Global meta-analysis reveals differential effects of microplastics on soil ecosystem

Article *in* The Science of The Total Environment · January 2023

DOI: 10.1016/j.scitotenv.2023.161403

6 authors, including:

Lingfan Wan
Chinese Academy of Sciences

Yuqing Liu
Institute of Tibetan Plateau Research Chinese Academy of Sciences

Yu Shen
Chinese Academy of Sciences

Guo-hua Liu
Chinese Academy of Sciences

Science of the Total Environment 867 (2023) 161403

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Global meta-analysis reveals differential effects of microplastics on soil ecosystem

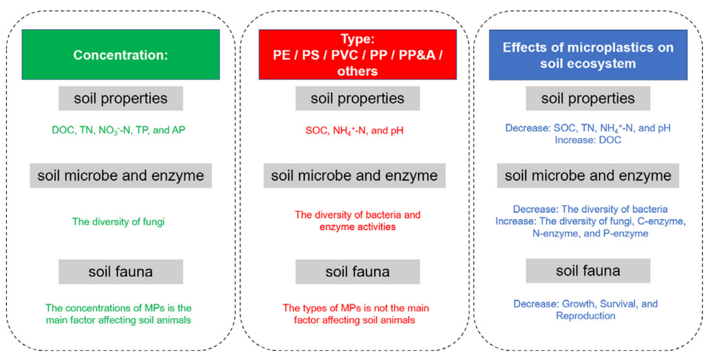
Lingfan Wan, Hao Cheng, Yuqing Liu, Yu Shen, Guohua Liu, Xukun Su *

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-environmental Sciences, Chinese Academy of Sciences, Beijing, China
College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China

HIGHLIGHTS

- Variations were detected in the different microplastics (MPs) on soil ecosystem.
- MPs have a remarkable negative effect on soil fauna.
- MPs reduce bacterial diversity, while increase fungal diversity and enzyme activity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Zhaozhong Feng

Keywords:
Soil ecosystem
Microplastics
meta-analysis
Quantitative analysis
Driving factor

ABSTRACT

A large number of individual studies and meta-analyses have shown that microplastics (MPs) affect soil ecosystems. However, the effects of different concentrations and types of MPs on soil ecosystem are still unclear. Here, a comprehensive meta-analysis was performed to examine the responses of 19 variables, associated with soil properties, microbes, enzymes, and fauna, to MPs, based on 114 peer-reviewed studies. The results showed that the addition of MPs significantly reduced the soil organic carbon (SOC), total nitrogen (TN), NH_4^+-N, pH, and diversity of bacteria, and increased the dissolved organic carbon (DOC), diversity of fungi and enzyme activities, especially enzymes related to the biogeochemical cycle. We further discussed that soil MPs exerted negative effects on soil fauna, including survival, growth, and reproduction, and that the concentration of MPs, rather than the type, was the biggest driving factor causing the toxicity of MPs affecting soil animals. More importantly, the concentrations of MPs were the main factor affecting the DOC, TN, NO_3^--N, total phosphorus (TP), available phosphorus (AP), and diversity of fungi, whereas the types of MPs were the main factors reflected in the SOC, NH_4^+-N, pH, diversity of bacteria, and enzyme activities. This study aimed to evaluate the response of soil ecosystems to the different concentrations and types of MPs, and the largest driving factor for the toxicity of MPs.

1. Introduction

The annual global plastic production has accelerated over the past 50 years, going from 1.7 million tons in 1950 to 368 million tons in 2020, resulting in a large amount of plastic waste (Geyer et al., 2017; Yang et al., 2021). One of the most serious consequences of plastic waste is microplastics (MPs), which are small plastic pieces <5 mm in size that are considered globally emerging contaminants and are widely distributed

* Corresponding author at: State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, No. 18 Shuangqing Road, Haidian District, Beijing 100085, China
E-mail address: xksu@rcees.ac.cn (X. Su).

http://dx.doi.org/10.1016/j.scitotenv.2023.161403
Received 4 November 2022; Received in revised form 20 December 2022; Accepted 1 January 2023
Available online 5 January 2023

in the environment (Thompson et al., 2004). MPs have serious impacts on soil ecosystems because of their longevity and low biodegradability; thus, they have received wide attention from ecologists and environmental scientists across the globe (Liu et al., 2017). Many MPs are retained in the soil because of plastic waste, sewage sludge, agricultural plastic film, atmospheric deposition, and household products (Blasing and Amelung, 2018; Zhang et al., 2020). According to a report, nearly 79 % of all the plastic waste generated between 1950 and 2015 (i.e., 6300 megatons) was directly or indirectly discharged into the soil, which has been identified as a major input of MPs to soil (Geyer et al., 2017; Lin et al., 2020). Widespread use of agricultural plastic film has also been recorded as a major source of MPs in soil (Baho et al., 2021). MPs in soil come from a wide range of sources, which are easy to transfer to and transform in the soil environment and pose a threat to the soil ecosystem (Rillig, 2012). MPs contaminate the terrestrial environment and serve as vectors of other contaminants. More importantly, MPs can be transferred along the food chain and endanger human health (You et al., 2022). MPs can also exert certain ecotoxicological effects on the soil ecosystem, such as affecting the physicochemical, faunal, and microbiological properties of the soil, however, further research is required (Machado et al., 2018; Wang et al., 2022a; Zhang et al., 2022a).

