to cope with climate change and plastic pollution (Luan et al., 2023), more attention will be paid to the effects of MPs' inputs on carbon cycling in soil (Rillig et al., 2021b; Salam et al., 2023; Shen et al., 2023b).

Carbon storage and soil organic carbon (SOC) decomposition are critical factors for maintaining soil fertility and soil health, and also have important implications for mitigating climate change which is a global challenge for all humankind (Tao et al., 2023). MPs are polymers rich in carbon, and thus MPs themselves may contribute to soil carbon storage (Rillig, 2018). For instance, polyethylene (PE) and polystyrene (PS) contain almost 90% of carbon, and biodegradable polybutylene adipate-co-terephthalate (PBAT) contains 65–85% of carbon. Moreover, MPs in soil gradually break down over time although slowly, and can provide carbon substrates or favorable ecological niches for soil microbes (Yao et al., 2022), modifying the microbial traits associated with carbon metabolism (Yu et al., 2021b), and ultimately affecting the decomposition of SOC and the production of greenhouse gases such as CO_2 and CH_4 (Li et al., 2022b; Chen et al., 2023). Recent studies have shown that MPs' addition can significantly increase active carbon pool and CO_2 emission in soil (Gao et al., 2022; Shi et al., 2022; Zhang et al., 2023b).

Though the above studies greatly advance our understanding of MPs' effects on soil carbon cycles, the information obtained is scattered due to the high diversity of MPs used and sometimes conflicting results are reported. For example, 1% (w/w, referring to mass concentration throughout this review) of PE MPs were reported to increase CO_2 emission in one study (Zhang et al., 2022), while no effect was observed in another study (Yu et al., 2022). Moreover, the specific mechanisms through which MPs affect soil carbon mineralization remain largely unexplored. The relationship of microbial changes and altered carbon mineralization should be properly summarized. Therefore, a systematic literature review focusing on MPs impacts on soil carbon cycling and the underlying mechanisms is greatly needed, to provide insights for future research. The purpose of this study is to summarize the current research on the impacts of MPs on soil carbon cycling and possible mechanisms, in terms of carbon stability and storage, greenhouse gas emission, and microbial community. Both the impacts of biodegradable and nonbiodegradable MPs are included, and the influence of plastic type, size and concentration is discussed. Future research directions to address the key unanswered questions are proposed.

Effect of MPs on soil carbon storage and stability

Soil carbon pool is the largest carbon pool in terrestrial ecosystems, with implications for global climate change (Wang et al., 2022). By altering soil aggregates, MPs can affect soil carbon cycling and thus carbon stocks. Soil aggregates could protect organic matter from the attack of microbes, influencing the volume and stability of soil carbon pools (Wu et al., 2022). The presence of MPs may disrupt the formation or structure of soil aggregates (Boots et al., 2019). Due to the high hydrophobicity and persistence of plastic polymers, MPs can physically block the interactions between soil matrices and reduce the adhesion force between soil particles, thus decreasing the stability of aggregates while increasing soil porosity/aeration and microbial activity, which in turn accelerates SOC mineralization (Shi et al., 2022). In a 2-year study, Zhao et al. (2021) found that plastic film residues together with the generated MPs significantly lowered the proportion of soil macro-aggregate (>0.25 mm), and decreased aggregate-associated organic carbon content.

In addition, MPs as carbon-based polymers may have a direct effect on soil carbon storage. Theoretically, MPs rich in carbon would increase the organic carbon content in soil. This might be true for biodegradable microplastics (BMPs), which could be utilized by soil microbes and be incorporated into microbial biomass (Zumstein et al., 2018), thus participating in soil carbon cycles. Whereas, for the conventional nonbiodegradable MPs that are inherently inert, such as PE, polypropylene (PP), PS and polyethylene terephthalate (PET), it is debated. Currently, MPs-carbon has not been regarded as SOC yet, and available test methods cannot distinguish MPs' carbon from natural SOC (Rillig et al., 2021b). According to Kim et al. (2021), the determination of SOC using strong oxidants could result in the release of organic compounds from MPs, which are mistakenly considered to be SOC. Therefore, it is argued that MPs are disguised as soil carbon storage, leading to an overestimation of soil carbon stocks (Rillig, 2018; Hu et al., 2019). The potential effect of MPs on soil carbon storage is shown in Figure 1. To conclude, there is still debate about whether MPs can

