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# Effect of nonbiodegradable microplastics on soil respiration and enzyme activity: A meta-analysis

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ABSTRACT

Nonbiodegradable microplastics (MPs) are emerging contaminants in the environment and potentially threaten soil health. In recent years, the impact of MPs on soil ecology has attracted widespread attention, but the responses of soil respiration and enzyme activity to MPs exposure remain unclear. Here, a meta-analysis including 1980 observations was used to assess the effects of MPs on soil microbial activity. MPs exposure significantly ($p < 0.05$) increased soil respiration by 18.2 % but did not significantly ($p > 0.05$) affect soil enzyme activity; moreover, these effects varied with MP type, concentration, size, and exposure period. The amendment of polypropylene (PP) MP increased soil respiration and enzyme activity by 58.8 % and 10.2 %, respectively, whereas exposure to polyethylene terephthalate (PET), polyethylene (PE) and polystyrene (PS) MPs reduced soil enzyme activities by 13.0 %, 6.8 % and 5.0 %, respectively. The soil respiration was unaffected and increased when the MPs concentrations were below and above 5 %, respectively, whereas soil enzyme activity was stimulated and inhibited when the MPs concentrations were less and >10 %, respectively. The size of MPs only significantly ($p < 0.05$) affected the response of soil respiration to MPs, as small (<500 μm) and large (≥500 μm) sizes of MPs increased and reduced soil respiration by 53.4 % and 5.8 %, respectively. Short-term (≤30 days) exposure to MPs increased soil respiration by 50.2 %, whereas the presence of MPs inhibited soil enzyme activity by 3.3 % when the incubation period ranged from 30 to 100 days. In addition, MPs exposure significantly ($p < 0.05$) increased soil respiration by 77.9 % in alkaline soil (pH > 7.5) and by 41.6 % in the absence of plants. The amendment of MPs significantly ($p < 0.05$) increased and reduced soil enzyme activities in acidic and alkaline soils by 4.3 % and 5.5 %, respectively, and significantly ($p < 0.05$) improved soil enzyme activity by 4.5 % in the presence of plants. Specifically, MPs significantly ($p < 0.05$) increased the activities of acid phosphatase and fluorescein diacetate hydrolase by 8.3 % and 17.1 %, respectively, but did not significantly ($p > 0.05$) influence urease, β-glucosidase, and catalase activities. Overall, our results suggested that MPs have nonnegligible impacts on soil microbial activity, and it is urgently necessary to explore the long-term effects of MPs on soil ecology in the natural environment.

## 1. Introduction

Plastics are widely used because of their low cost, excellent performance and portability (Andrady and Neal, 2009; Zhang et al., 2022c). It is predicted that by 2050, approximately 12,000 million tons of plastic waste will accumulate in the environment (Geyer et al., 2017). Plastic fragments in the environment can decompose into microplastics (MPs) with diameters < 5 mm (Thompson et al., 2004). Over the past few

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years, the accumulation of MPs in terrestrial ecosystems has been nearly 4–23 times higher than that in oceans (Horton et al., 2017), whereas current publications have mainly focused on the abundance of MPs in aquatic ecosystems. Soil is a vast contamination sink for MPs via various pathways, such as plastic film mulching, wastewater irrigation, the use of organic fertilizers and atmospheric deposition (Guo et al., 2020; Wang et al., 2022d). Moreover, once MPs enter the soil, they usually require hundreds or even thousands of years to degrade (Zubris and Richards, 2005) and affect soil physicochemical properties and microorganisms in the long term (Wang et al., 2022b).

In recent years, the enormous threat of MPs to soil health has attracted widespread attention, which is important for human health, sustainable agricultural development and environmental protection (Doran and Zeiss, 2000; Guzmán et al., 2019; Lehmann et al., 2020). Furthermore, the large specific surface areas of these plastic particles can adsorb pollutants from soil, which probably threaten soil biology. Soil biological indicators, such as soil respiration and enzyme activity, can reflect the dynamic changes in biological systems and health in the soil environment (Singh et al., 2011; Zhu et al., 2021). These biological variables can regulate the conversion of organic residues and nutrient cycling, and reflect the intensity and direction of biochemical processes in the soil (Allison et al., 2010; Burns, 1982). However, until now, there has been no consensus on the effects of MPs on soil respiration and enzyme activity due to the various MP types and exposure conditions (Wang et al., 2022b).

Previous experiments showed that the addition of MPs increases (Feng et al., 2022), decreases (Zhao et al., 2021a) or has no effect (Xu et al., 2020) on soil enzyme activity; these differences may depend on the type, dose and exposure duration of MP and soil properties. MPs are usually composed of polymers and ingredients with plasticizers and stabilizers as auxiliary materials. Accordingly, the potential components of different MPs may differentially affect the soil physical, chemical and biological properties (Wang et al., 2022b). However, the effects of different types of MP on soil respiration and enzyme activity are still controversial. For example, de Souza Machado et al. (2019) reported that the addition of polyamide (PA), polyethene (PE), and polyethersulfone (PES) MPs increased the enzyme activity of fluorescein diacetate hydrolase (FDAse), whereas the addition of polyethylene terephthalate (PET), polypropylene (PP), and polystyrene (PS) MPs did not change enzyme activity. In addition, the presence of MPs can change the soil porosity and aggregate structure, and increasing MPs concentrations are probably beneficial for aerobic microbial growth (Liu et al., 2017; Ng et al., 2018; Rubol et al., 2013). Long-term exposure to MPs can increase dissolved organic matter and soil nutrient concentrations, and then stimulate soil enzyme activity (Liu et al., 2017). However, these plastic particles can also reduce enzyme activity by competing with microorganisms for niches (Yu et al., 2020). In addition, soil properties, such as pH, can change the plastisphere bacterial communities (Li et al., 2021) and the adsorption capacity of MPs for pollutants (Yang et al., 2019), whereas the effect of MPs addition on microbial activity under different pH conditions remains unclear.