Soil physicochemical, faunal, and microbiological properties represent the three main indicators of soil health (Kibble white et al., 2016). Therefore, further analysis of the effects and risks of MPs on the soil ecosystem is necessary (Jacques and Prosser, 2021). For example, investigation on how MPs will affect the soil biota, soil properties, and biogeochemical cycles, and more importantly, further clarification on how concentrations and types of MPs would be altered in terrestrial ecosystems. Recently, several studies have investigated the effect of MPs on the soil ecosystem, including soil properties, microbial communities, enzyme activities, and fauna, showing contradictory results with negative (Acconcia et al., 2022; Lwanga et al., 2016; Yang et al., 2022), positive (Kwak and An, 2021; Ma et al., 2020; Qian et al., 2018), and no effects (Hodson et al., 2017). Studies on the effects of MPs at various concentrations have shown conflicting results. MPs altered the size distribution of water-stable soil aggregates, and the effects of different concentrations were significant (Boots et al., 2019). MPs at low exposure concentrations had little effect on dissolved organic carbon (DOC) and dissolved organic nitrogen (DON); however, high concentrations of MPs stimulated enzymatic activity, leading to an increase in DOC and DON (Liu et al., 2017). MPs had neutral effects on the survival rates of earthworms under low exposure concentrations, whereas MPs with high concentrations significantly increased earthworm mortality (Cao et al., 2017). Contradictory results have also been reported on the responses of soil ecosystems to different types of MPs. For example, polyester, polyamide, and acrylic (PP&A) can significantly reduce soil water-stable aggregates, whereas polystyrene (PS) can significantly increase the amount of soil water-stable aggregates (Machado et al., 2018). Moreover, polyvinyl chloride (PVC) had the greatest impact on the diversity of microbial communities in a study discussing the effects of polyethylene (PE), PS, and PVC on soil enzyme activities and microbial communities (Fan et al., 2022). In contrast, PE had more severe effects than PVC (Fei et al., 2020). Polypropylene (PP) and PE disturbed the lipid metabolism in earthworms (Chen et al., 2022), whereas PE had no effect on the survival and body weight of earthworms and earthworms had no tendency to ingest it (Hodson et al., 2017). In most cases, MPs can directly or indirectly alter soil properties, thereby affecting soil function, fauna, and microbial communities; however, the effects vary and depend on the polymer type and dose (Chen et al., 2019; Gao et al., 2021; Wang et al., 2022a). These contradictory results hinder us from obtaining a pattern of universality regarding the effects of MPs on soil ecosystems and, more seriously, from further studying the underlying principles and mechanisms. Therefore, elucidation of the interactions and ecological processes between MPs and soil ecosystems is important to provide in-depth insights into the prevention and management of MP pollution in the soil environment.

Meta-analysis provides a statistical method to compare and integrate general conclusions from a collection of studies while recognising the differences in the effects of MPs of various concentrations and types on soil ecosystems in specific studies (Hedges et al., 1999; Yu et al., 2022). Although some meta-analyses of MPs in soil ecosystems have been conducted (Li et al., 2022; Wei et al., 2022; You et al., 2022; Zhang et al., 2022a), the effect of different concentrations and types of MPs on terrestrial ecosystems remains controversial (Wang et al., 2020b; Ya et al., 2021), especially by exploring the dominant factors for the toxicity of MPs, remains controversial. In this study, a meta-analysis of 3334 data series was conducted from 114 studies to research the effects of MPs on soil ecosystems. Our aims were to: (1) assess the effects of MPs on soil properties, enzyme activities, and microbial and faunal communities around the globe; (2) investigate the response of soil properties, enzyme activities, and microbial and faunal communities at different concentrations and types of MPs; and (3) identify the types and concentrations of MPs that act as the largest driving factors for their toxicity.

2. Materials and methods

2.1. Literature search and data collection

Our meta-analysis was retrieved by conducting a systematic literature search following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Liberati et al., 2009; Nakagawa et al., 2017) aimed at recruiting all studies that assessed the differential effects of MPs on soil microbes, enzymes, and fauna in the global terrestrial ecosystem. Published literature only including indexed articles from September 2005 to December 2022 were retrieved by searching the Web of Science (https://www.webofscience.com) and China National Knowledge Infrastructure (https://www.cnki.net/) using the following search strings: (microplastic* OR nanoplastics*) and (soil or land or terrestrial environment) and (microb* OR fung* OR bacter* OR archae* OR soil fauna* OR Earthworm* PR Collembola* OR Nematode* OR terrestrial arthropod* OR terrestrial invertebrates* OR soil enzyme OR enzyme activities OR soil properties OR physicochemical properties). This yielded 3186 articles in the databases and was reduced to 1805 articles after abstracts were screened and duplicate articles were removed. Subsequently, the full text of the selected articles was reviewed, and 114 articles were included in this meta-analysis (see Supporting Information Part 2). In summary, these papers were selected for our study according to the following selection criteria to avoid bias in publication selection: (i) the experimental groups must have the addition of MPs solely without extra addition of heavy metals and plasticisers; (ii) at least one pair of data (experimental treatments against controls) were reported and at least one quantitative description of the concentrations and types of MPs was given; (iii) the initial conditions, species compositions, and soil parameters were similar in the control and treatments; (iv) the study contained at least one of the following variables: soil property, enzymatic activity, microbial, and fauna communities; and (v) the descriptive statistics of the mean, standard error (SE), standard deviation (SD) and sample size (n) for selected variables in the control and treatment groups could be obtained (Wan et al., 2014).

