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Global Responses of Soil Carbon Dynamics to Microplastic Exposure: A Data Synthesis of Laboratory Studies

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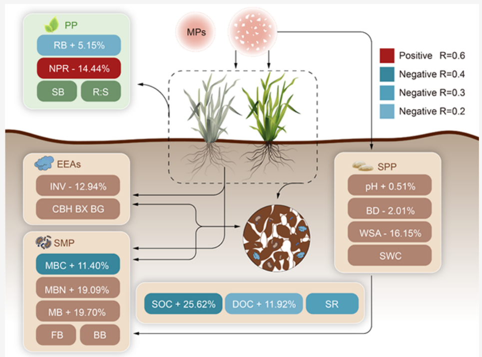
ABSTRACT: Microplastics (MPs) contamination presents a significant global environmental challenge, with its potential to influence soil carbon (C) dynamics being a crucial aspect for understanding soil C changes and global C cycling. This meta-analysis synthesizes data from 110 peer-reviewed publications to elucidate the directional, magnitude, and driving effects of MPs exposure on soil C dynamics globally. We evaluated the impacts of MPs characteristics (including type, biodegradability, size, and concentration), soil properties (initial pH and soil organic C [SOC]), and experimental conditions (such as duration and plant presence) on various soil C components. Key findings included the significant promotion of SOC, dissolved organic C, microbial biomass C, and root biomass following MPs addition to soils, while the net photosynthetic rate was reduced. No significant effects were observed on soil respiration and shoot biomass. The study highlights that the MPs concentration, along with other MPs properties and soil attributes, critically influences soil C responses. Our results demonstrate that both the nature of MPs and the soil environment interact to shape the effects on soil C cycling, providing comprehensive insights and guiding strategies for mitigating the environmental impact of MPs.



KEYWORDS: *microplastics, soil organic carbon, soil respiration, meta-analysis*

1. INTRODUCTION

Plastic pollution, a growing global concern,[1−3] primarily arises from the fragmentation of larger plastics into microplastics (MPs) typically ranging in size from 1 μm to less than 5 mm in diameter.[4−6] Detected in aquatic and terrestrial ecosystems and even the atmosphere,[3,7−9] these MPs represent a widespread environmental threat primarily due to the improper disposal of plastics.[2,3,10] In terrestrial environments, significant MPs sources include biosolid application, agricultural practices, and plastic mulch.[11−13] Recognizing the potential direct and indirect impacts of MPs on soil health and biota is crucial for understanding the ecological risks they pose.[14−18]

Soil carbon (C) stocks in terrestrial ecosystems are 3 times larger than the atmospheric C pool, highlighting that even minor changes in soil C could significantly affect atmospheric greenhouse gas concentrations.[19,20] MPs pollution is increasingly recognized as a significant environmental concern, with emerging research suggesting its potential influence on soil C dynamics.[5,8] Despite numerous individual experiments conducted in recent years to determine the effects of MPs exposure on terrestrial ecosystem C cycles, results remain inconsistent.[4,21] Some studies report that MPs increase soil organic C[22,23] or neutral responses at lower concentrations of MPs and polyvinyl chloride MPs.[24,25] The inconsistency extends to soil respiration, with studies reporting varied effects of MPs exposure.[26−29] Past reviews have explored MPs' impacts on soil ecosystems, but often these investigations have been limited to certain soil C components, contributing to mixed conclusions regarding MPs' overall influence on soil C dynamics.[14,16,30]

The influence of MPs on soil C is shaped by various factors, notably MPs characteristics, experimental conditions, and soil attributes.[5,31] Research has demonstrated varying impacts of MPs on soil organic C (SOC), revealing that the effects are contingent on MPs' type and concentration. For example, Qin et al.[32] found no significant differences in SOC among HDPE-MPs, PP-MPs, and PS-MPs at a dose of 1 g kg^{-1} dry soil, while Yu et al.[33] observed significant differences among PE-MPs, PP-MPs, and PS-MPs at a dose of 10 g kg^{-1} dry soil. Similarly, the influence on dissolved organic carbon (DOC) varies with MP types, with Shang et al.[34] finding more positive effects on DOC with nondegradable PE-MPs than biodegradable PBAT-MPs. In contrast, Sun et al.[35] observed greater effects on DOC from biodegradable PBS-MPs and PLA-MPs than nonbiodegradable

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PE-MPs and PS-MPs. MPs size also plays a critical determinant, affecting soil respiration rates differently based on MPs diameter, as reported by Zhang et al.,[36] which suggested that 10 g kg^{-1} PE-MPs with a diameter of 187.5 μm had no significant effects on soil respiration, while respiration significantly increased with 10 g kg^{-1} PE-MPs of 252.71 μm in diameter. The soil's inherent characteristics further modulate the response of soil C to MPs, with distinct variations in respiration rates under different soil types and temperatures observed. A previous study found significant differences in black soil respiration at 25 °C between 5 and 10 g kg^{-1} PE-MPs, but not in loess.[28] Moreover, the duration of MPs exposure plays a significant role in their impact on soil C dynamics. Long-term exposure to MPs increased DOC, regardless of the MPs type, while short-term exposure had no significant effect.[37] Furthermore, the context of agricultural practices also reveals varied responses in soil C; the study showed that PET-MPs exposure did not stimulate DOC in the soil of a wheat-rice rotation crop[38] but significantly reduced DOC in the absence of plants.[39] These findings underscore the intricate interactions among MPs, soil characteristics, and environmental conditions, emphasizing the need for a comprehensive global analysis. Such analysis is vital to understand and predict the changes in soil C dynamics and their broader environmental implications in the context of ongoing environmental changes.[40]

In this global meta-analysis, we aimed to synthesize existing research to clarify how MPs characteristics, soil attributes, and environmental conditions collectively influence soil C changes. The objectives were three-fold: (i) to identify the responses of soil C and soil respiration to MPs exposure; (ii) to evaluate the effects of MPs on soil C changes, factoring in the interplay of MPs characteristics, edaphic attributes, and experimental conditions; and (iii) to identify these factors as the primary contributors modulating the responses of soil C processes to MPs.