To our knowledge, Zhang et al. (2022a) evaluated the impact of MPs and soil properties on soil respiration and enzyme activity based on a meta-analysis method, but the effects of the properties of MP and soil on the response of soil microbial activity to MPs addition were not fully considered. Recently, the impact of MPs on soil health has attracted widespread attention, and many researchers have reported the impact of MPs on soil ecology. We performed a global meta-analysis based on 1980 observations to evaluate the impact of the MP type, exposure dose, size, duration, soil pH and plants on the responses of soil respiration and enzyme activity to MPs addition and answered the following questions: (1) can exposure to MPs affect soil respiration and enzyme activity? and (2) how do different types, doses, sizes and exposure durations of MP and environmental variables (including soil properties and plants) affect the response of soil microbial activity to MPs addition?

## 2. Materials and methods

### 2.1. Data collection

Publications were searched for on the Web of Science, China National Knowledge Infrastructure (CNKI) and Google Scholar before April 2022, with the keywords "microplastics", "plastic microparticles", "nanoplastic", "soil enzyme activity" and "soil respiration". All plastic-related keywords were linked by the Boolean operator "OR" and connected with "soil enzyme activity" or "soil respiration" with the operator "AND". In addition, we also searched entry terms related to these keywords through the PubMed MeSH database, which was used to seek other literature that was not covered by the above keywords.

Four inclusion criteria were used to select data from the literature. First, each study had to contain at least one type of MP. Second, each selected publication must include soil respiration or enzyme activity. Third, these observations had to compare experimental treatments with control groups. Fourth, the articles had to present mean values and the number of replications (≥3) for our analysis. Based on these criteria, data (168 and 1812 observations for soil respiration and enzyme activity, respectively) from 51 articles were collected in this study, and the distribution of these experiments was shown in Fig. 1. In addition, preferred reporting items for systematic reviews and meta-analyses (PRISMA) website (http://www.prisma-statement.org/) were used to draw the flow diagram of data collection (Fig. S1).

### 2.2. Data extraction and classification

The data were collected directly from the tables or indirectly from the graphs by GetData Graph Digitizer 2.22. Some studies did not provide standard deviations (*SDs*), or it was not clear whether the errors represented standard errors (*SEs*) or *SDs*. We regarded these errors as *SEs* (Jeffery et al., 2016) and then converted them to *SDs* using the following equation (Hao and Yu, 2005):

$$SD = \sqrt{n} \times SE \tag{1}$$

where $n$ is the sample size. Some articles did not provide *SEs* or *SDs*; therefore, we used the coefficient of variation (*CV*) from all available data to calculate the missing *SDs* (*MSDs*) as follows (Bai et al., 2013):

$$MSD = M \times CV \tag{2}$$

where M indicates the mean value reported in collected articles that did not report *SDs* or *SEs*. In addition, detailed information on the experimental sites (latitude and longitude), climatic conditions (mean annual temperature and precipitation), soil pH and the presence or absence of plants was collected from the selected literature. Moreover, the soil enzyme type, MP type, size, exposure concentration, time were also extracted from the literature. The effect of MPs on soil respiration and enzyme activity in this study was divided into six groups: (1) different MP types: PET, PP, PE, polyvinyl chloride (PVC), PS, PA, polyurethane (PU), PES and polytetrafluoroethylene (PTFE); (2) four MP contents: <1 %, 1 %–5 %, 5 %–10 % and ≥10 %; (3) two MP sizes: <500 μm and ≥500 μm; (4) three incubation periods: <30, 30–100 and ≥100 days; (5) soil pH: acidic (<6.5), neutral (6.5–7.5), and alkaline (≥7.5) soils; and (6) the presence or absence of plants. In addition, the impact of MPs on different soil enzyme activities, and the responses of five typical enzyme activities (urease, β-glucosidase, acid phosphatase, catalase and FDAse) to different MP types were also investigated.

### 2.3. Data analysis

The response ratio (*RR*) was used to evaluate the impact of MPs addition on soil respiration or enzyme activity by the following equation (Hedges et al., 1999):