In total, 3334 paired observations were identified from 114 publications that matched the requirements (Supplementary Appendix), of which 1175, 1806, and 353 were related to soil physicochemical properties, soil microorganisms, and soil faunal properties, respectively. Nineteen variables were extracted and grouped into three categories (eight soil properties, eight soil microbes and enzymes, and three soil fauna variables) from the papers to test for differences in responses in soil ecosystems to MPs. Owing to the multiple types of enzymes collected in the database, 16 enzymes were classified into four classes based on soil C, N, and P cycling from the papers, including C-cycling enzymes: (1) phenol oxidase, (2) peroxidase, (3) α-1,4-glucosidase, (4) β-1,4-glucosidase, (5) cellobiohydrolase, (6) β-1,4-xylosidase, and (7) invertase; N-cycling enzymes: (8) *N*-acetyl-β-glucosaminidase, (9) L-leucine aminopeptidase, and (10) urease; P-cycling enzymes: (11) phosphatase; and other enzymes: (12) protease, (13) phytase, (14) amylase, (15) dehydrogenase, and (16) fluorescein diacetate. The database included reports on soil properties [i.e., soil organic carbon (SOC), DOC, total nitrogen (TN), ammoniacal nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), total phosphorus (TP), available phosphorus (AP), and pH], soil microbial variables [i.e., Microbe, Bacteria, Fungi, Enzyme, C-enzyme (C-cycling enzymes), N-enzyme (N-cycling enzymes), P-enzyme (P-cycling enzymes), other enzymes] and soil fauna variables [i.e., Growth, Survival, and Reproduction]. The digitizing software WebPlotDigitizer was used to extract the results presented in the figures and tables of selected published papers (Drevon et al., 2017).

2.2. Data analysis

All studies that tested the effects of MPs were reassessed to determine whether they contained sufficient information to be included in a meta-analysis to compare reported effects between studies. Because of the different approaches used to measure and gather data, the Hedges' g was used as it uses weighted standardised deviations (Gurevitch et al., 2001) as a measure of effect size to estimate the differences in the effects of MPs. The Hedges' g was calculated as follows:

$$\text{Hedges}' \ g = \frac{X_t - X_c}{\sqrt{\frac{(n_t-1)S_t^2 + (n_c-1)S_c^2}{n_t + n_c - 2}}} J \quad (1)$$

where X_t and X_c are the mean values of a specific variable in the treatment and control groups, respectively; n_t and n_c are the sample sizes of a specific variable in the treatment and control groups, respectively; and S_t and S_c are the SD of a specific variable in the treatment and control groups, respectively. Given that Hedges' g requires a pooled standard deviation estimate if a study reported an SE, it converted was into SD using SD = SE × √ n.

The correction for bias attributed to different sample sizes, represented by J, was estimated through a differential weighting study as follows:

$$J = 1 - \frac{3}{4(n_t + n_c - 2) - 1} \quad (2)$$

The corresponding pooled variance (v_d) of Hedges' g was estimated by:

$$v_d = \frac{n_t + n_c}{n_t n_c} + \frac{d^2}{2(n_t + n_c)} \quad (3)$$

In studies in which neither SD nor SE was reported, one-tenth of the mean was used, instead of SD (Zhou et al., 2020b). A random-effects meta-analysis model was used to calculate the effect size of MPs on soil properties, microbes and enzymes, and fauna variables in soil ecosystems for each observation. To explore the different effects of the concentrations and types of MPs in soil ecosystems, only the concentration data was used, whose unit can be converted into g/kg, and divided the MPs into six types (Erni-Cassola et al., 2019), namely PE, PP, PS, PVC, PP&A and others (Table S1). As the concentration of MPs was a continuous variable, the type of MPs was a discontinuous variable. Subsequently, single meta-regression models (van Houwelingen et al., 2002; Yu et al., 2022) were created using the concentration of MPs (g/kg) as a continuous variable to quantify the different effects of MPs concentrations on the soil ecosystem. A mixed-effect meta-analysis of the different types of MPs was also conducted to explore the impact of different types of MPs on the soil properties, microbe, and fauna variables. In our meta-analysis, the weighted effect size and 95 % confidence interval (CI) was calculated. For ease of understanding, the effects of MPs were considered significant if the corresponding 95 % confidence intervals (CI) of the target variables of the effect size did not overlap zero (Luo et al., 2006). The omnibus test (QM) was performed to measure heterogeneity among effect sizes (Zhou et al., 2020b). When the QM values were significant ($P < 0.05$), the responses among the different types of MPs were different for each predictor variable in the model (Cordier et al., 2021). In addition, random forest mean predictor importance (increase in Node Purity) was used to characterise the main predictors. In our analysis, only results with a sample size >4 are presented.

Finally, publication bias was assessed for all evaluated variables using a regression test for funnel plot asymmetry (Egger et al., 1997) and Rosenberg's fail-safe number (Rosenberg, 2005). Our statistical tests showed the absence of publication bias for all variables (Fig. S2). All statistical analyses were conducted using the "metafor" package of R software (version 4.1.5) (Viechtbauer, 2010).

3. Results

3.1. Effects of MPs on soil properties

The response of soil properties to MPs was mainly reflected in the changes in soil basic properties, like, carbon, nitrogen, and phosphorus contents, and pH. Among the eight soil properties considered as variables, MPs significantly reduced soil SOC, TN, NH_4^+-N, and pH; increased DOC; and did not show any significant changes in NO_3^--N, TP, or AP (Fig. 1). The total content of these elements (i.e., SOC, TN, and TP) in soils decreased in the presence of MPs (Fig. 1). Correlation analysis showed that the effect sizes of most variables were significantly positively correlated indicating that most indicators of soil properties decreased synchronously after the addition of MPs (Fig. 2). In addition, TP was negatively correlated with the NO_3^--N concentration (Fig. 2). The main predictors of DOC, TN, NO_3^--N, TP, and AP were the concentrations of MPs, whereas, the main predictors of SOC, NH_4^+-N, and pH were the types of MPs (Fig. 3). As the concentration increased, the effect sizes of SOC, NO_3^--N, and pH gradually decreased. The effect size of DOC gradually increased as the concentration increased (Fig. 4), and DOC showed the same positive effect with all types of MPs (Fig. 5a), indicating that DOC was only affected by concentration. Significant heterogeneity was found in all indices among the different types ($P < 0.05$), which showed that different types of MPs had different effects on soil properties (Fig. 5a). As shown in Fig. 5a, PP and others significantly increased the effect size of NH_4^+-N, whereas PE, PS, and PVC showed neutral and negative effects. PP, PS, and others significantly decreased SOC; however, no significant changes were observed in SOC with the addition of PE (Fig. 5a). For all types of MPs, no significant changes were discerned in pH, except for PP, which significantly decreased pH (Fig. 5a).