2. MATERIALS AND METHODS

2.1. Literature Search and Screen. We collected peer-reviewed studies published up to January 12, 2023, focusing on the responses of soil C cycling to MPs exposure. The database included the Web of Science (Core Collection) and Google Scholar. We employed various combinations of the following keywords/phrases: (microplastic* OR nanoplastic* OR "plastic microparticles" OR microfiber) and (SOC OR "soil organic carbon" OR SOM OR "soil organic matter" OR DOC OR "dissolved organic carbon" OR "soil respiration" OR "soil CO_2 emission*" OR "carbon emission*" OR "C emission*" OR "carbon flux*" OR "C flux*" OR "greenhouse gas*" OR MBC OR "microbial biomass C" OR "microbial biomass carbon" OR MBN OR "microbial biomass N" OR "microbial biomass nitrogen" OR PLFA OR "phospholipid fatty acid" OR "bacterial biomass" OR "fungal biomass" OR invertase OR sucrase OR β-1,4-glucosidase OR β-xylosidase OR cellobiohydrolase OR "bulk density" OR "soil water content" OR "soil moisture" OR "water-stable aggregate*" OR "soil propert*" OR "root biomass" OR "below biomass" OR "shoot biomass" OR "above biomass" OR "root:shoot ratio" OR "photosynthetic rate").

Afterward, We followed strict criteria to minimize bias: (i) involving MPs exposure in soil; (ii) examining specific variables associated with soil C cycling like SOC, DOC, and microbial biomass; (iii) detailing the MPs concentration and having treatment and control groups; (iv) excluding data if combined with other factors like fertilizers or heavy metals; (v) providing clear statistical details, such as means and standard deviations; (vi) treating factors like different types and concentrations of MPs as categories within variables; (vii) only considering the latest sampling date; and (viii) using the most recent data if multiple sources reported the same experiment. Following these criteria and the PRISMA guidelines,[41] we included 580 paired observations from 110 articles in this meta-analysis (Supporting Information, Figure S1 and Notes S1).

2.2. Data Extraction. For each study, we extracted information about the means, SDs or SEs, and sample sizes of SOC, DOC, SR (soil respiration), SWC (soil water content), BD (bulk density), WSA (water-stable aggregate), MBC (microbial biomass C), MBN (microbial biomass N), BB (bacterial biomass), FB (fungal biomass), MB (microbial biomass), INV (invertase), BG (β-1,4-glucosidase), BX (β-xylosidase), CBH (cellobiohydrolase), RB (root biomass), SB (shoot biomass), R:S (root:shoot ratio), and NPR (net photosynthetic rate) in both MPs treatment and control group. Meanwhile, supporting information such as the type of MPs, size of MPs, concentration of MPs, experimental duration, MPs biodegradation, initial soil pH, initial SOC, and plant species was also collected in the data set.

2.3. Data Calculation. When only the SOM value was reported in data source references, we transformed SOC (g kg^{-1}) from SOM (g kg^{-1}) using a standard conversion factor of 0.58.[42] If the soil pH was determined with $CaCl_2$, then we employed the formula $pH[H_2O] = 1.65 + 0.86 \times pH[CaCl_2]$ suggested by Zeng et al.[43] When only the standard error (SE) was available in the data source reference, the standard deviation (SD) was calculated with the equation SD = SE $\times$ ($n^{0.5}$), where n is the sample size.[17] If neither SE nor SD was included from selected studies, then the mean was converted to SD by SD = mean $\times$ 1/10.[15]

2.4. Data Categorization. Effects of MPs exposure on studied soil C variables compared to without MPs were identified according to the subgroups (types of MPs, MPs biodegradation, sizes of MPs, initial soil pH, initial SOC, experimental duration, and the absence or presence of plants). The factors driving the responses of soil C changes to MPs exposure were subdivided as follows. The types of MPs were categorized into six categories: polybutylene adipate-*co*-terephthalate (PBAT), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polyscience (PS). MPs biodegradation was grouped into Yes (biodegradable MPs) and No (non-biodegradable MPs).[14] The sizes of MPs (μm) were divided into three groups: <50, 50−100, and >100 μm. The initial soil pH was categorized into three categories: acid (pH < 6.5), neutral (pH 6.5−7.5), and alkaline (pH > 7.5).[44] The initial SOC (g kg^{-1}) was grouped into three classes: <10, 10−20, and >20 g kg^{-1}.[45] In light of our results of meta-regression analysis under random model effects, the experimental duration was divided by <30, 30−60, and >60 days.[30,46] In addition, we had a category that contained two plant subgroups in the experiments (with and without planting, named "present" and "absent").[30]

2.5. Meta-Analysis. To quantify the impact of MPs on soil C dynamics, the natural logarithm of the response ratio (ln*RR*) was used, where ln*RR* represents the ratio of soil C variables between MPs-treated and control.[47] The variance (v) of ln*RR* was calculated as outlined by Hedges et al.[47] To verify the meta-analysis's foundational assumptions, we evaluated the heterogeneity among the weighted response ratios (RR_{++}) within our compiled data set.[48] This involved calculating RR_{++} and CIs for distinct categories under a random effect model. Details of the meta-analysis are included in the Supporting Information.