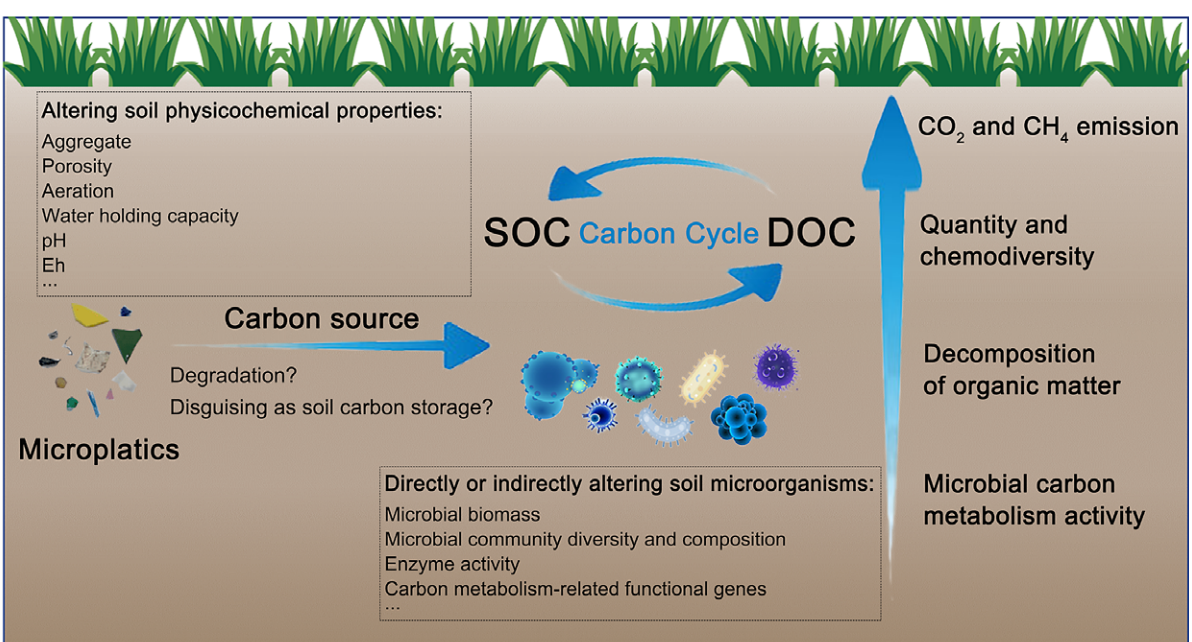

Figure 1. Impact of MPs on carbon cycling in soil environment.

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Table 1. Effects of microplastics on soil carbon storage and stability

MP type	Size	Concentration	Specific effects	Reference
PE, LDPE, PS, PAN (bead, fragment, film, and fiber)	29–485 μm	0.001%, 0.005%, 0.01%, 0.05%, 0.1%	SOC in soils containing PE MPs can be overestimated when using chemical oxidation method.	Kim et al. (2021)
LDPE (powder)	<1 mm	10%	In the context of straw incorporation, MPs reduced microbially available SOC and increased mineral–associated SOC.	Yu et al. (2021b)
PE, PLA (film)	–	–	Plastic film residues and the generated MPs massively re–shaped soil aggregate structure, and decreased the organic carbon content of soil aggregates.	Zhao et al. (2021)
PE, PS, PLA, PBS (granule)	150–180 μm	1%	MPs introduced labile carbon molecules and thus increased soil DOM lability.	Sun et al. (2022c)
PBAT (particle)	0.63 mm	5%, 10%	MPs significantly increased SOC and microbial biomass carbon (MBC) in soil.	Liu et al. (2023b)
PE, PLA (film)	–	0.5%, 1%	MPs increased soil DOC content.	Shi et al. (2022)
LDPE (film)	<187.5 μm	0.01%, 0.1%, 1%	MPs did not significantly affect soil DOC content.	Zhang et al. (2022)
PE (particle)	<13 μm, <150 μm	5%	MPs of both particle sizes did not significantly change the DOC content in soil, but small–sized MPs affected the composition of DOM.	Ren et al. (2020)
PP (particle)	<180 μm	7%, 28%	High levels of MPs tended to facilitate the long–term accumulation of high–molecular–weight aromatic compounds of DOM.	Liu et al. (2017)
PBAT (particle)	0.63 mm	5%, 10%	MPs significantly increased DOC molecules in soil and changed the aromaticity, molecular weight and humification of soil DOM.	Chen et al. (2022a)
LDPE, PLA/PBAT (particle)	250–500 μm, 500–1,000 μm	0.5%, 1%, 1.5%, 2%, 2.5%	LDPE MPs showed no significant effects on soil DOC, while 2.0% and 2.5% of PLA/PBAT BMPs significantly increased soil DOC.	Meng et al. (2022)

directly increase soil carbon storage, and it may be more appropriate to take plastic biodegradability into consideration when addressing this issue. Besides, it should be noted that, as MPs may be present at much lower levels than soil organic matter, MP concentration is an important factor when assessing the direct effect on soil carbon storage.

Furthermore, MPs can affect soil carbon stability, by altering the content and composition of dissolved organic matter (DOM) in soil. Dissolved organic carbon (DOC) is an active fraction of the SOC pool, which could be rapidly assimilated or mineralized by microbes; therefore, DOC content and composition are often used for monitoring the dynamic changes of soil active carbon pool (Wu et al., 2020). On the one hand, MP degradation in soil could lead to DOC accumulation. It has been demonstrated that BMPs (2–10%) could increase soil DOC content by releasing dissolved carbon molecules due to their superior degradability, and that higher MP concentrations result in a greater effect (Meng et al., 2022; Chen et al., 2022a; Sun et al., 2022c). High concentrations (28%) of PP MPs have also been reported to increase soil DOC content, which enhanced phenol oxidase activity and promoted the formation of high-molecular-weight aromatic compounds (Liu et al., 2017). As time proceeds, DOC content may show a trend of increasing first and then decreasing, due to that DOC molecules with higher bioavailability can be further decomposed by the microorganisms (Chen et al., 2022a). On the other hand, variations in the molecular properties and composition of DOM after MP addition may influence SOC mineralization (Zhang et al., 2019b). For example, 5–10% of PBAT BMPs altered both the quantity and chemodiversity of soil DOM; the aromaticity, molecular weight, and humification of DOM were increased, possibly because plastic degradation stimulated enzyme activities and promoted the accumulation of aromatic substances (Chen et al., 2022a; Liu et al., 2023b). In another study, 5% of PE MPs did not significantly change soil DOC content but affected DOM composition by accelerating the formation of aromatic compounds and humic substances (Ren et al., 2020). Recently, a positive correlation between DOC concentration, DOM electron-donating ability, and CO_2 emission was observed, suggesting that MPs may facilitate soil organic matter mineralization by modifying DOM concentration and components (Shi et al., 2023).