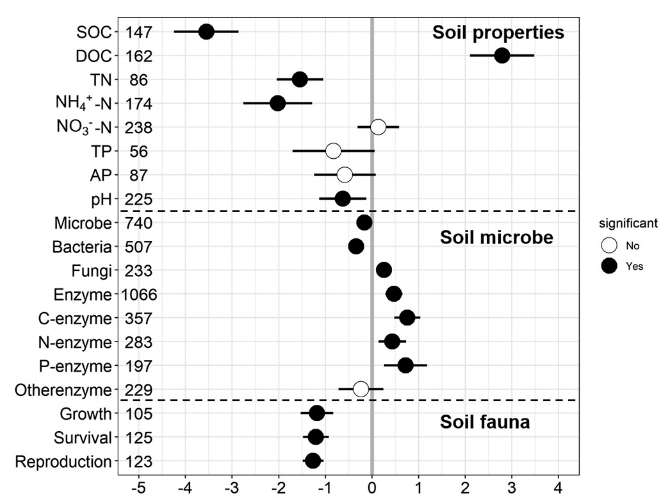


Fig. 1. Effect size (Hedges' g) of microplastics (MPs) on 19 variables related to soil properties, microbe, and fauna factors. The spot symbols show the average value of effect size of MPs on each variable and the horizontal solid lines represent 95 % confidence interval. The vertical dashed line represented effect size = 0. If a spot is solid (Yes), the effects of MPs are significant. If a spot is hollow (No), the effects of MPs are non-significant. Numbers indicate the sample sizes.

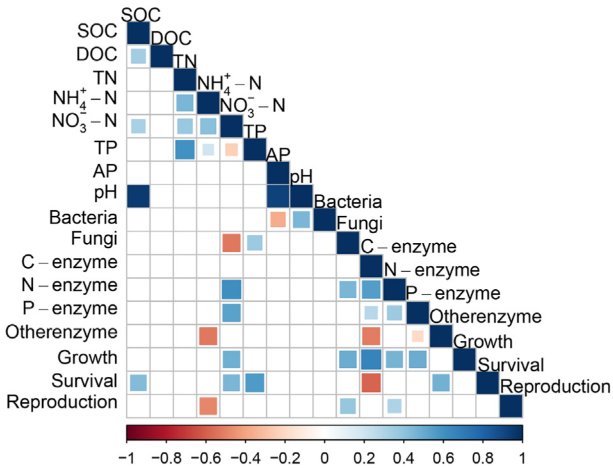


Fig. 2. Relationships of the effect sizes (Hedges' g) of each variable with others. Square size and colours represent Pearson correlations. Only significant results with sufficient sample sizes ($n > 4$) were displayed.

3.2. Effects of MPs on soil microbe and enzyme

The meta-analysis results showed that MPs significantly increased the effect size of fungi, enzymes, C-enzymes, N-enzymes, and P-enzymes, whereas they significantly decreased microbes and bacteria. (Fig. 1), However, no significant changes were noted in other enzymes (Fig. 1). Correlation analysis showed that C-enzyme was positively correlated with N-enzyme and P-enzyme, indicating that all enzyme indicators related to the biogeochemical cycle were positively correlated with each other (Fig. 2). Moreover, other enzymes were negatively correlated with C-enzyme and P-enzyme (Fig. 2). Notably, the concentrations of MPs were the main predictors of the diversity of fungi, and the types of MPs were the main predictors of the diversity of bacteria and enzyme activities (Fig. 3). As the concentrations increased, the effect size of fungi and P-enzyme gradually decreased from positive to negative values, which meant that MPs promoted the growth of the diversity of fungi and P-enzyme activities at lower concentrations, but inhibited them at higher concentrations (Fig. 4). Furthermore, the effect size of other enzymes gradually increased from negative to positive value as the concentration increased. Significant heterogeneity was found in the effects among the different types of MPs ($P < 0.05$) (Fig. 5b), suggesting that the types of MPs have different effects on soil microbes and enzymes. No significant changes were observed in bacteria for all types of MPs, except for PP&A, which significantly decreased the bacterial diversity (Fig. 5b). Our results showed that PP&A significantly reduced the effect size of the enzyme, whereas PP, PS, PVC, and others significantly increased the effect size of the enzyme, and PE showed neutral effects (Fig. 4b). PP and PVC decreased activities of other enzymes, while increasing biogeochemical cycle enzyme activity (Fig. 4b). In this study, changes in different concentrations and types of MPs are suggested to have different effects on soil microbe and enzyme.

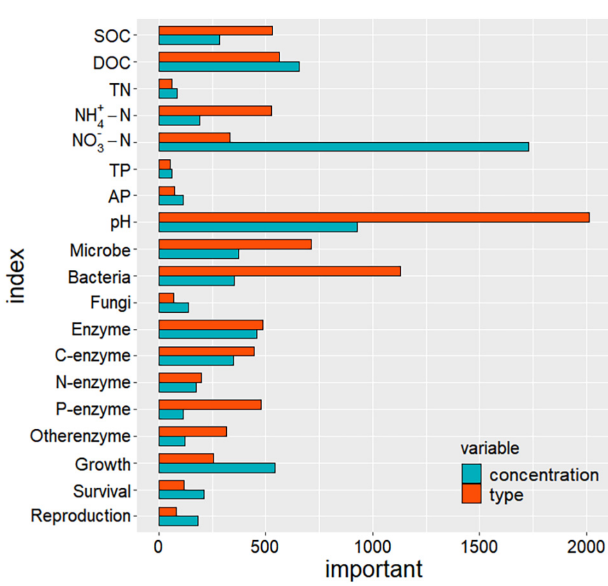


Fig. 3. Random Forest analysis to identify the main predictors of the effect sizes (Hedges' g) of SOC (a), DOC (b), TN (c), NH_4^+-N (d), NO_3^--N (e), TP (f), AP (g), pH (h), microbe (i), bacteria (j), fungi (k), enzyme (l), C-enzyme (m), N-enzyme (n), P-enzyme (o), other enzymes (p), growth (q), survival (r), and reproduction (s). Increase in Node Purity (important) show the importance of main predictors.