2.6. Statistical Analysis. Linear regression analysis was adopted to study the relationships among the MPs concentration and various soil factors like SOC, DOC, SR, MBC, RB, and NPR under MPs exposure using Origin 2023 software (OriginLab Corporation, Northampton, MA, USA). The model selection analysis was performed in R 4.2.2[49] with the "gbmplus" package, using 500 trees and other specified parameters to understand the relative importance of MPs characteristics, soil characteristics, and experimental conditions on soil carbon's response to MPs. Influential factors were identified with a threshold value of 0.8 based on Akaike's Information Criterion.[46,50] Forest Plots were also made using Origin.

3. RESULTS

3.1. Comprehensive Impacts of MPs on C Dynamics. Compared to control groups, the exposure of soils to MPs at a concentration range of 0.01−280 g kg^{-1} significantly increased SOC (mean: 25.62%; Figure 1a, with abbreviations defined in Table 1) and DOC (11.92%), and slightly raised soil pH

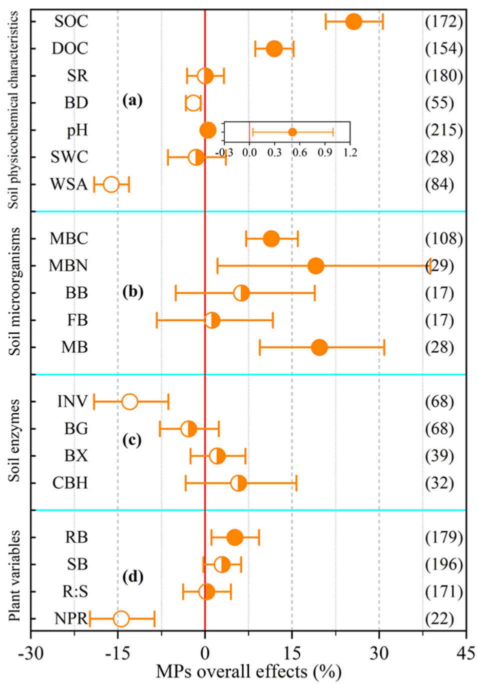

Figure 1. (a−d) Overall effects of MPs on soil physicochemical properties, soil microorganisms, soil enzymes, and plant variables. The red vertical line is drawn at an effect size of zero. The error bar represents the 95% confidence interval (CI) of the weighted percentage change. If 95% CI did not overlap zero, then the MPs effect was considered significant. The orange semiopen points represent a neutral effect (95% CI overlapping with zero), and the orange open and solid points represent a negative effect and positive effect (95% CI not overlapping with zero), respectively. The numbers in the right-side brackets represent the sample sizes of pairwise observation. Abbreviations refer to Table 1.

Table 1. List of Abbreviations

abbreviations	full name
MPs	microplastics
PBAT	poly(butyleneadipate-*co*-terephthalate)
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
SOC	soil organic carbon
DOC	dissolved organic carbon
SR	soil respiration
BD	bulk density
SWC	soil water content
WSA	water-stable aggregate
MBC	microbial biomass carbon
MBN	microbial biomass nitrogen
BB	bacterial biomass
FB	fungal biomass
MB	microbial biomass
INV	invertase
BG	β-1,4-glucosidase
BX	β-xylosidase
CBH	cellobiohydrolase
RB	root biomass
SB	shoot biomass

(0.51%), while significantly decreasing bulk density (−2.01%) and water-stable aggregate (−16.15%). MPs had no significant effect on SR and SWC.

MPs significantly enhanced MBC, MBN, and MB by 11.40, 19.09, and 19.70%, respectively, while having nonsignificant effects on BB and FB (Figure 1b). Compared with control groups, soil invertase was significantly decreased by 12.94% under MPs exposure in soil (Figure 1c). Meanwhile, MPs had no significant effects on β-1,4-glucosidase, β-xylosidase, and cellobiohydrolase activities (Figure 1c). MPs significantly increased RB (5.15%) and decreased NPR (−14.44%) while having no significant positive effects on SB and R/S (Figure 1d).

3.2. Factors Affecting the Soil C and Soil Respiration Responses to MPs. The effects of MPs on soil C and SR depended on the MPs characteristics, soil characteristics, and experimental conditions (Figure 2). Among the six types of MPs, the response of SOC to MPs significantly increased under PBAT-MPs, PE-MPs, PP-MPs, and PS-MPs (Figure 2a), while the response of DOC to MPs significantly increased under PBAT-MPs and PE-MPs and significantly decreased under PET-MPs (Figure 2b). The response of SR to MPs significantly increased under PBAT-MPs (Figure 2c). The positive effects of MPs on SOC were observed regardless of the biodegradability of the MPs (Figure 2d). The significantly positive effects of MPs on DOC were greater under biodegradable MPs than under nonbiodegradable MPs (Figure 2e). However, the MPs effect on SR was significantly increased under biodegradable MPs and significantly decreased under nonbiodegradable MPs (Figure 2f).