The effects of MPs on soil carbon stability and storage are summarized in Table 1. Since few studies have examined SOC changes (and MPs themselves can have an effect on SOC quantification), it is difficult to predict whether MPs would have a far-reaching impact on soil carbon storage. In addition, previous studies mainly focused on the changes in DOM content and chemical diversity, while few have explored the relationship between changes in DOM, SOC, and key carbon cycling processes. This information is important for elucidating the response mechanism of soil carbon cycle to MPs, especially in the context that the use of biodegradable plastics is growing which have a stronger effect on soil carbon stability.

Effect of MPs on greenhouse gas emission from soil

CO_2 and CH_4, the gaseous end products of organic carbon mineralization, are the two most significant contributors to the anthropogenic greenhouse effect (Yang et al., 2023). Investigating the association between MPs and soil CO_2 and CH_4 emission aids in predicting the impact of microplastic pollution on global climate change and the carbon cycles. Table 2 shows the current studies that examined the effects of MPs on soil CO_2 and CH_4 emission.

Effect of MPs on soil CO_2 emission

The presence of MPs may alter soil structure, leading to a variation in CO_2 emission. MPs can impede the formation of stable

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Table 2. Effects of microplastics on soil CO_2 and CH_4 emission

Process	MP type	Size	Concentration	Specific effects	Reference
CO_2 emission	PE	<13 μm, <150 μm	5%	MPs with larger size significantly promoted the release of CO_2.	Ren et al. (2020)
	LDPE (particle)	—	0.1%, 0.5%, 1%, 3%, 6%, 18%	MPs significantly promoted soil CO_2 emission, which increased with increasing microplastic concentration.	Gao et al. (2021)
	LDPE	<187 μm	0.01%, 0.1%, 1%	A high dose of MPs (1%) stimulated CO_2 production while low doses (0.01% and 0.10%) had negligible effects.	Zhang et al. (2022)
	PE, PLA (film)	—	0.5%, 1%	1% of PLA increased CO_2 emission by 19–74% at 25 °C.	Shi et al. (2022)
	PE, PLA (granular)	150–180 μm	1%	MPs increased soil CO_2 emission by 160–613%.	Shi et al. (2023)
	PLA, PBS, PHA (particle)	150–180 μm	3%	PHA has the highest degradability, resulting in a stronger priming effect and higher cumulative CO_2 emission.	Zhang et al. (2023a)
	LDPE, PBAT	50–200 μm, 200–500 μm, 0.63–1.2 mm	0.1%, 1%	No effect of LDPE on soil CO_2 emission could be detected, but a positive effect was found for 1% of PBAT.	Rauscher et al. (2023)
	PE	<187 μm	1%	Virgin or aged MPs did not significantly affect soil CO_2 emission.	Yu et al. (2022)
	LDPE (powder)	<1 mm	10%	MPs partially offset the increase of CO_2 emission induced by maize straw, and reduced the mineralization of SOC; the inhibitory effect was weaker in fluvo–aquic soil than in latosol soil.	Yu et al. (2021b)
	LDPE (powder)	<2 mm	10%	MPs reduced CO_2 emission from straw–added soil by 11%, compared to the soil containing only straw.	Shah et al. (2024)
	PE	40–48 μm	0.01%, 1%	In the context of straw and glucose addition, 0.01% of MPs decreased SOM–derived CO_2 by 13.2% and 7.1%, respectively.	Xiao et al. (2021)
	PE, PP, PS, PA, PVC	50–250 μm	0.3 g	Four minerals shaped the habitat for microbial growth, thus increasing DOC release and CO_2 emission from MPs.	Chen et al. (2022b)
CH_4 emission	PP, PE, PS, PET, PVC	100 μm	0.25%, 2%, 7%	All but 7% of the PVC MPs significantly increased soil CH_4 emission.	Chen et al. (2023)
	PE, PAN	200 μm	0.5%	CH_4 emission increased by 83.5% in the co–occurrence of hydrochar and PE compared to the hydrochar only.	Han et al. (2022)
	PE	<13 μm, <150 μm	5%	MPs of large size decreased CH_4 uptake.	Ren et al. (2020)
	PET	200 μm	0.5%	MPs reduced CH_4 emission by 53%. *mcrA* abundance was strongly correlated with CH_4 emission ($p < 0.001$).	Guo et al. (2022)
	PE	<187 μm	1%	MPs inhibited the release of CH_4, probably by regulating NH_4^+ substrate and methanogens.	Zhang et al. (2023b)
	PE, PLA (granular)	150–180 μm	1%	CH_4 emission in PLA and PE treatments were lower than that in the control.	Shi et al. (2023)
	PE	106–125 μm	1%	MPs addition alone did not affect CH_4 emission.	Li et al. (2022c)

agglomerates, making mineral-bound organic matter more susceptible to microbial oxidation, or create cracks between soil particles, resulting in an increase in soil porosity (Shi et al., 2022). Microbial mineralization of SOC benefits from good aeration, and thus an increase in air permeability may stimulate CO_2 production (Rillig et al., 2021a).