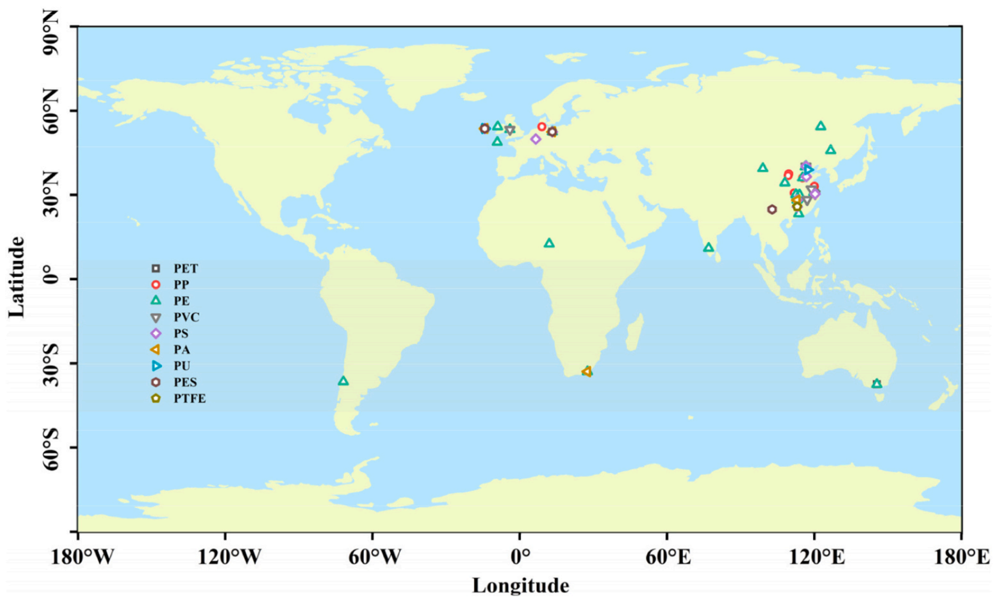


**Fig. 1.** Distribution of 1980 paired experimental observations. The study sites were classified into six groups of microplastics. PET, polyethylene terephthalate. PP, polypropylene. PE, polyethylene. PVC, polyvinyl chloride. PS, polystyrene. PA, polyamide. PU, polyurethane. PES, polyether sulfone. PTFE, polytetrafluoroethylene.

$$RR = ln(\overline{X}_e/\overline{X}_C) = ln\overline{X}_e - ln\overline{X}_C \quad (3)$$

where $\overline{X}_e$ and $\overline{X}_C$ denote the mean soil respiration or enzyme activity from the treatments with and without MPs, respectively. The corresponding variances ($v$) of $RR$ were calculated using the following equation (Chen et al., 2018):

$$v = \left(\frac{1}{n_e}\right) \times \left(\frac{SD_e}{X_e}\right)^2 + \left(\frac{1}{n_c}\right) \times \left(\frac{SD_c}{X_c}\right)^2 \quad (4)$$

where $n_e$ and $n_c$ denote the number of MPs exposure and control groups, respectively, and $SD_e$ and $SD_c$ represent the corresponding standard deviation. The weighted $RR$ ($RR_{++}$) was computed as follows (Hedges et al., 1999):

$$RR_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}RR_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \quad (5)$$

where $m$ and $k$ are the samples representing the MPs application and control treatments, respectively, and $w_{ij}$ is the weight factor for each $RR_{++}$ value. Then, the 95 % confidence interval ($CI$) of $RR_{++}$ was calculated as follows (Hedges et al., 1999):

$$95\%CI = RR_{++} \pm 1.96\sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}}RR_{++} \quad (6)$$

A random-effects model was used to determine the effect of MPs addition on soil respiration and enzyme activity. The $RR_{++}$ values of these variables to MPs addition and the 95 % CIs of the $RR_{++}$ values were calculated using the meta-analysis software Stata 16.0. We considered the effect values to be significant at $p < 0.05$ when the 95 % CIs did not overlap with zero (Yu et al., 2021b). Last, the impacts of MPs on soil respiration and enzyme activity were shown as percentage change of the variables to the control treatment using the following equation (Bai et al., 2013):

$$P = \left(exp^{RR_{++}} - 1\right) \times 100\% \quad (7)$$

Moreover, total heterogeneity ($Q_T$) was divided into between-group ($Q_b$) and within-group ($Q_w$) variations to determine the differential response of variables to MPs exposure under different subgroups, and the $p$ value (<0.05) was identified to indicate significant differences among the responses of the groups. Datasets that greatly impacted the original results were removed through sensitivity analysis (3 abnormal pairs in this study).

In the field experiment, previous studies showed the content of MPs as the mass of soil per hectare, and we converted it to the mass concentration ($M$) as follows (Deng et al., 2020):

$$M = BD \times H \quad (8)$$

where $BD$ is the soil bulk density and $H$ is the depth of the soil profile. Some studies did not specify the soil bulk density; in these cases, we estimated the bulk density using an empirical equation (Deng et al., 2020): $BD = 0.4123 + 1.0326e^{-0.0413C_{SOC}}$, where $SOC$ is the soil organic matter content. In addition, the "ggmap" package in R was used to draw the map of the distribution of study sites.

## 3. Results

### 3.1. Effects of MPs on soil respiration

MPs addition significantly ($p < 0.05$) increased soil respiration by 18.2 %, and these effects varied with MP type, concentration, size, and exposure duration (Fig. 2). PP MP significantly ($p < 0.05$) increased soil respiration by 58.8 %, while other types of MPs had no significant effect on soil respiration (Fig. 2). MPs did not significantly affect soil respiration when their concentrations were below 5 %, but significantly ($p < 0.05$) increased soil respiration by 59.7–86.5 % as MPs contents were above 5 % (Fig. 2). Small (<500 μm) and large (≥500 μm) plastic particles increased and decreased soil respiration by 53.4 % and 5.8 %, respectively (Fig. 2). Short-term (≤30 days) MPs exposure significantly ($p < 0.05$) enhanced soil respiration by 50.2 %, whereas no significant ($p > 0.05$) effect of MPs on soil respiration was observed after >30 days incubation period (Fig. 2). Soil pH and plants also significantly ($p < 0.05$) changed the response of soil respiration to MPs addition. MPs exposure significantly ($p < 0.05$) increased soil respiration by 97.8 % in alkaline soil (pH > 7.5) and by 41.6 % in the absence of plants (Fig. 2).