Regarding MPs sizes, the effects of MPs on SOC, DOC, and SR significantly increased for particle sizes ranging between 50 and 150 μm (Figure 2g−i). In addition, the effect of MPs with a size of >150 μm on SOC significantly increased (Figure 2g), while the response of SR to MPs with a size of >150 μm

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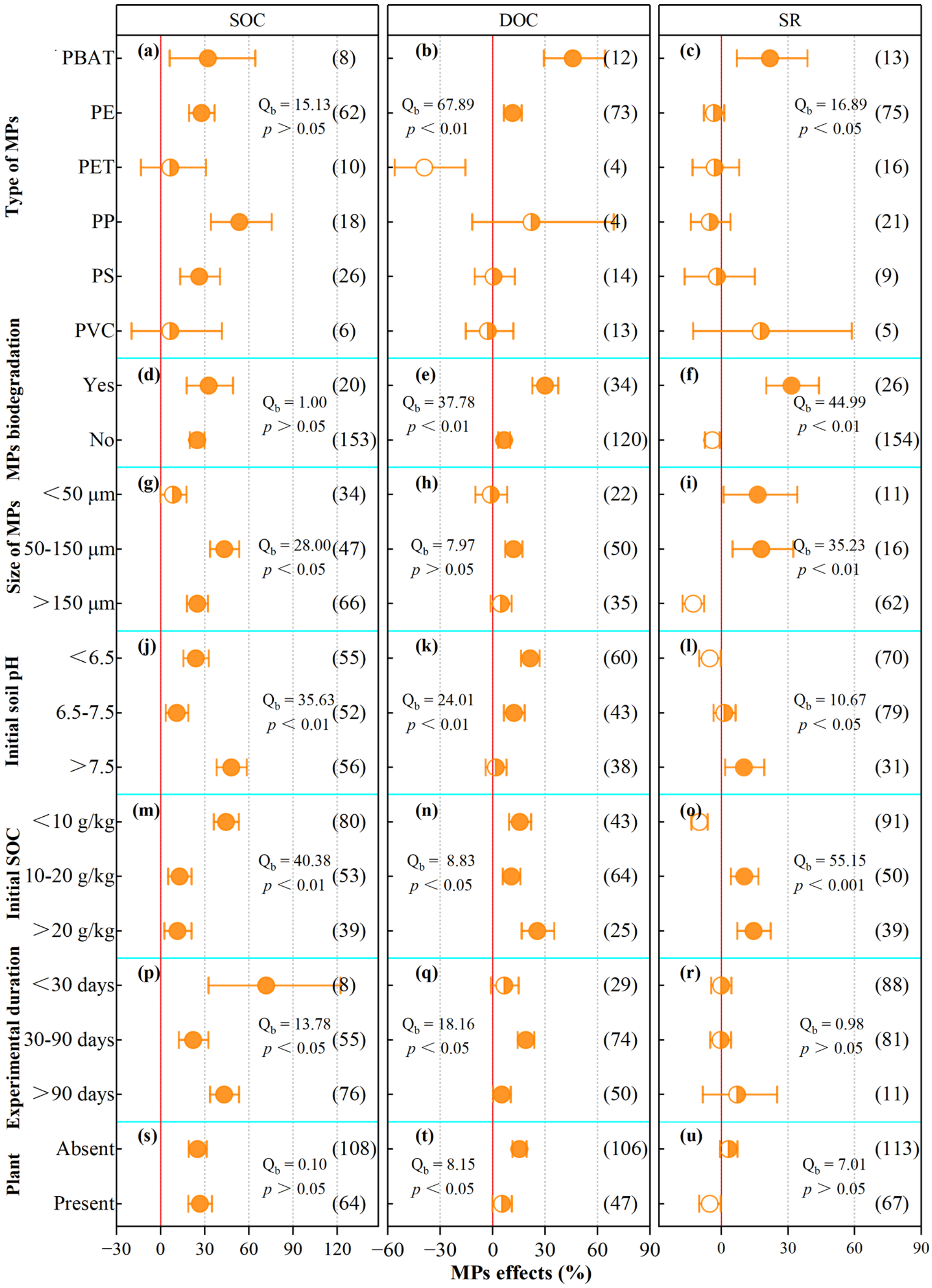

Figure 2. (a–u) Effect sizes of MPs properties (e.g., type of MPs, MPs biodegradation, size of MPs, and MPs concentration), edaphic attributes (e.g., initial soil pH and initial SOC), and experimental conditions (e.g., experimental duration and the absence or presence of plants) on soil C. The red vertical line is drawn at an effect size of zero. The error bar represents the 95% confidence interval (CI) of the weighted percentage change. If 95% CI did not overlap zero, then the MP effect was considered significant. The orange semiopen points represent a neutral effect (95% CI overlapping with zero), and the orange open and solid points represent a negative effect and positive effect (95% CI not overlapping with zero), respectively. The numbers in the right-side brackets represent the sample sizes of pairwise observation.

significantly decreased (Figure 2i). MPs on SOC, DOC, and SR significantly varied among three groups of initial soil pH ($p < 0.01$), with the largest effects observed under specific pH conditions (Figure 2j–l).

MPs consistently increased the SOC and DOC across all initial SOC concentrations (Figure 2m,n), while an enhancement in the SR was observed only when initial SOC concentrations exceeded 10 g kg^{-1} ($p < 0.05$; Figure 2o). However, MPs significantly inhibited SR under initial SOC < 10 g kg^{-1} (Figure 2o). The effects of MPs on SOC and DOC significantly varied among three categories of experimental duration ($p < 0.05$) (Figure 2p,q), but the response of SR to MPs was irrespective to experimental duration (p >0.05; Figure 2r). MPs caused the largest effects on SOC and DOC when the experimental durations were <30 and 30–90 days, respectively. MPs significantly promoted both SOC and DOC in the absence of plants (Figure 2s,t), while MPs significantly led to a positive effect on SOC and a negative effect on SR in the presence of plants (Figure 2s,u). Furthermore, the MPs-

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induced effects on DOC were significantly different between the absence and presence of plants (Figure 2t).

3.3. Effects of the MPs Concentration on Soil C. Linear regression analysis revealed that the responses of soil C to MPs were influenced by the concentration of the MPs (Figure 3).