3.3. Effects of MPs on soil fauna

The meta-analysis results showed that MPs had the same negative effect on the growth, reproduction, and survival of soil fauna (Fig. 1). Correlation analysis showed that the growth, reproduction, and survival of soil fauna were significantly positively correlated with soil properties (Fig. 2), which was important for maintaining good soil physical and chemical properties. The main factors influencing the growth, reproduction, and survival of the soil fauna were the concentrations of MPs (Fig. 3). In addition, the soil fauna of reproduction and survival gradually decreased with increasing concentrations, indicating that MPs had negative effects on soil animals, and the size of the negative effects increased with increasing concentrations (Fig. 4). For the three soil fauna variables, significant heterogeneity was found in the effects among the different types ($P < 0.05$) (Fig. 5c). Moreover, all types of MPs inhibited animal growth, reproduction, and survival to different degrees (Fig. 5b), except PVC, which may benefit soil animal reproduction. Compared to other types of MPs, PS had the most negative effect on the soil fauna growth (Fig. 5b). In our study, MPs inhibited the growth, reproduction, and survival of soil fauna.

4. Discussion

4.1. Response of soil properties to different MPs

Because MPs interact with various soil properties, changes in soil properties are the main measure to understand the risks posed by MPs to soil ecosystems (Zhou et al., 2020a). The results of our meta-analysis showed that the addition of MPs significantly reduced soil SOC, TN, NH_4^+-N, and pH but increased DOC (Fig. 1). Soil pH is a major abiotic factor that determines soil properties. Soil pH decreased with increasing MPs concentration (Fig. 4), implying a dose-dependent relationship between soil pH and MPs (Dong et al., 2021). The alteration of soil pH can influence soil nutrient fixation and, consequently, nutrient availability (Li and Liu, 2022). Furthermore, the SOC of the acidic soil decreased more significantly than that of the alkaline soil (Wang et al., 2022a). MPs in the soil age faster when the pH is reduced, destroying their internal chemical balance and thereby accelerating the release of SOC (Piccardo et al., 2020). Soil TP fixation by calcium could be strongly increased when pH was increased (Penn and Camberato, 2019), which could explain why AP had a stronger positive effect on soil pH (Fig. 2). MPs destroyed the soil structure and physically protected soil aggregates from SOC, resulting in a decrease in SOC (Yu et al., 2020). Moreover, previous studies have found that SOC content decreases with increasing MP concentrations (Liu et al., 2021), which is consistent with our findings (Fig. 4). The most intuitive finding was that higher MP concentrations accompany higher concentrations of DOC in soils because soil bacteria might decompose MPs into soluble carbon in soil (Wang et al., 2021), which was consistent with our study (Fig. 4). Additionally, MPs can increase soil DOC by changing the spectral characteristics of DOC (Gao et al., 2021; Shi et al., 2022).