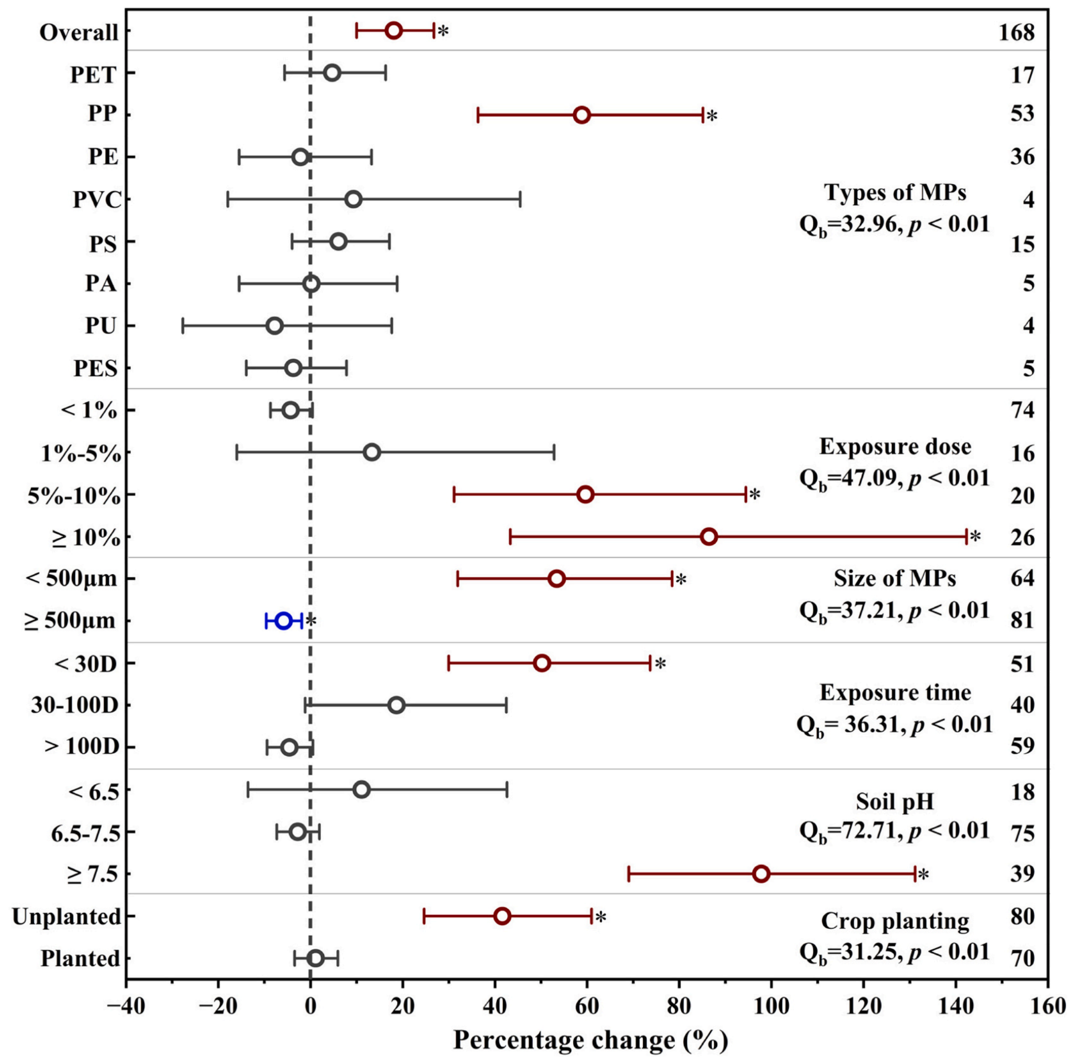


**Fig. 2.** Response in soil respiration to MPs exposure as affected by different microplastic (MP) types, exposure doses, MP sizes, exposure time, soil pH and the presence or absence of plants. The number is the sample size in each group. The dots and error bars represent the mean values and 95 % confidence intervals, respectively. Asterisks denote that the effect of microplastics on soil respiration was significantly different ($p < 0.05$). PET, polyethylene terephthalate. PP, polypropylene. PE, polyethylene. PVC, polyvinyl chloride. PS, polystyrene. PA, polyamide. PU, polyurethane. PES, polyether sulfone. D, days.

### 3.2. Effects of MPs on soil enzyme activity

MPs exposure did not significantly affect soil enzyme activity, but these effects were significantly ($p < 0.05$) regulated by MP type, concentration, and exposure time (Fig. 3). The amendment of PP and PES MPs significantly ($p < 0.05$) increased soil enzyme activities by 10.2 % and 22.8 %, respectively, whereas PET and PE significantly ($p < 0.05$) reduced the activities of soil enzymes by 13.0 % and 6.8 %, respectively (Fig. 3). Exposure to <1 % and 5–10 % MPs significantly ($p < 0.05$) improved soil enzyme activities by 7.0 % and 6.0 %, respectively, whereas exposure to >10 % MPs significantly ($p < 0.05$) inhibited soil enzyme activity by 9.4 % (Fig. 3). After exposure to MPs, soil enzyme activities were not significantly ($p > 0.05$) changed in short- (<30 days) or long-term (>100 days) periods, whereas this variable was significantly ($p < 0.05$) reduced by 3.3 % when the incubation period ranged from 30 to 100 days (Fig. 3). The response of soil enzyme activity to MPs addition was also significantly ($p < 0.05$) affected by soil pH and plants (Fig. 3). The amendment of MPs significantly ($p < 0.05$) increased and reduced soil enzyme activities in acidic and alkaline soils by 4.3 % and 5.5 %, respectively, and significantly ($p < 0.05$) improved soil enzyme activity by 4.5 % in the presence of plants (Fig. 3).