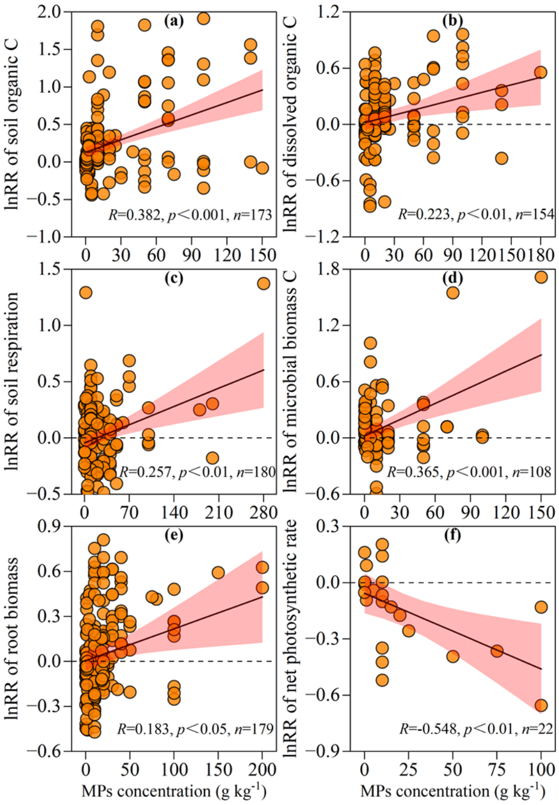

Figure 3. Relationships between the MPs concentration and response ratio (ln*RR*) of soil organic C (a), dissolved organic C (b), soil respiration (c), microbial biomass C (d), root biomass (e), and net photosynthetic rate (f).

The results indicated positive relationships between MPs concentrations and the ln*RR* of SOC ($R = 0.38$, $p<0.01$; Figure 3a), ln*RR* of DOC ($R = 0.22$, $p < 0.01$; Figure 3b), ln*RR* of SR ($R = 0.26$, $p < 0.01$; Figure 3c), ln*RR* of MBC ($R = 0.37$, $p < 0.001$; Figure 3d), and ln*RR* of RB ($R = 0.18$, $p<0.05$; Figure 3e). In contrast, significant negative correlations were found between MPs concentrations and the ln*RR* of NPR ($R = -0.55$; Figure 3f), suggesting that the responses of NPR to MPs decreased with increasing concentrations of MPs.

3.4. Importance of Explanatory Variables. Model selection analysis results suggested that initial SOC and the MPs concentration were the dominant drivers of responses driving the change of SOC under MPs exposure (Figure 4a). Initial SOC was negatively related to ln*RR* of SOC (Figure 4b, $p < 0.001$), while there was a positive relationship between the MPs concentration and MPs-induced shifts in SOC (Figure 3a, $p < 0.001$). Furthermore, initial soil pH and types of MPs were the leading factors for changes in DOC under MP exposure (Figure 4c). Initial soil pH was negatively associated with ln*RR* of DOC due to MPs exposure in soil (Figure 4d), and subgroup analysis indicated that the change in DOC varied considerably depending on the type of MPs ($p < 0.01$; Figure 2c). The size and concentration of MPs were the most essential drivers of change in SR under MPs exposure (Figure 4e). Additionally, the size of MPs showed a negative relation to ln*RR* of SR (Figure 4f, $p < 0.01$), whereas the MPs concentration was significantly and positively correlated with ln*RR* of SR (Figure 3c).

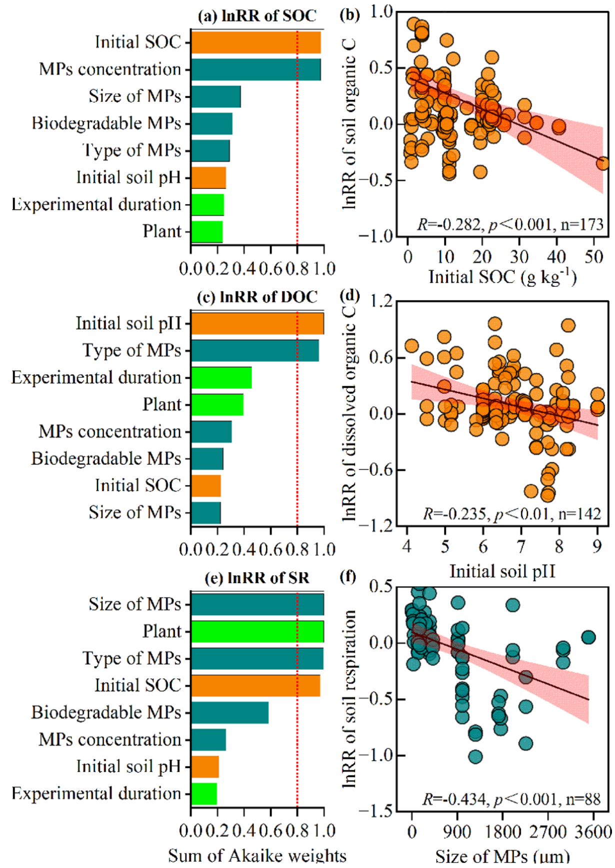

Figure 4. Model-averaged importance of MPs properties (e.g., type of MPs, MP biodegradation, size of MPs, and MPs concentration), edaphic attributes (e.g., initial soil pH and initial SOC), and experimental conditions (e.g., experimental duration and the absence or presence of plants) for the effects of MPs on soil C. (a) Relative importance of predictors mediating the responses of SOC to MPs. (b) Relationship between initial SOC and the response ratios (ln*RRs*) of SOC to MPs. (c) Relative importance of predictors mediating the responses of DOC to MPs. (d) Relationship between initial soil pH and the response ratios (ln*RRs*) of DOC to MPs. (e) Relative importance of predictors mediating the responses of soil respiration to MPs. (f) Relationship between the size of MPs and the response ratios (ln*RRs*) of soil respiration to MPs. The red cutoff line is set at 0.8 to distinguish the most essential predictors. Abbreviations refer to Table 1.