Previous studies demonstrated that MPs had a positive or no effect on soil CO_2 emission, which was dependent on microplastic

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biodegradability, type, size, concentration, and soil type. For instance, Ren et al. (2020) investigated the effect of 5% of PE MPs with different particle sizes on CO_2 emission from a fertilized soil during 30 days of incubation, and found that MPs with a small size (<13 μm) had no significant effect, while those with a large size (<150 μm) significantly increased the cumulative CO_2 emission by 9.79%. Rauscher et al. (2023) found that 0.1% and 1% of low-density polyethylene (LDPE) MPs had no significant effect on CO_2 emission in sandy loam and loamy soils with small (50–200 μm), medium (200–500 μm), and large (630–1,200 μm) particle size over 28 days. This could be due to that PE plastics are characterized by high-molecular-weight, C-H linear structure, high hydrophobicity, and high chemical stability (Meng et al., 2022). Higher doses or longer incubation time may be needed to observe a significant effect. In another study, 1% of PE MPs (150–180 μm) enhanced CO_2 emission by 146% in sandy loam soil over 60 days (Shi et al., 2023). The discrepancy could be due to differences in MP size or molecular weight (which information is not provided in most studies); moreover, soils of different origins were used in the above studies.

BMPs that can provide labile carbon have been reported to enhance soil carbon emission and show a greater effect than the conventional nondegradable MPs of the same dosage. Shi et al. (2023) found that 1% of polylactic acid (PLA) BMPs increased soil CO_2 emission by 648% (while it was 146% for PE MPs). In the above study by Rauscher et al. (2023), while 1% of LDPE MPs had little effect, 1% of PBAT BMPs significantly increased soil CO_2 emission in both soils (by 13–57%), with smaller particles having a more profound effect in the sandy loam soil, probably because smaller particles have a larger surface area for microbial attachment (Rillig et al., 2021b). The effect of different BMPs on SOC decomposition and mineralization also depends on their biodegradability. For example, poly-hydroxyalkanoates (PHA) which are more degradable than PLA and polybutylene succinate (PBS), could stimulate soil carbon loss to a greater extent by co-metabolism or "microbial nitrogen mining" (Zhang et al., 2023a). As observed for DOC variation, changes in CO_2 emission also show a dose-effect relationship in response to MPs, with greater changes generally observed at higher concentrations (Zhang et al., 2022).

Given the complexity of real soil environments, several studies have examined the influence of the coexistence of MPs with other organic matter or minerals. For example, Yu et al. (2021b) investigated the effects of LDPE MPs on CO_2 emission from fluvo-aquic and latosol soils amended with maize straw. It was found that MPs reduced SOC mineralization, offsetting the increase in CO_2 emission caused by maize straw, and that the inhibitory effect was more evident in the fluvo-aquic soil. Similarly, Shah et al. (2024) found that the presence of PE MPs reduced the carbon emission in soils amended with legume straw. When combined with glucose or rice straw, PE MPs (0.01%) reduced SOM-derived CO_2 by 13.2% or 7.1%, implying that MPs may limit the decomposition of soil organic matter, glucose or straw (Xiao et al., 2021). As for minerals, Chen et al. (2022b) added MPs into artificial soils comprised of different minerals, either quartz, montmorillonite, kaolinite, or goethite. By modifying MPs' physicochemical properties and shaping the habitat for microbial growth, four minerals increased the DOC release and CO_2 emission from nonbiodegradable MPs. The above studies provide basic data for the impacts of MPs on CO_2 emission in soil environments where straw residues and minerals are present.

At present, the proposed mechanisms for MPs-induced CO_2 emission changes involve the following aspects: (1) Improved aeration due to soil structure alteration after the addition of MPs could lead to increased CO_2 production (Rillig et al., 2021b; Shi et al., 2023), and vice versa, when effective pores are blocked by microplastic particles (Guo et al., 2022), a decline in CO_2 production may be observed; (2) MPs can induce soil colloids to release organic molecules, providing substrates for carbon mineralization. To be specific, MPs can form negatively charged surfaces, which interact with negatively charged soil colloids, resulting in the release of organic molecules from the clay-organic matter complex (Blöcker et al., 2020); (3) MPs themselves could act as carbon source or toxicant (e.g., additives and degradation products) and affect soil CO_2 emission by directly influencing microbial biomass and activity (Jian et al., 2020; Rauscher et al., 2023); and (4) The "negative or positive priming hypothesis" was proposed by Rillig et al. (2021b). While positive priming suggests that biodegradable plastics or more labile additives can accelerate SOC decomposition through co-metabolism, negative priming may be due to the dilution effect of MPs, adsorption of DOC on the plastic surface, and preferential utilization of the labile organic C derived from MPs. In a specific situation, whether the effect of MPs on soil CO_2 emission is positive, negative, or no influence, is determined by the combination of the above mechanisms. Most studies focus on one or two of the above mechanisms, while few attempt to explore multiple mechanisms or provide direct evidence for the proposed mechanism. Evaluating the contribution of each mechanism is very challenging, as the mechanisms can be interconnected.

Effect of MPs on soil CH_4 emission

The impact of MPs on soil CH_4 emission has been investigated in a few studies (Table 2), which is also greatly dependent on the type, concentration, and size of MPs. PE, PP, and polyvinyl chloride (PVC) MPs were reported to enhance soil CH_4 emissions, which increased with increasing PE concentrations (0–7%) but peaked at the low concentration (0.25%) in PP and PVC treatments (Chen et al., 2023), highlighting the influence of plastic type and concentration. The increasing trend in PE treatments was attributed to increased organic carbon content in soil after microplastic addition (caution is needed as the potassium dichromate oxidation method may lead to an overestimation of organic carbon content in soil with MPs and a similar increase in SOC content in other MPs treatments was also observed), while the inhibitory effect at high MPs concentrations of other plastic types may be due to suppressed hydrolysis, acidification, and methanation (Chen et al., 2023). Indeed, PE MPs have also been reported to negatively affect soil CH_4 emission (Shi et al., 2023; Zhang et al., 2023c), suggesting that the effect cannot be generalized based on MP type only. Moreover, the effect of MPs on CH_4 emission also varies by soil property. For example, PE MPs reduced CH_4 emission in acidic (by 16.9%) and alkaline (by 16.1%) soils, while the effect was not significant in neutral soils (Zhang et al., 2023c).