The effect of MPs amendment on five typical enzyme activities was further analyse. MPs significantly ($p < 0.05$) increased the activities of acid phosphatase and FDAse by 8.3 % and 17.1 %, respectively, but did not significantly ($p > 0.05$) influence urease, β-glucosidase, and catalase activities (Fig. 4a). Moreover, the responses of these enzyme activities to MPs amendment varied with their types: 1) PVC, PS and PU MPs addition significantly ($p < 0.05$) increased urease activities by 13.3 %, 10.9 % and 4.3 %, respectively (Fig. 4b); 2) PP MP significantly ($p < 0.05$) increased β-glucosidase activity by 13.7 %, but PE, PVC, PS and PA MPs significantly ($p < 0.05$) inhibited the activity of this enzyme by 14.7 %, 29.1 %, 15.4 % and 8.3 %, respectively (Fig. 4c); 3) the amendment of PP, PVC and PTFE MPs significantly ($p < 0.05$) enhanced acid phosphatase activity by 14.6 %, 12.4 % and 11.7 %, respectively (Fig. 4d); 4) the exposure of PP and PE MPs significant ($p < 0.05$) inhibited catalase activity by 8.9 % and 4.7 %, respectively, whereas PS and PA MPs addition significant ($p < 0.05$) increased the activity of this enzyme by 9.6 % and 36.3 %, respectively (Fig. 4e); and 5) PP and PVC MPs significantly ($p < 0.05$) enhanced and decreased FDAse activity by 37.7 % and 10.2 %, respectively (Fig. 4f). In addition, MPs addition significantly ($p < 0.05$) improved the activities of alkaline phosphatase, peroxidase, β-xylosidase and leucine aminopeptidase, but significantly ($p < 0.05$) inhibited nitrate reductase, hydroxylamine reductase, sucrase, cellobiohydrolase, *N*-acetyl-β-glucosaminidase, phenol oxidase

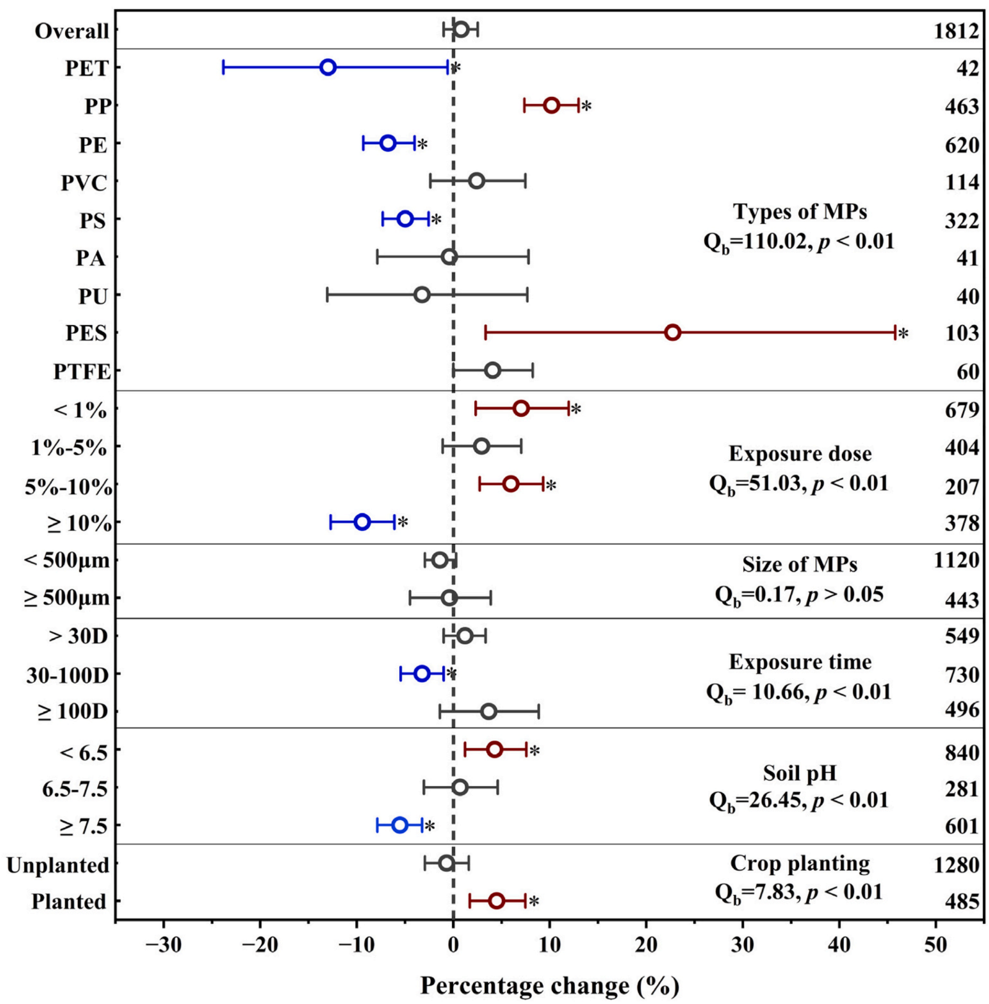


**Fig. 3.** Response in soil enzyme activity to MPs exposure as affected by different microplastic (MP) types, exposure doses, MP sizes, exposure time, soil pH and the presence or absence of plants. The number is the sample size in each group. The dots and error bars represent the mean values and 95 % confidence intervals, respectively. Asterisks denote that the effect of microplastics on soil respiration was significantly different ($p < 0.05$). PET, polyethylene terephthalate. PP, polypropylene. PE, polyethylene. PVC, polyvinyl chloride. PS, polystyrene. PA, polyamide. PU, polyurethane. PES, polyether sulfone. PTFE, polytetrafluoroethylene. D, days.

and manganese peroxidase (Fig. S2).