4. DISCUSSION

4.1. Overall Effect of MPs on Soil C. Our meta-analysis has revealed a consistent and significant increase in SOC due to the presence of MPs in soil. This effect was observed across various characteristics of MPs, soil characteristics, and experimental conditions on a global scale. We also found a positive correlation between the concentration of MPs added and the subsequent increase in the SOC (Figure 3a). This suggests that the presence of MPs directly adds C to the SOC and also enhances natural SOC formation and mineralization processes. Our study further indicates that the increase in SOC is partially attributed to the enhanced RB and soil MB (Figure 5). First, MPs in soil can promote PB accumulation by

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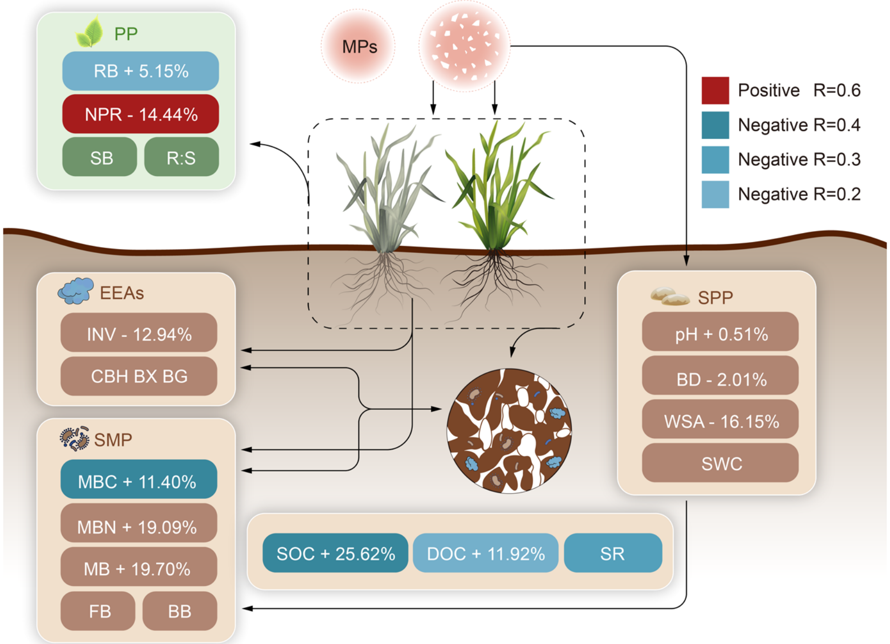

Figure 5. Conceptual diagram illustrating how MPs exposure affects plant parameters (PP), which in turn impacts soil C parameters. Both soil C parameters and plant parameters influence soil microbial properties (SMP) and soil extracellular enzyme activities (EEAs). Furthermore, soil C parameters interact with soil microbial properties and soil EEAs. Soil physical properties (SPP) are affected by MPs exposure and in turn influence plant parameters. Additionally, experimental factors such as MPs exposure time, MPs size, and addition concentration modulate the effects of MPs exposure on plant and soil properties. The relationships between the microplastic concentration and the response ratios for specific parameters were indicated by the *R* values from linear regression analyses. These relationships are illustrated by colored gradients. Only significant results are shown. Abbreviations refer to Table 1.

reducing soil bulk density, improving aeration, and facilitating better root penetration into the soil.[51] Consequently, the enhancement of plant production after MPs addition to soil supports greater soil C input through increased litter mass and root turnover. Second, C is the primary element of MPs.[8,14] For instance, PP-MPs have a C concentration as high as 99.99%.[52] This means that when experiments have assessed soil C, they have included the proportion of soil C that is in MPs.[4] Thus, in a way, these measurements reflect the application of the treatment itself. MPs, as a great C source,[8] at least the leachates coming from the particles, can be absorbed by soil microbes, thereby contributing to increased soil microbial biomass.[14] However, it is crucial to note that MPs leachates can also inhibit microbial activity.[31,53]

In general, our meta-analysis results indicated that MPs significantly increased DOC, which is in line with the recent meta-analysis.[16] However, another global meta-analysis showed that MPs' presence does not significantly increase DOC.[18,54] Discrepancies among studies may arise because the data sets concerning DOC response to MPs in this study (n = 153) and Wan et al.[16] (n = 162) are far larger than those from Qiu et al.[18] (n = 33) and Li et al.[54] (n = 8). This suggests that obtaining as many related studies as possible for meta-analysis methods might more effectively reduce biased estimates.[55] DOC, a small soluble fraction of SOM primarily originating from root exudates and soil microorganisms,[56] is highly susceptible to soil microbial activity.[57] Our findings align with existing research, indicating that MPs exposure enhances DOC in soil, showcasing the nuanced role of MPs in soil C dynamics. Furthermore, MPs are recognized as facilitators in the soil ecosystem, promoting microbial biomass and altering community structures.[14] It is posited that MPs contribute not only to the immediate soil environment but also to long-term soil C storage by facilitating the transformation and C sequestration.[35,53,58]

Our analysis corroborates the notion that MPs, through varied interactions with soil biota and plant roots, play a multifaceted role in soil C processes.[6,59] The impact of MPs on DOC highlights the interplay between physical presence and biological activity, underscoring the importance of considering both the direct and mediated effects of MPs on soil C pathways.[60] This comprehensive view encourages a deeper exploration of the mechanisms through which MPs influence soil systems, emphasizing the need for future studies to dissect the intricate relationships between MPs, microbial communities, and plant-root exudates in enhancing SOC.[10,59]