The possible mechanisms through which MPs influence CH_4 emission are summarized as follows: (1) MPs can incorporate into soil aggregates and increase soil Eh by improving aeration, which may inhibit methane production or accelerate its oxidation, thereby reducing CH_4 emission (Zhang et al., 2023c); (2) MPs may alter the abundance and activity of soil microorganisms involved in CH_4 oxidation (Ren et al., 2020); (3) Carbon-rich MPs can also stimulate N mineralization, producing NH_4^+ substrates that indirectly control CH_4 oxidation by competing with methanotrophs for oxygen, consequently leading to increased CH_4 emission (Yu et al., 2022; Zhang et al., 2023c); (4) The high surface area of MPs may facilitate

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DOC adsorption, thus limiting the utilization of unstable carbon by methanogens (organo–organo persistence hypothesis) (Rillig et al., 2021b); and (5) Redox-active functional groups can be formed on the surface of weathered MPs, which attract microbes who use MPs as electron sinks or donors. If the electron transfer makes microbial metabolism more energy efficient, it would result in faster organic carbon decomposition and altered methane emission (electrochemistry "electron shuttling" hypothesis) (Rillig et al., 2021b). Currently, few data are available on the effects of MPs (especially BMPs) on soil CH_4 emission. The mechanisms remain to be elucidated.

MPs alter microbial communities to affect soil carbon transformation

Soil microorganisms play pivotal roles in carbon cycling, participating in various processes such as carbon fixation, methane metabolism, and organic carbon decomposition (Naylor et al., 2020). Given that global production of plastics continues to grow, MPs contamination in soil may cause significant changes in microbial community composition and carbon metabolism activity, affecting the release of greenhouse gases and the stability of carbon pools, and eventually carbon storage. As a result, there is an urgent need to obtain a comprehensive and in-depth understanding of the effect of MPs on soil microbial communities and their association with carbon metabolism, which would help reveal the microbial mechanisms underlying altered carbon metabolism. In this review, MPs-induced changes in microbial biomass, community composition, enzyme activity, and functional genes involved in carbon cycling are discussed.

Effect of MPs on soil microbial biomass

Microbial biomass is one of the most commonly used parameters in soil C cycle modeling (Albright et al., 2020). MPs have been demonstrated to increase soil microbial biomass in several studies, implying that MPs may stimulate carbon emission by promoting basal microbial respiration. This is supported by the finding that total phospholipid fatty acids (PLFAs) increased with increasing LDPE microplastic concentration (0–18%), being consistent with the trend of CO_2 emission (Gao et al., 2021).

The effect of MPs on microbial biomass depends on plastic type, concentration, and biodegradability. Both PE and PVC MPs (1–20%) significantly increased soil microbial biomass, but the total PLFAs increased by 2.0, 1.3 and 1.6 times compared with the control at 5%, 10%, and 20% of PVC, respectively, while the total PLFAs increased only slightly (17–45%) with PE addition and exhibited little variation at different concentrations (Zang et al., 2020).

BMPs are more readily utilized by microorganisms as a carbon source and can greatly stimulate the growth of microbes (Fan et al., 2022). For example, the addition of 10% of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) MPs significantly enhanced the microbial biomass (as indicated by microbial biomass carbon) in soil, up to 12 times higher than that in the control soil (Zhou et al., 2021). The ability of soil microorganisms to incorporate plastic polymers into their biomass has been demonstrated in a previous study: by using the ^{13}C isotope tracer technique, the authors found that the carbon atom of PBAT molecules was utilized by soil microorganisms, such as filamentous fungi and unicellular organisms (Zumstein et al., 2018). In general, high concentrations (>1%) of MPs are more likely to cause a significant increase in microbial biomass, probably because high levels of MPs supply more readily available carbon (e.g., polymers, additives, and impurities).

Effect of MPs on soil microbial community diversity and composition

Microbial community diversity

MPs can stimulate or inhibit specific microbial taxa by modifying soil physical properties and nutrient conditions, leading to altered microbial community diversity (Yu et al., 2021a). The effect of MPs on soil microbial diversity (also known as alpha diversity) is closely related to MPs size, dose, and type. For example, small-sized (<13 μm) PE film MPs increased the richness and diversity of bacterial and fungal communities in soil, whereas large-sized (<150 μm) ones increased and decreased bacterial richness and diversity on days 3 and 30, respectively, and decreased fungal richness and diversity on both days (Ren et al., 2020). Judy et al. (2019) found no significant changes in bacterial community diversity in soils with 0.01–1% of PVC MPs, while Fei et al. (2020) reported a dramatic decrease at a high concentration (5%). PBAT BMPs had a greater effect than the conventional LDPE MPs within the same concentration range (0–5%) (Li et al., 2022a; 2023a), probably because BMPs were more readily utilized by microorganisms, thus having stronger interactions with microorganisms. In many cases, the effect of microbial diversity shows the tendency: positive or no effect at low MP concentrations, while negative effect at high concentrations (Li et al., 2022a; 2023a). This may be related to the fact that higher levels of MPs can have a stronger stimulatory or inhibitory effect on specific taxa. In addition, the response of microbial diversity to MPs can be quite different in different soils (Shi et al., 2022). It is reported that MPs exposure has a greater impact in soils with a lower microbial diversity (Li et al., 2022a).