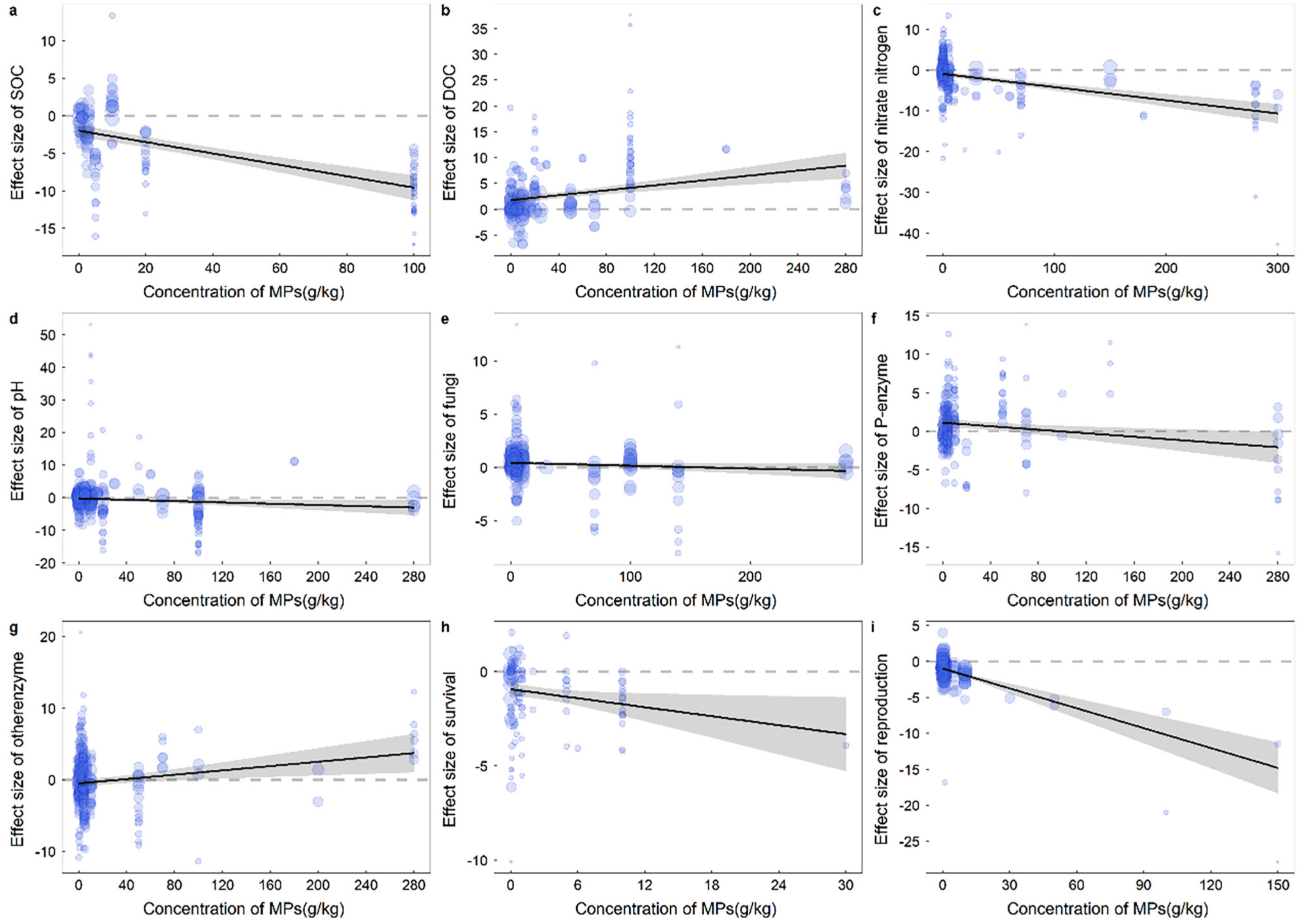


Fig. 4. Relationships between the concentration of MPs (g/kg) with effect size (Hedges' g) of SOC (a), DOC (b), NO_3^--N (c), pH (d), fungi (e), P-enzyme (f), other enzymes (g), survival (h), and reproduction (i). Effect size (Hedges' g) = 0, dashed grey line; predicted mean effect size (with 95 % CI in grey), black lines.

Our results revealed that the type of MP was the main factor affecting SOC, pH, and NH_4^+-N (Fig. 3). This indicated that the same concentration of MPs, but of different types, could have different effects on soil pH. For example, PE significantly reduced pH (Yu et al., 2020), but PLA and clothing fibre MPs caused no significant effects (Boots et al., 2019). In addition to concentration and type, small-sized MPs displayed a greater impact than larger particles, and soil pH was also affected by MP shape and incubation time (Yang et al., 2021). SOC showed stronger positive effects on soil pH (Fig. 2), which may be caused by soil pH having a binding capacity for minerals and SOC. This was the reason why the types of MPs were also the main factors affecting SOC. Our results showed that PE and PVC significantly decreased NH_4^+-N content, but other MPs did not (Fig. 5b). Soil samples with different MP had different ammonia conversion rates (Lu et al., 2021). For instance, PLA decreased the content of NH_4^+-N, implying that PLA may facilitate the nitrification of NH_4^+-N (Chen et al., 2020).

In general, MPs can drive shifts in soil pH, reduce the total soil nutrient content and increase DOC content, thereby changing the soil microbial community and enzyme activities. These results indicate an interaction between the soil physicochemical properties caused by MPs. The interactions between these indicators should be investigated when studying the impact of MPs on the soil ecosystem in the future, which can help us better understand the role of MPs in the soil ecosystem.

4.2. Response of soil microbe and enzyme to different MPs

Our meta-analysis showed that MPs significantly increased the fungal diversity (Fig. 1). Evidence has shown that microorganisms are enriched on plastic surfaces as potentially distinct habitats (Wang et al., 2020b), making them significantly different from the microbial community in the surrounding environment (Sarker et al., 2020). MPs altered the arbuscular mycorrhizal fungi community structure and diversity in a dose-dependent manner (Wang et al., 2020a), which is consistent with our study (Fig. 3). With increasing concentrations, the effect size of fungi decreased significantly, and the total content changed from increasing to decreasing (Fig. 4). For ease of understanding, this means that although MPs are beneficial for fungal reproduction, a concentration that is too high is harmful to fungi. Moreover, a low amount of MPs could improve the microbial community abundance, however, the microbial community decreased significantly in the soil with a large number of MPs (Zhang et al., 2017). Our results showed that the type of MPs was the main factor affecting the bacterial diversity (Fig. 3). Most types of MPs had a negative effect on bacterial diversity (Fig. 5b). For example, PE and PVC reduced the richness and diversity of the bacterial communities (Fei et al., 2020). Evidence suggests that MPs selectively influenced microbial abundance and led to a fungi-prevalent soil microbial community (Gao et al., 2022), which was the reason for the decrease in the diversity of bacteria but an increase in the diversity of fungi (Fig. 1). In general, MPs affect a series of soil properties that exert selective pressure on microbes, leading to changes in community structure and diversity (Rillig et al., 2019). Research on the effect of MPs on soil microbial communities is still in its infancy; consequently, more studies are needed to assess the effects of MPs on soil microbial communities.