Our findings suggest that MPs exposure only slightly stimulated SR, contrasting with previous studies that reported significant increases of 5−18.2%.[10,61] This discrepancy may arise from several factors, including the limited number of observations in earlier studies, variations in the types of MPs used, and differences in environmental conditions and experimental designs. Our data set, comprising 180 sample sizes from 29 publications, offers a broader perspective compared to previous meta-analyses by Wei et al.[10] and Zhang et al.,[61] which were based on smaller data sets. This expansion in data not only makes our results more robust but also provides a more generalized representation of MPs' effects on SR. Crucially, our analysis underscores the importance of considering a wide range of factors, including MPs characteristics and ecological contexts, to fully understand the impact of MPs on SR dynamics.

4.2. Variability of the Effects of MPs on Soil C.

4.2.1. Soil C Response to MPs Exposure as Affected by MPs

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Characteristics. Our meta-analysis indicated that the effects of MPs on soil C varied among different types of MPs. For instance, PBAT-MPs, PE-MPs, PP-MPs, and PS-MPs significantly increased SOC, while both PET-MPs and PVC-MPs had only a minor effect on SOC. Additionally, the significantly positive effects on DOC resulted from both PBAT-MPs and PE-MPs, while PET-MPs led to an apparent reduction in DOC. Among the six types of MPs, only PBAT-MPs had a remarkably positive effect on SR. Given the fact that polyethylene is the most widely used plastic type,[62] PE-MPs should be prioritized from the perspective of net soil C sequestration. However, due to the limited number of observations, resulting in broad CIs (Figure 2b,c), interpretations of the results should be made with caution.

Concerning the impact of MPs on soil C, our findings indicate that the positive effects on SOC were consistent regardless of the biodegradability of the MPs. However, an interesting observation was made regarding DOC, where the positive effects were significantly more pronounced when biodegradable MPs were present compared to nonbiodegradable ones. This suggests that when biodegradable plastics unintentionally find their way into soils, they may contribute to an increase in SOC and potentially play a role in C sequestration. While our study points to a potential positive impact of biodegradable MPs on soil C, this should not be seen as an endorsement for careless disposal. Proper waste management, recycling, and responsible disposal practices are essential to prevent environmental pollution, safeguard ecosystems, and promote sustainability. However, we recognize the methodological challenges in accurately measuring the SOC in the presence of MPs. Specifically, the C content of MPs may contribute to the SOC measurements, potentially leading to an overestimation of the SOC contents. This highlights the need for advanced methodologies in future studies to distinguish between SOC derived from natural sources and those contributed by MPs.

Our results align with the findings of several studies.[35,63] Conventional MPs particles with high chemical stability in soil cannot be accessed and degraded by microbes,[64] resulting in no significant effects on soil respiration.[63] In contrast, biodegradable MPs provide a rich microbial C source and stimulate the decomposition of marine-buried C. Thus, a higher concentration of biodegradable MPs exposure in soil leads to elevated levels of CO_2 release.[65]

Previous research has demonstrated that the effects of MPs on soil C vary depending on their size.[4,8] In our study, we also observed a similar pattern, where MPs with particle sizes ranging from 50 to 150 μm had significantly positive effects on SOC, DOC, and soil respiration. However, when the particle sizes were smaller (<50 μm), the increases in both SOC and DOC were insignificant. On the other hand, MPs with particle sizes larger than 150 μm suppressed soil respiration but significantly increased SOC.

This observed pattern aligns with the concept of the surface-to-mass ratio: larger particles have smaller surface areas relative to their mass, which makes microbial or enzymatic activity per unit of mass more challenging and could lead to slower rates of respiration. Consequently, larger particles may contribute to an increase in SOC by reducing the rate at which they are metabolized or respired. In contrast, smaller-sized MPs (<50 μm) might have a negative impact by potentially disrupting nutrient transportation[66] or reducing soil fertility.[67] Additionally, larger-sized MPs (>150 μm) could adversely affect soil bacterial communities.[32]

Our findings suggest an overarching pattern where a portion of the C from MPs is respired, while another part is transformed by microbes and ultimately accumulates in the soil as SOC. Therefore, the size of the MPs appears to play a crucial role in determining the balance between these two processes.

4.2.2. Soil C Response to MPs Exposure as Affected by Edaphic Attributes. Soil pH plays a crucial role in regulating soil C processes.[68,69] Our study found that the effects of MPs exposure on soil C depended on soil C fractions and initial soil pH. For instance, the MPs-induced effects on SOC and SR were largest when the initial soil pH was above 7.5 (Figure 2j), while the effect of MPs on DOC was greatest when the initial soil pH was below 6.5 (Figure 2k). Surprisingly, MPs significantly decreased SR in soil with a pH lower than 6.5 (Figure 2l). Furthermore, soil pH was the most important factor influencing DOC following MPs exposure (Figure 3d). One possible explanation for these MPs-mediated changes in soil C is that MPs decompose faster in acidic (pH < 6.5) or alkaline soils (pH > 7.5) than in neutral (pH = 6.5−7.5) soils.[70] As a result, MPs exposure in soil with a pH above 7.5 may enhance soil C storage.