Microbial community composition

Studies have found that MPs with a large specific surface area can provide new niches for microbes (Arias-Andres et al., 2018), rendering them unique habitats for microbial colonization (forming "plastisphere"), which has the potential to alter the overall soil microbial community composition. For example, the MPs derived from mulch films possessed distinct bacterial communities from the surrounding soil in the cotton fields in Xinjiang (Zhang et al., 2019a); PE MPs in soil was colonized by a unique bacterial community, with potential plastic degraders and pathogens being more abundant (Huang et al., 2019). A significant effect of LDPE MPs on the overall soil bacterial community structure was observed in another study, with some enriched taxa being associated with plastic degradation or biofilm formation (Wang et al., 2020). Modified microbial communities seem to benefit the degradation of MPs, and can also lead to changes in the decomposition or mineralization of SOM, as some enriched taxa may be involved in the decomposition of natural organic matter. PE MPs (1%) were reported to increase the relative abundance of r-strategic bacteria belonging to Clostridia (e.g., *Ruminiclostridium*, *Mobilitalea*, *Eubacterium*, *Anaerobacterium*, and *Papillibacter*) in soil, which was positively correlated with CO_2 emission rates (Xiao et al., 2022).

Influencing factors

Changes in soil microbial community composition vary considerably in different studies, largely depending on plastic type/biodegradability and other factors. Although most nonbiodegradable

MPs lack other reactive functional groups on the C–C main chain and not a good carbon source for microorganisms (Shen et al., 2023b), they can provide niches (Wang et al., 2022; Zhang et al., 2024) or affect soil physical properties (de Souza Machado et al., 2018b; Shi et al., 2022) for selection of specific microbial taxa; and due to the accumulation and duration of MPs in the environment, the ultimate impact cannot be ignored. For instance, PE MPs (1–20%) were found to decrease actinomycetes, whereas PVC MPs stimulated actinomycetes and arbuscular mycorrhizal fungi in soil (Zang et al., 2020). In another study, PE MPs (0.2%) showed a significant effect on soil fungal community structure, possibly by affecting the growth of fungal hyphae through blocking soil pores (Li et al., 2021a). The addition of PP MPs significantly increased the relative abundance of bacterial phyla *Actinobacteria* and *Patescibacteria*, while decreased the relative abundance of *Proteobacteria*, *Bacteroidetes*, *Gemmatimonadetes* and *Chloroflexi* (Sun et al., 2022b). Since MPs effects differ in different soils (Salam et al., 2023), it is difficult to draw a general conclusion for a specific plastic type. Additionally, temperature has also been reported to affect the interactions between MPs and soil microorganisms (Shi et al., 2022; Shen et al., 2023a), but relevant studies are scarce.

BMPs generally exhibit a more profound effect on soil microbial community composition than nonbiodegradable MPs at the same dosage. For example, a shift in bacterial community composition (enrichment of the polyester-degrading *Caulobacteraceae*) was observed in PBAT-amended soils but not in LDPE-amended soils (Rauscher et al., 2023). PBS and PLA MPs increased the relative abundance of *Proteobacteria*, *Bacteroidetes,* and *Firmicutes* in soil, while there was no significant difference in bacterial composition after the addition of nonbiodegradable PE and PS MPs (Sun et al., 2022a). Shi et al. (2022) found that PLA MPs stimulated *Actinobacteria*, *Chloroflexi*, *Acidobacteria*, and *Bacteroidetes,* which were strongly and positively correlated with DOC content and CO_2 emission in soils at 25 °C, while PE MPs had a minor effect on bacterial community and soil organic matter stability. The discrepancy in microbial community response to biodegradable and nonbiodegradable MPs can be explained by the fact that BMPs can be more easily degraded by biotic and abiotic processes, releasing soluble organic carbon, which can serve as additional carbon sources for microorganisms in the surrounding environment (Feng et al., 2023; Zhou et al., 2023).

In summary, both biodegradable and nonbiodegradable MPs could affect soil microbial community diversity and composition, While the former can directly interfere with soil microbes by supplying extra labile carbon, the latter's impact may be more indirect due to its recalcitrance. Alterations in the overall microbial community composition or the relative abundance of specific taxa after MPs addition, may considerably influence carbon or nutrient cycling processes, as have been observed in a few studies (Shi et al., 2022; Xiao et al., 2022). However, the interactions between microbiota and MPs are complicated, being influenced by various factors (i.e., MPs and soil properties). Further research is required, to gain a better understanding of the relationship of microbial community changes (which is commonly analyzed based on bacterial 16S or fungal 18S rRNA genes not functional genes) and SOC decomposition in MPs-polluted soils.

Effect of MPs on soil enzyme activities

Microbial metabolism is mainly mediated by intracellular and extracellular enzymes. Soil organic matter (e.g., starch, sucrose, cellulose, hemicellulose, and lignin) is decomposed by microorganisms that harbor corresponding enzymes, contributing to the carbon cycle and energy flow in soil (Mayer et al., 2020). Therefore, enzyme activities are important indicators of soil carbon metabolism capacity (Wu et al., 2021). MPs may affect enzyme activities by modifying the abundance and composition of microbial communities, resulting in altered soil functions.