## 4. Discussion

### 4.1. Effect of MPs on soil respiration

Based on a meta-analysis method, Wei et al. (2022) showed that exposure to MPs increased soil respiration by 5 % using 28 studies, and Zhang et al. (2022a) found that MPs addition significantly accelerated the release of $CO_2$ by 2.97-fold from 67 observations. In this study, based on a larger dataset (168 observations) collected from publications, the presence of MPs increased soil respiration by approximately 18 %, indicating that these plastic particles have the potential to induce the loss of SOC in soils. These differences indicated that the positive effect of MPs addition on soil respiration varied with the sample size, and the impact of MPs on soil respiration should be reconsidered in the future. The increase in soil respiration following MPs addition can be explained in the following ways. First, introduced MPs can enter soil aggregates, making it easier for water and oxygen to enter the soil microenvironment, increasing the activity of polyphenol oxidase to decompose recalcitrant compounds, and then providing soluble organic matter for microorganisms to produce $CO_2$ (Prorokova et al., 2012; Yu et al., 2022; Zheng et al., 2016). Second, MPs can adsorb and enrich a variety of substances as carriers because of their large specific surface areas and hydrophobic characteristics. Thus, the surfaces of plastic fragments can provide habitats for a variety of microorganisms and provide short-term reaction hot zones (Zhu et al., 2022). Zhang et al. (2019) found that the abundances of Actinomycetes and Bacteroidetes on the surface of MPs were higher than those in bulk soil, suggesting that MPs can act as microbial accumulators in soil and enrich some taxa to decompose soil organic matter. Third, MPs may drive microorganisms to decompose soil labile carbon and accelerate $CO_2$ production. For example, Yu et al. (2022) found that the addition of PE MP increased the abundance of a functional gene (*abfA*) involved in encoding hemicellulose degradation enzymes.

The impacts of MPs on soil respiration varied with the MP type and concentration. First, PP MP significantly increased soil respiration, while other types of MPs had no effect on this variable. This difference was probably attributed to the fact that PP MP are more susceptible to chemical damage (Koerner and Koerner, 2018). Carbon atoms bonded to methyl groups in PP MP are more susceptible to chemical damage than those bonded to hydrogen atoms in other MPs (Gewert et al., 2015). Second, the application of MPs at low doses (<5 %) did not influence soil respiration, probably because of the functional resistance of microbial communities to low MPs applications that exhibited no significant harmful effects on microbes (Blöcker et al., 2020). However, under high-dose (>5 %) treatments, MPs addition increased soil respiration, which was probably due to high concentrations of MPs being able to alter the community composition of soil bacteria. For example, Gao et al. (2021) found that the bacterial community formed an obvious cluster in the high-concentration (18 %) treatment, and then stimulated the release of $CO_2$ emissions from vegetable soils. In addition, smaller sized (< 500 μm) MPs with large specific surface areas can increase soluble organic carbon content and oxygen content by inserting into soil aggregates