In our study, MPs significantly increased the effect size of enzyme activity (Fig. 1). As a reason for this result, MPs increased the attachment area of microorganisms and enabled them to form a bio-membrane that could improve enzyme activities in soil on the MPs surface (Huang et al., 2019). Our findings showed that concentration had a certain influence, but the type of

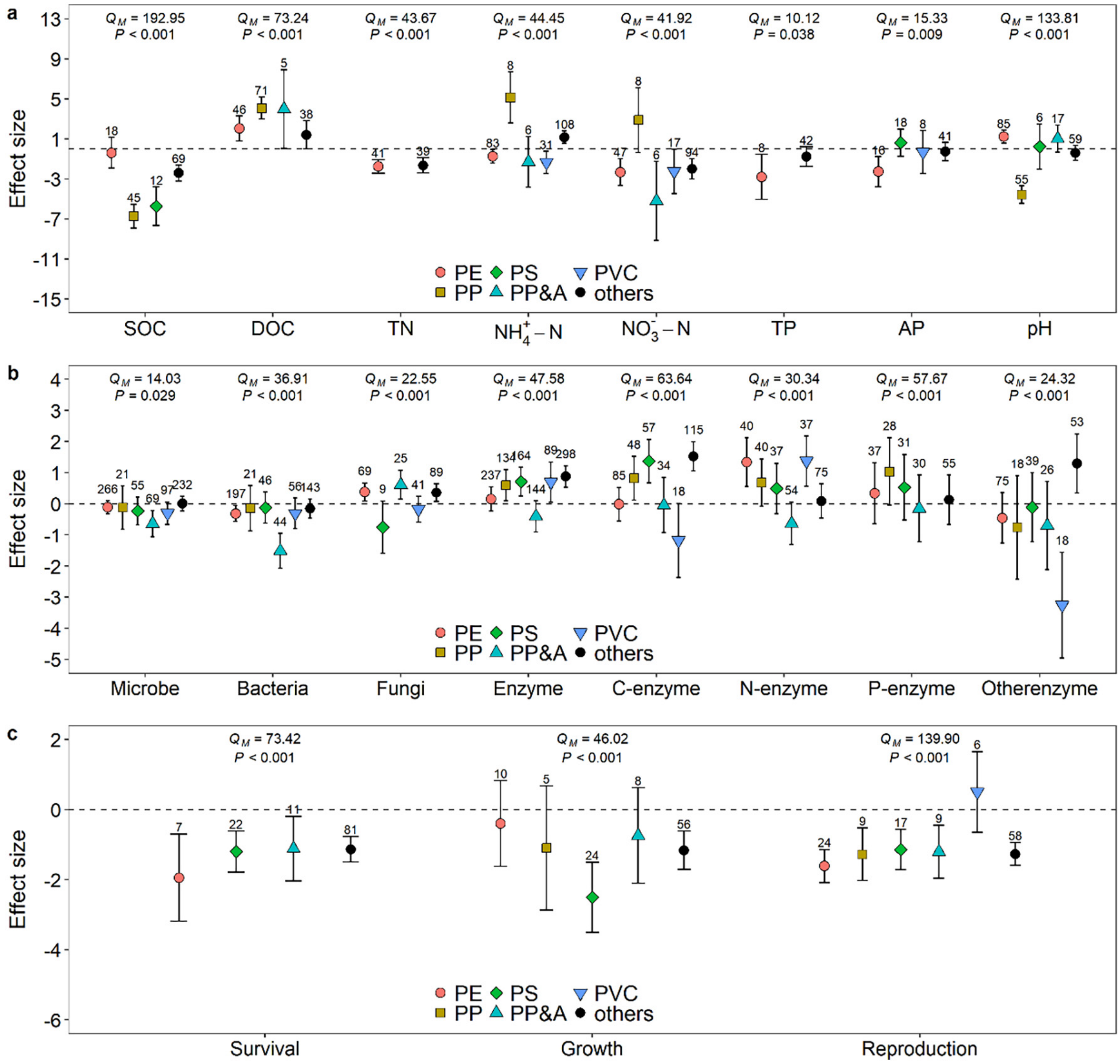


Fig. 5. Effect size (Hedges'g) of 19 variables related to soil properties (a), microbes (b), and fauna factors (c) in response to different types of MPs. The spot symbols show the average value of effect size of MPs on each variable and the horizontal solid lines represent 95 % confidence interval. The significances of different concentrations and types were tested by the omnibus test. QM and *P* values are given at the top of the figure. The vertical dashed line represented effect size = 0. The numbers at the top of the confidence intervals represent the sample sizes.

MPs was the main impact factor of the enzyme (Fig. 3), which is consistent with previous studies (Zang et al., 2020). Not only did different types of MPs have different effects on the overall enzymes, but also on enzymes related to different soil C, N, and P cycles (Fig. 5b). This was consistent with our study showing that the addition of PE significantly increased enzyme activities, whereas PS reduced enzyme activities (Machado et al., 2019). Taking carbon cycle-related enzymes as an example, enzyme activities involved in C-cycling decreased by 20–46 % in soil amended with PVC (Zhou et al., 2022), whereas MPs increased enzyme activities involved in C-cycling (Guo et al., 2021). The polymers are ranked according to the hazard classification of monomers, with PVC classified as the most hazardous level 5, PA, PS, PE, and PET as level 2, and PP as the least hazardous level 1 (Lithner et al., 2011). The toxicity of different types of MPs may explain this phenomenon.

MPs affect the microbes in the soil, thus changing the microbial community biodiversity and enzyme activities of the soil ecosystem, thereby affecting the health of the soil ecosystem (Gao et al., 2021). However, their impact on soil microbiota and related biogeochemical processes remains poorly understood (Zhu et al., 2022). Although this phenomenon has received increasing attention, the mechanism behind it is still unknown; therefore, the dose-dependence and MPs type specificity of the soil microbial communities and enzyme activities needs to be studied further.

4.3. Response of soil fauna to different MPs

Our research showed that soil MPs exerted negative effects on soil fauna including survival, growth, and reproduction, indicating that MPs are harmful to soil animals (Fig. 1). MPs can affect soil animals in many ways. Firstly, MPs that adhere to the external surfaces of fauna can directly hinder their mobility and cause surface damage. Second, owing to the small size of MPs, they can be eaten by soil animals, causing direct toxicity (Teuten et al., 2009). Third, owing to their low degradability, MPs may accumulate in the soil food chain, thus affecting soil animals at various trophic levels (Wang et al., 2022b). Finally, MPs indirectly affect the activity of soil animals by changing their habitat (Lin et al., 2020). Most MPs (various types of components) hindered the growth, survival, and reproduction of the soil fauna (Fig. 5).