Some studies have demonstrated that the presence of MPs could affect enzyme activities associated with carbon metabolism. For BMPs, 2% of PLA MPs increased soil DOC content as well as sucrase and catalase activities (Feng et al., 2022). PBAT MPs significantly increased soil sucrase and cellulase activities and accelerated the hydrolysis of polysaccharides (e.g., oligosaccharides and sucrose) into monosaccharides, which in turn provided energy for microorganisms to degrade MPs (Chen et al., 2022a). Similarly, Zhou et al. (2021) found that PHBV MPs improved β-glucosidase activity in soil, which may accelerate carbon transformation. In comparison to BMPs, nonbiodegradable MPs have stable polymer chains and are difficult to degrade, providing less available carbon for microorganisms in the short term, but may affect enzyme activities at high concentrations. For example, 28% of PP MPs significantly increased phenol oxidase activity in soil (Liu et al., 2017); soil β-glucosidase and xylosidase activities were significantly reduced by 16–43% after the addition of 20% of PVC MPs (Zang et al., 2020).

Enhanced soil enzyme activities could be explained by the following two aspects: First, MPs addition may have changed carbon and nutrient conditions in soil, shaping microbial communities towards copiotroph organisms that can synthesize high quantities of hydrolytic enzymes (Lin et al., 2020); Second, MPs addition may increase soil water holding capacity, and greater water availability has often been linked to an increase in enzyme activity (de Souza Machado et al., 2018a). Whereas, MPs may inhibit soil enzyme activities through the adsorption of organic substrates (Yu et al., 2022), causing N and P limitation for microorganisms (Yu et al., 2020), releasing toxic additives (Wang et al., 2016), and negatively affecting the growth and activity of carbon-metabolizing microbes (Yao et al., 2022).

The effect of MPs on enzyme activities varies in different studies. Is there a general pattern? Recently, a meta-analysis focusing on the effects of nonbiodegradable MPs on soil respiration and enzyme activities showed that the specific effects varied with MPs type, concentration, and incubation conditions. The pattern can be summarized as follows: as a whole, PP and polyethersulfone (PES) MPs significantly increased soil enzyme activities while PE, PS and PET MPs significantly inhibited it; when MPs concentrations were $< 1\%$ and $> 10\%$, soil enzyme activities were stimulated and inhibited, respectively, which could be due to the higher stress posed by high levels of MPs; MPs enhanced enzyme activities in acidic soils while inhibited them in alkaline soils, which might be related to the different adsorption capacity of MPs at different pH values (Luo et al., 2020); in the presence of plants, MPs significantly increased soil enzyme activities (Liu et al., 2023a). In terms of carbon metabolism enzymes, β-glucosidase activity was the most frequently studied. In general, PET and PES had no significant effect, PP increased β-glucosidase activity, while PE, PVC, PS, and polyamide (PA) decreased it (Liu et al., 2023a).

Currently, no systematic meta-analysis has been conducted on BMPs. To precisely predict the impacts of MPs (both biodegradable and nonbiodegradable) on soil carbon metabolism, there is a great need to conduct a comprehensive analysis of the impacts of BMPs on soil enzymes. Apart from β-glucosidase activity, the activities of other key enzymes, as well as the related mechanisms, should be included.

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Effect of MPs on functional genes involved in carbon cycling

While microbial community composition and enzyme activity analysis help gain a clue on carbon metabolic changes caused by MPs, investigation of the functional genes involved in carbon cycling can greatly expand our understanding of the key processes or functional microbial groups that are affected. It is useful for revealing the driving mechanisms of altered soil carbon cycling from the molecular level. Molecular techniques such as quantitative polymerase chain reaction (PCR), amplicon sequencing and metagenomic sequencing can be used, and the genes commonly targeted include carbon fixation, carbon degradation, methanogenic, and methane-oxidizing genes.

Some nonbiodegradable MPs have been found to affect the abundance of genes related to carbon fixation and degradation in soil. PA MPs increased the abundance of *accA* and *pccA* genes, inferring improved carbon fixation potential in soil (Sun et al., 2023). In PE film-contaminated soils, *β*-glucosidase and chitinase activities were reduced, and the abundances of one carbon fixation gene (*cbbL*) and two carbon source hydrolase-coding genes (*β-glu* and *chiA*) were also decreased, suggesting that MPs may reduce soil organic matter content and soil fertility by down-regulating genes and enzyme activities involved in carbon cycling (Qian et al., 2018). In the soils with lettuce, 1% of phenol formaldehyde-associated MPs significantly reduced the abundance of lignin degradation gene (*lig*) (Li et al., 2023b). A linear relationship was found between the abundance of functional genes related to hemicellulose (*abfA*) and lignin (*mnp*) degradation and soil CO_2 emission after the addition of PE MPs, indicating that MPs accelerate carbon mineralization by affecting microorganisms that could decompose soil organic matter (Yu et al., 2022). For carbon fixation, functional genes may respond earlier to MPs pollution than gas emission. Gao et al. (2022) found that LDPE MPs (0.5%) had little effect on soil CO_2 emission while significantly reduced the abundance of carbon fixation genes (*acsE* and *frdA*) after 23 days of incubation.

For methane metabolism, MPs (mainly nonbiodegradable ones as former studies pay more attention to the conventional plastics) can have a positive, negative, or no effect, depending on MPs type and soil type. For example, PE MPs (1%) decreased the abundance of the methanogenic gene *mcrA* in acidic soil and increased the abundance of the methane-oxidizing gene *pmoA* in the alkaline soil, which led to a reduction in CH_4 emission; however, no significant effect was observed in the neutral soil (Zhang et al., 2023c). MPs effect can be different when they coexist with other organic substrates (e.g., biochar, and straw), with improved soil aeration. Han et al. (2022) found that the coexistence of PE MPs and hydrochar significantly increased *mcrA* and decreased *pmoA* gene abundance, resulting in accelerated CH_4 release during the growing season of rice. In addition, MPs concentration is also an important factor to be considered. For example, 0.3% of PA MPs increased the abundance of *mnp*, *chiA*, *mcrA*, *pmoA*, and *mmoX* genes, indicating accelerated SOC decomposition and methane metabolism, while 1% of PA MPs showed a tendency to inhibit them (Sun et al., 2023).