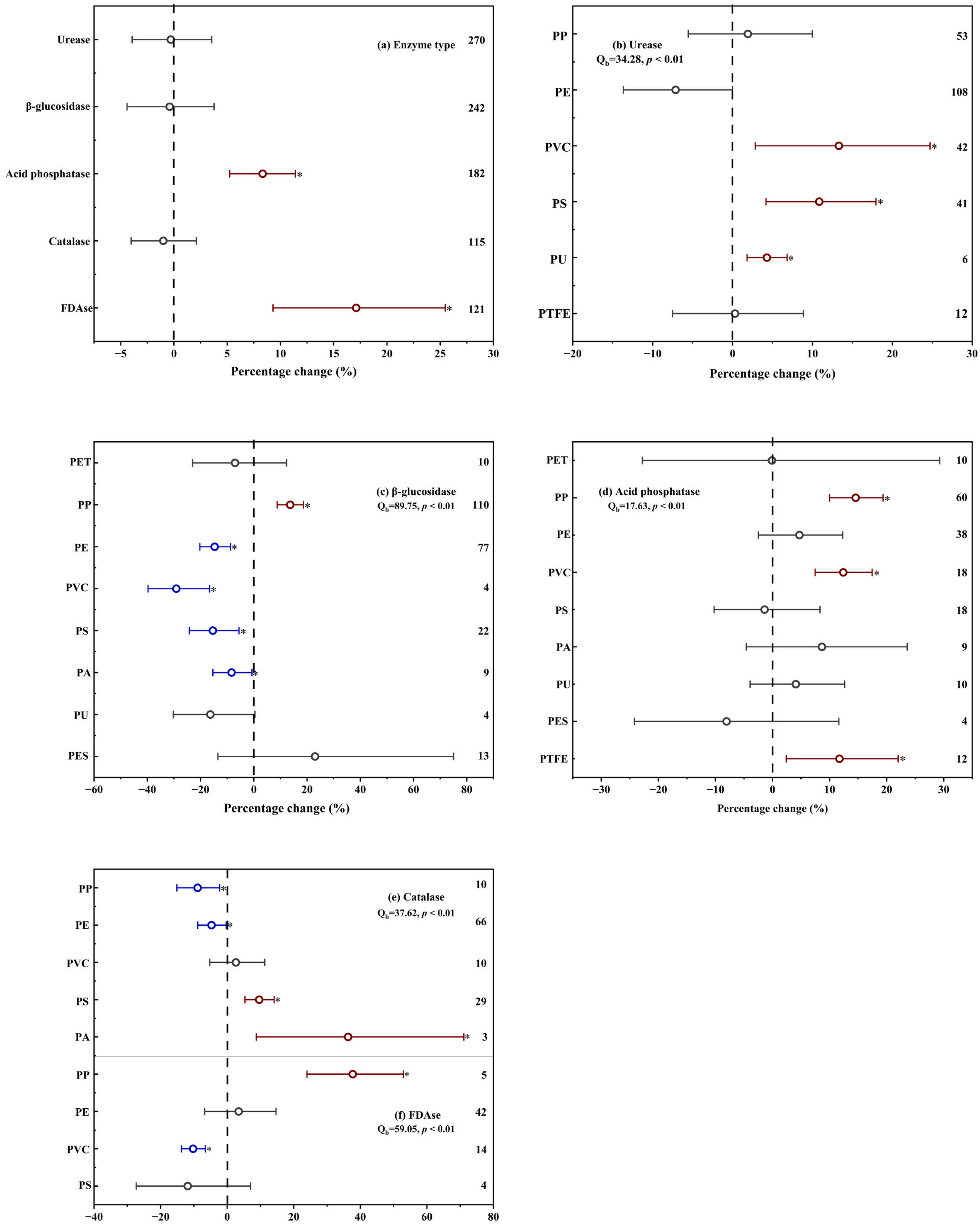


**Fig. 4.** Response of five typical enzyme activities to MPs addition(a), and different MP types (urease (b), β-glucosidase (c), acid phosphatase (d), catalase(e), FDAse (f)). The number is the sample size in each group. The dots and error bars represent the mean values and 95 % confidence intervals, respectively. Asterisks denote that the effect of microplastics on soil respiration was significantly different ($p$ < 0.05). FDAse, fluorescein diacetate hydrolase. PET, polyethylene terephthalate. PP, polypropylene. PE, polyethylene. PVC, polyvinyl chloride. PS, polystyrene. PA, polyamide. PU, polyurethane. PES, polyether sulfone. PTFE, polytetrafluoroethylene.

(Guo et al., 2022; Singh et al., 2021), and then largely enhance soil respiration. However, larger MPs (≥500 μm) inhibited the release of $CO_2$ from soils, indeed, few studies have focused on the size effect of MPs on soil respiration, and more studies are required to evaluate the size effect of MPs on soil respiration in the future.

The presence of MPs accelerated soil respiration for the soil pH > 7.5, which was probably due to the higher diversity and richness of bacteria in the "microplastisphere" in alkaline soil (Li et al., 2021). The presence of plants also affected the response of soil respiration to MPs addition. One possible explanation for this finding is that the addition of MPs can damage plant roots and thus decrease the release of $CO_2$ from root respiration, which counteracts the positive effect of MPs on microbial respiration, and then results in no significant effect on soil respiration (Šourková et al., 2021). Indeed, previous studies have reported that the presence of MPs induced the phytotoxicity characteristics of plants, thus significantly reducing both above- and belowground plant biomass (Pignattelli et al., 2020; Qi et al., 2018; Wang et al., 2022a; Zhao et al., 2021b).

### 4.2. Effect of MPs on soil enzyme activity

Overall, the application of MPs to soil did not significantly affect soil enzyme activity. This result is inconsistent with the findings of Zhang et al. (2022a), who used 367 observations to find that the presence of MPs increased soil enzyme activity by 7 %–441 %. These differences were mainly due to previous study only considered the effects of plastic residues and PE MP on soil enzyme activities (Zhang et al., 2022a), whereas in this study, we collected a larger dataset (1812 observations) that included the impacts of nine types of MPs on enzyme activity. Indeed, previous studies reported the impact of MPs on soil enzyme activity through the following pathways. First, the introduction of MPs to soils disrupts the structure of soil aggregates, and the released organic matter encapsulated in these aggregates is utilized by microorganisms and then promotes microbial activity (Liu et al., 2017; Lozano et al., 2021). Second, MPs can serve as unique habitats for bacterial enrichment due to their strong adsorption capacity, thus promoting microbial growth and changing the function of the soil ecosystem (Huang et al., 2019; Lian et al., 2021). Third, MPs can alter the soil environment and nutrient composition, thus directly affecting the effectiveness of extracellular enzymes in the soil (Yu et al., 2020).

The effect of MPs addition on soil enzyme activity differed among the MP types. PP MP mainly increased the activities of β-glucosidase, acid phosphatase and FDAse, which was probably because the methyl side branch of PP is easily destroyed by biochemical processes (Zhang et al., 2021), and the addition of PP MP improved the soil dissolved organic matter (DOM) levels, which was beneficial for the utilization of microbes and then enhanced enzyme activity (Liu et al., 2017). Exposure to PE MP inhibited the activities of urea, β-glucosidase and catalase, which was probably because this plastic particle reduced the available nutrients for soil microorganisms (Yu et al., 2020), and limited the diversity and richness of the soil bacterial community and this finding was consistent with the decline in microbial activity (Fei et al., 2020). In addition, the higher surface area of PE MP can adsorb more contaminants, and then reduce enzyme activity (Wang et al., 2022c). The addition of PS had a negative effect on soil enzyme activity, probably for two reasons. First, the benzene ring structure of PS may affect the stability of the enzyme structure by breaking the chemical bonds between molecules (Dong et al., 2021). Second, molecular simulation experiments revealed that PS nanoparticles easily penetrate lipid membranes and severely affect cell membrane activity, thus affecting cell function (Awet et al., 2018).