Previous studies reported that the initial SOC concentration influences C-derived amendments (e.g., crop straw, cover crop, and biochar) driving the change of soil C.[45,71] Our meta-analysis showed that the distinct effects of MPs exposure on SOC were influenced by varying levels of the initial SOC concentration (Figure 2m−o). MPs exhibited the largest increase in SOC and the most significant reduction in SR when exposed to soil with an initial SOC of less than 10 g kg^{-1}, indicating that MPs play a more prominent role in promoting SOC, especially in low SOC soil environments. However, the subgroup analysis in this study revealed that exposure to MPs had significant impacts on soil C among the three levels of initial SOC. Therefore, it is essential to consider the initial SOC when predicting changes in soil C under MPs exposure.

4.2.3. Soil C Response to MPs Exposure as Affected by Experimental Conditions. The responses of the three C components to experimental conditions under MPs exposure in soil varied to some extent. The experimental duration was significantly associated with the variations in SOC and DOC induced by MPs (Figure 2p,q). Our findings indicate that the most pronounced effect of MPs on SOC was observed in short-term experiments (<30 days), while a lesser response was noted in medium-term experiments (30−90 days). This pattern may not suggest that MPs become less of a threat over time but rather could reflect a variety of complex soil processes. These could include the adaptation of soil biota to MPs, alterations in MPs properties, or their integration into the soil matrix over time. It is also important to note that the long-term environmental impacts of MPs, extending beyond these durations, require further exploration to fully understand the persistence and ecological consequences of MPs in soil ecosystems.

While our study indicates a reduction in the impact of MPs on SOC over time, it is essential to interpret these findings with caution. The observed trend may not necessarily signal a complete recovery of soil systems from MPs pollution. Consequently, the potential for soil systems to recover from MPs pollution over time remains an open question, requiring long-term studies and thorough analyses to understand the

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enduring impacts of MPs on soil health and ecological function. Interestingly, short-term exposure to MPs (less than 30 days) had the least effect on DOC, while 30−90 days of exposure led to the highest increase. This inconsistency may result from a quick initial breakdown and release of C from MPs followed by a slower release over time. Short-term changes in SOC may also be influenced by factors like soil density, aeration, and water retention, rather than the direct effect of MPs.[4,39,54] Careful examination of these and other potential influences is crucial.

MPs-induced effects on SOC were not influenced by the presence of plants (Figure 2s). However, MPs-related changes in the DOC and SR were modulated by the presence of plants (Figure 2t,u). In detail, MPs exposure considerably enriched the DOC in the absence of plants relative to the control, possibly because MPs provided an additional C source for soil microbes, enhancing their activity and DOC production. A recent meta-analysis study reported that the remarkably positive effect of MPs exposure on SR was observed in unplanted soil.[30] In contrast, our results revealed that MPs exposure significantly decreased SR in the presence of plants (Figure 2u).

Our study agrees with earlier research that plants might release harmful substances when exposed to soils with MPs.[27,72] This could lower the SR by affecting tiny organisms in the soil. However, our study does not prove this, and more research is needed to understand exactly how it happens. We also found that plants faced challenges with photosynthesis and grew more roots when exposed to soils with MPs (Figure 1d). This might be due to the MPs blocking the soil, making it harder for roots to absorb water and nutrients. Plants might also grow more roots to survive this stress. However, these are speculative hypotheses that require further exploration and confirmation through future studies.

4.3. Predominant Drivers of the MPs-Induced Effect on Soil C. Initial SOC and MPs concentrations are the most important factors mediating the MPs-induced changes in SOC (Figure 4a). In addition, the current meta-analysis reveals that initial soil pH and MP type are critical predictors regulating the MP-induced changes in DOC (Figure 4c). The predominant role of MPs type in influencing the effect of MPs on DOC in this study is consistent with previous studies around the globe.[16] In this meta-analysis, we found that the MPs-induced effect on SR was predominantly regulated by MPs size, the presence of plants, the MPs type, and the initial SOC (Figure 4e). Furthermore, there were significant positive relationships between the MPs concentration and the response of SOC, DOC, and SR (Figure 3a−c) and notable negative correlations between initial SOC and the response of SOC (Figure 4b), initial soil pH and the response of DOC (Figure 4d), and MPs size and the response of SR (Figure 4f) under MPs exposure to soil. This further confirms that MPs-induced changes in soil C pools are primarily driven by edaphic attributes and MPs characteristics.

This meta-analysis has offered important insights into the impacts of MPs on soil C dynamics and respiration. Our findings highlight that edaphic factors (initial soil pH and SOC) and MPs characteristics (concentration, size, and type) are key in evaluating the response of soil C pools to MPs exposure. Exposure to MPs generally increased SOC and DOC concentrations with SOC effects being more pronounced. This increase in SOC may partially be attributed to the C content of MPs (MPs-C), rather than an actual change in SOC dynamics.

No significant global effect of MPs on SR was detected in our study, with the influence on soil C pools and respiration varying according to the MPs characteristics, soil characteristics, and experimental conditions. The fate of MPs-C—whether mineralized and released as CO_2 or transformed into stable SOC compounds—depends on these variables. Biodegradable plastics enhanced SOC accumulation and decomposition more rapidly, indicating a potential environmental benefit.

In conclusion, our study underscores the intricate interactions among MPs characteristics, soil characteristics, and their impacts on soil C pools. Future research must explore the true contributions of MPs to SOC increases, considering both direct C addition and changes in inherent SOC. A sensitivity analysis to estimate MPs-C's influence on soil C dynamics would be insightful. Our findings illuminate the complexity of MPs on soil C cycling and the potential environmental implications of biodegradable plastics.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.3c06177.

The PRISMA flow diagram for the current meta-analysis (Figure S1), sensitivity analyses (Figures S2−S5), and publication bias tests (Table S1 and Figures S6−S9); details of the meta-analysis process; the 110 studies used in this paper (Notes S1) and the data set for the meta-analysis (Table S2) (PDF)

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Notes

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