Our meta-analysis found that the effect size of soil animal survival and reproduction decreased with an increase in the concentration of MPs in a dose-effect with MPs (Fig. 4). Many studies have confirmed that exposure to higher concentrations of MPs can lead to more negative effects on the growth, survival, and reproduction of soil fauna (Ding et al., 2022; Yeates et al., 1993; Zhang et al., 2022b), which is consistent with the results of our study. Generally, intestinal damage is considered a key toxic effect of MPs on soil animals, affecting their feeding ability (Jiang et al., 2020) and even threatening their life of soil animals (Song et al., 2019). MPs had little effect on the fitness of soil fauna under low exposure concentrations, whereas MPs exposure at high concentrations significantly inhibited the growth and increased the mortality of soil fauna, which has also been observed by other researchers (Cao et al., 2017). In addition, greater accumulation and more serious intestinal damage to soil fauna are caused by higher concentrations of MPs (Rodriguez-Seijo et al., 2017). MPs can pose a threat to metabolic systems and histopathological changes in the soil fauna, leading to growth arrest (Ji et al., 2021). Moreover, higher concentrations in PS caused an increase of severe histopathological changes in soil fauna (Jiang et al., 2020). MPs significantly inhibited microorganisms as well as C- and N-cycling functional genes in earthworm guts, and it has become an increasingly serious leading metabolic system disorder as the concentration of MPs increases (Gao et al., 2022). MP exposure can also induce DNA damage in the soil fauna, altering the expression levels of the genes related to specific enzymes involved in sperm development and energy metabolism, leading to a decline in reproduction rates (Xu et al., 2021). The number of sperm significantly decreased and the sperm deformity rate gradually increased with increasing concentrations of MPs (Xie et al., 2020).

Our study summarised the negative effects of MP on soil fauna, and the biological toxicity of MPs to soil fauna mainly comes from the concentration (Fig. 2), meaning that the concentrations of MPs in the soil should be controlled to protect soil animals. Soil fauna are integral members of soil food webs that contribute to the ecological functioning of soil, such as soil nutrient cycling, energy flow, and sustaining soil health (Wang et al., 2019; Wang et al., 2020b). Hence, the soil fauna should be protected by developing substitutes for plastic products that do little harm, which deserves further research.

4.4. Limitations

Based on a dataset of 114 published articles, this synthesis provides an assessment of the different concentrations and types of MP in global soil ecosystems (soil physicochemical properties, soil animal health, and the diversity of soil microorganisms). Undeniably, the analysis methods of these articles are different, and the research results are contradictory. However, because of the differences and contradictions in research on a small scale, it is necessary to integrate these studies for analysis and evaluation to come up with widely applicable conclusions. The limitations of our meta-analysis are as follow. First, most of these quantitative results are based on laboratory or plot experiments, and the concentration of MPs added to the soil in experimental treatments is far greater than that in the soil in real life and has a shorter exposure time, which is quite different from the actual complex environment. Second, half of the cases were indoor control experiments, not regional experiments, so there may be uncertainty when our experiments are extended to natural ecosystems. Third, meaningful indicators were not included in the analysis. For example, MPs alter soil aggregation stability; however, our study has yet to determine whether these alterations further affect the microbial community structure and diversity within different soil aggregates (Hou et al., 2021). Finally, only consider the two most influential properties of MPs, i.e., their concentration and type, were considered and MPs in terms of chemistry, aging, size, and shape had different effects on their toxicological effects (Rillig et al., 2021). Further research is required to consider the immense diversity of MPs.

5. Conclusion

Our comprehensive meta-analysis demonstrated that MPs not only significantly reduced the diversity of bacteria, pH, and some soil nutrients (SOC, TN, and NH_4^+-N) but also had a significant negative effect on the survival, growth, and reproduction of soil fauna (Fig. 1). The role of MPs also exists, which is a consistent positive overall effect on fungi, DOC, and enzymes, especially C-enzymes, N-enzymes, and P-enzymes (Fig. 1). There is also a neutral effect on other enzymes, TP, AP, and NO_3^--N. Previous meta-analyses studies have also shown the effect of MPs on soil ecosystems, but our results are more comprehensive than those of the previous meta-analysis because, in this study, the effects of the concentrations and types of MPs on the soil ecosystem were quantitatively analysed. MPs have been shown to cause a series of biological effects in soil, but the direction and intensity of these effects remain unclear. This study provides evidence that the type of MPs was the main factor affecting SOC, NH_4^+-N, pH, bacterial diversity and enzyme activities, but not the main factor affecting soil animals. In addition, the concentrations of MPs were the main factors affecting DOC, TN, NO_3^--N, TP, AP, and fungal diversity. These findings are helpful for the exploration of dose-dependence and MPs types specificity in soils. Future studies should focus on the mechanisms underlying the effects of different concentrations and types of MPs on soil ecosystems. Finally, we identify knowledge gaps that need to be filled and provide suggestions for future research.

CRediT authorship contribution statement

Lingfan Wan: Conceptualization, Methodology, Software, Data curation, Visualization, Writing – original draft. **Hao Cheng:** Conceptualization. **Yuqing Liu:** Data curation. **Yu Shen:** Data curation. **Guohua Liu:** Conceptualization, Methodology. **Xukun Su:** Conceptualization, Methodology.

Data availability

The authors do not have permission to share data.

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.

Acknowledgements

We thank all people for helping us to complete the research. Dong Zhu from Chinese Academy of Sciences provided editorial comment. This study was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), Grant No. 2019QZKK0402.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161403.

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