In general, the presence of MPs in the soil environment can improve soil aeration, and then stimulate soil microbial activity by supplying oxygen content. However, high concentrations of MPs can bring more ecological risks by releasing harmful substances such as phthalates or absorbing organic substances and heavy metal contaminants (Wang et al., 2016). In this study, low-dose MPs amendment did not affect soil respiration but stimulated enzyme activity, whereas high dose MPs enhanced soil respiration but inhibited enzyme activity. These discrepancies were likely due to microorganisms being stressed by high concentrations of MPs, which required more substrates and energy during their metabolism, and the higher metabolic quotient of microorganisms induced greater soil respiration (Zhang et al., 2022b). Moreover, higher MPs contents largely reduce the soil available nutrients (such as phosphorus and potassium), which limits the secretion of extracellular enzymes by microorganisms (Yang et al., 2021). In addition, the application of large amounts of MPs increases competition with soil microbes for physicochemical niches and thus reduces microbial activity (Wan et al., 2019).

The exposure of MPs over a short-term period increased soil respiration. This result was probably because microorganisms can colonize the surfaces of MPs within hours and gradually form biofilms, which are conducive to microbial growth and utilize labile carbon to produce $CO_2$ (He et al., 2022; Harrison et al., 2014). However, as the exposure period was further increased, MPs had a limited effect on soil $CO_2$ emissions, which was probably because the active component of carbon was exhausted. Interestingly, the impact of MPs addition on soil enzyme activity in short- or long-term incubation periods was insignificant, whereas this effect was significant when the exposure period ranged from 30 to 100 days. It is difficult to explain the time effect of MPs exposure on soil enzyme activity in this study, which should be a focus in the future.

Soil pH and plants also affect the response of soil enzyme activity to MPs addition. Specifically, MPs enhanced soil enzyme activity in acidic environments but inhibited this variable in alkaline conditions. This result highlights the important role of pH in controlling soil ecology. Indeed, a previous study found that the surface of MPs becomes more electronegative with increasing pH, which competes with $OH^-$ for adsorption sites and then induces a decrease in absorption ability (Luo et al., 2020). Accordingly, it is expected that the less absorbed organic matter around the "microplastisphere" probably reduced the positive effect of MPs on enzyme activity in alkaline conditions, and their toxicological effect likely induced the negative effect of MPs on enzyme activity. In addition, plant roots directly promote enzyme activity by providing organic carbon for microorganisms (de Souza Machado et al., 2019), and the presence of MPs has the potential to threaten crop productivity and plant safety, which likely inhibits enzyme activity in soils. However, interestingly, MPs promoted the activity of enzyme in the presence of plants. This unexpected result was probably because MPs can increase the abundance of some special microbial taxa encoding nitrogen transformation in the plant-soil-microorganism system (Yu et al., 2021a), which accelerated nitrogen cycling in rhizosphere soil, and then improved soil enzyme activity.

### 4.3. Limitations of this study

In this study, the effects of MPs on soil microbial activity were quantified by meta-analysis, and it was found that the type, concentration, and exposure duration of MPs significantly altered the responses of soil respiration and enzyme activity to MPs. However, there were still some limitations regarding the impacts of MPs on soil respiration and enzyme activity. First, most of the present studies were based on short-term laboratory incubation experiments, but few field experimental datasets were applied to consider the effects of MPs migration, fragmentation or ageing on soil ecology under natural conditions (Kumar and Sheela, 2021). Second, our meta-analysis did not consider the coeffect of MPs and organic/metal contaminants on soil ecology. Indeed, MPs can adsorb heavy metals, organic pollutants, and antibiotics and then produce antagonistic or synergistic effects affecting soil ecosystems, thus impacting soil microbial activity with increasingly complex mechanisms; exploring this concept will be necessary when researching the interactions of MPs with other pollutants in the future.

## 5. Conclusions

This meta-analysis presented evidence that the presence of MPs increased soil respiration by 18 % but had a limited effect on soil enzyme activity, and these effects depended on the MP type, concentration, size, and exposure period. The amendment of PP MP increased soil respiration and enzyme activity, whereas exposure to PET, PE and PS MPs inhibited soil enzyme activity. Interestingly, the environmentally relevant concentration (<1 %) of MPs did not affect soil respiration but stimulated soil enzyme activity. The response of soil respiration to MPs addition was also dependent on MP size, as small (<500 μm) and large (≥500 μm) plastic particles increased and decreased soil respiration, respectively. Short-term (≤30 days) exposure to MPs significantly increased soil respiration, whereas the presence of MPs significantly inhibited soil enzyme activity when the incubation period ranged from 30 to 100 days. In addition, soil pH and plants also regulated the response of soil microbial activity to MPs amendment. MPs exposure significantly increased soil respiration in alkaline soil or in the absence of plants; the amendment of MPs increased soil enzyme activity in acidic soil but reduced it in alkaline soil, and improved soil enzyme activity in the presence of plants. Overall, our results highlighted that nonbiodegradable MPs accelerated the release of $CO_2$ from soils but had an insignificant effect on enzyme activity. We suggest management measures such as increased the application of organic fertilizers and planting green manure should be implemented to enhance the SOC in microplastic contaminated soils, and future studies should focus on the ecological effect of these plastic particles in fields.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

No data was used for the research described in the article.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2022.104770.

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