MPs effects on enzymes and functional genes are summarized in Figure 2. Since microorganisms are involved in a range of carbon cycling processes, the overall impact of MPs on soil carbon cycling is determined by the combined outcomes of functional gene changes, which means that targeting various genes rather than one or two genes is more appropriate. So far, only a few studies have investigated the changes in functional gene abundance triggered by MPs. Little is known about the effects of BMPs and the changes in the taxonomic information of functional genes, which should be strengthened.

Conclusion and future research perspectives

In this review, the effects of MPs on soil carbon stability and storage, greenhouse gas emission, and microbial community are summarized. Previous studies have demonstrated that in most cases MPs can alter the physicochemical and microbial traits of soil, which in turn affect soil carbon cycling (although the case that no-effect results are not fully reported cannot be excluded). In particular, biodegradable plastics whose usage is growing rapidly in recent years are susceptible to microbial degradation, and thus may have a more profound impact on soil carbon pool and greenhouse gas emission, ultimately influencing global climate change. To improve our understanding of how MPs affect soil carbon cycling, more attention should be paid to the following aspects:

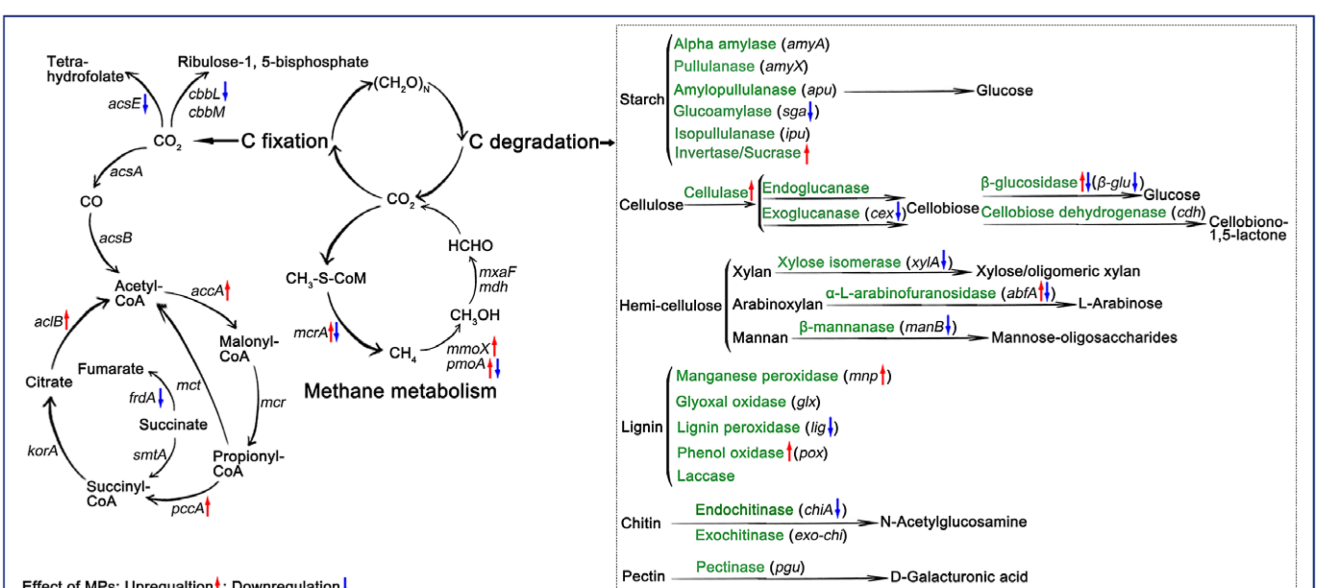

Figure 2. An overview of MPs effect on enzyme activities and functional genes involved in soil carbon cycling. The diagram is adapted from Gao et al. (2022) and Zheng et al. (2018).

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(1) MPs are reported to affect CO_2 emission from soils, but it is unclear whether the increased CO_2 emission originates from MPs breakdown or enhanced mineralization of native organic matter in soil. Future studies should consider using the ^{13}C isotope technique to elucidate the fate of MPs in soil and to identify the source of CO_2. Then, we can figure out whether MPs (especially BMPs) have a positive priming effect on SOC mineralization.
(2) It is unclear, for which plastic type, which contamination level, and in which soils, MPs would promote SOC mineralization and CO_2 emission. This information is essential for predicting greenhouse gas emission and for preventing soil degradation. It may be necessary to establish a database on the impacts of MPs on carbon mineralization, based on detailed information of MPs and soil properties.
(3) The specific mechanisms by which MPs affect soil carbon cycling have not been fully understood. For abiotic mechanisms, we need to better define the role of changes in soil porosity, physical protection by aggregates, Eh, and electron transfer capacity in organic carbon mineralization; for biotic mechanisms, we need to better understand the functional microbial groups involved in carbon metabolism.
(4) The combined effects of MP mixtures or MPs and other organic matter on soil carbon cycling should be studied in depth. In real soil environments, MPs often coexist with other organic matter (e.g., crop residues), which brings uncertainty to microbial community succession and greenhouse gas emission. Furthermore, long-term field experiments are needed to better evaluate the risks of MPs in soil ecosystems.

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