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Effects of plastic residues and microplastics on soil ecosystems: A global meta-analysis

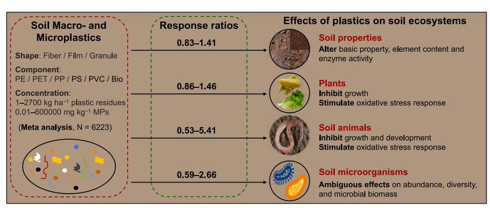
Jinrui Zhang [a,b,c,1], Siyang Ren [a,b,c,d,1], Wen Xu [a,b,c], Ce Liang [a,b,c], Jingjing Li [a,b,c], Hanyue Zhang [a,b,c,e], Yanan Li [a,b,c,f], Xuejun Liu [a,b,c,*], Davey L. Jones [d,g], David R. Chadwick [d], Fusuo Zhang [a,b,c], Kai Wang [a,b,c,*]

[a] *Key Laboratory of Plant-Soil Interactions of Ministry of Education, Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China*
[b] *National Academy of Agriculture Green Development, China Agricultural University, Beijing, 100193, China*
[c] *National Observation and Research Station of Agriculture Green Development (Quzhou, Hebei), China Agricultural University, Beijing, 100193, China*
[d] *School of Natural Sciences, Bangor University, Bangor, LL57 2DG, UK*
[e] *Soil Physics and Land Management Group, Wageningen University & Research, Wageningen, 6700 AA, the Netherlands*
[f] *Water Systems and Global Change Group, Wageningen University & Research, Droevendaalsesteeg 4, Wageningen, 6708 PB, the Netherlands*
[g] *SoilsWest, Centre for Sustainable Farming Systems, Food Futures Institute, Murdoch University, Murdoch, WA 6105, Australia*

HIGHLIGHTS

- Effect of plastic residue and MPs on soil ecosystem was quantified by meta-analysis.
- Effect of plastic residue and MPs on soil ecosystem depends on types and quantity.
- Plastic residue and MPs can alter soil physicochemical properties.
- Plastic residue and MPs inhibit growth and development of plant and soil animal.
- Effect of plastic residue and MPs on soil microorganism is uncertain.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution is one of the global pressing environmental problems, threatening the health of aquatic and terrestrial ecosystems. However, the influence of plastic residues and microplastics (MPs) in soil ecosystems remains unclear. We conducted a global meta-analysis to quantify the effect of plastic residues and MPs on indicators of global soil ecosystem functioning (i.e. soil physicochemical properties, plant and soil animal health, abundance and diversity of soil microorganisms). Concentrations of plastic residues and MPs were 1–2700 kg ha^{-1} and 0.01–600,000 mg kg^{-1}, respectively, based on 6223 observations. Results show that plastic residues and MPs can decrease soil wetting front vertical and horizontal movement, dissolved organic carbon, and total nitrogen content of soil by 14%, 10%, 9%, and 7%, respectively. Plant height and root biomass were decreased by 13% and 14% in the presence of plastic residues and MPs, while the body mass and reproduction rate of soil animals decreased by 5% and 11%, respectively. However, soil enzyme activity increased by 7%—441% in the

* Corresponding authors at: Key Laboratory of Plant-Soil Interactions of Ministry of Education, Beijing Key Laboratory of Farmland Soil Pollution Prevention and Remediation, College of Resources and Environmental Sciences, China Agricultural University, Beijing, 100193, China.
E-mail addresses: liu310@cau.edu.cn (X. Liu), kaiwang_ly@cau.edu.cn (K. Wang).
[1] Jinrui Zhang and Siyang Ren should be considered joint shared first author

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presence of plastic residues and MPs. For soil microorganisms, plastic residues and MPs can change the abundance of several bacteria phyla and families, but the effects vary between different bacteria.

1. Introduction

Over the past 50 years, plastics have become widely used in various industries (Maity and Pramanick, 2020; Yang et al., 2021; Zhang et al., 2022b). Annual global plastic production has accelerated over the past decade, reaching 368 million tons in 2020 (Plastics Europe, 2021). Much of this plastic results in pollution of the environment and has attracted great attention due to its global ubiquity (Jambeck et al., 2015; Maity and Pramanick, 2020; Zhang et al., 2022b), and its potential to cause ecological damage in aquatic and terrestrial systems (Kwak et al., 2022; Ng et al., 2018; Rochman et al., 2016). Plastics in the environment can decompose into small plastic pieces with a diameter < 5 mm, defined as microplastics (MPs). Particles > 5 mm are called macroplastics, and the smaller size classification of 1 nm to 1 μm are defined as nanoplastics (Frias and Nash, 2019; Thompson et al., 2004). In the last decade, the ubiquitous presence of MPs in aquatic environments (e.g. oceans, lakes, and rivers) have been reported in many studies and MPs have been shown to adversely impact aquatic organisms, causing a loss of marine and freshwater ecosystem functioning (Dong et al., 2021; Rochman et al., 2016; Wang et al., 2019). As 80% of plastics arriving in the oceans are produced, used, and disposed of on land, the pollution of terrestrial systems with plastic residues and MPs could be just as serious (Rochman, 2018).

Because plastic residues and MPs are long-lasting with very low biodegradability, they have accumulated rapidly in the global terrestrial environment (Jambeck et al., 2015; Zhang et al., 2022b), with the abundance of plastic residues and MPs varying by up to 6 orders of magnitude between different terrestrial environments (Koutnik et al., 2021). It is estimated that around 63,000–430,000 and 44,000–300,000 tons of MPs have been generated annually in European and North American farmland soils, respectively (Nizzetto et al., 2016). A survey of soils in Lahore, Pakistan displayed that the abundance of MPs varied from 1750 to 12,200 pieces kg^{-1} (Rafique et al., 2020). The concentrations of MPs in farmland soils of Yong-In, Korea were about 10–7630 pieces kg^{-1} (Kim et al., 2021). The abundance of MPs in farmland across Ontario, Canada were observed at between 4 and 541 pieces kg^{-1} (Crossman et al., 2020). As China is the world's biggest producer and consumer of plastic and is suffering from serious plastic pollution, a substantial number of studies of plastic residues and MPs in farmland soils have been carried out in China (Plastics Europe, 2021; Qi et al., 2020a). The occurrence and distribution of plastic residues and MPs in several Chinese farmlands have been investigated, showing a large spatial difference of their abundance, 0.1–411.2 kg ha^{-1} and 1.6–690, 000 pieces kg^{-1}, respectively (Du et al., 2005; Hu, 2019; Huang et al., 2020; Liu et al., 2018; Lv et al., 2019; Zhou et al., 2019a). A study by Ren et al. (2021) reported that agricultural much film contributed 10%—30% of total MPs in Chinese agricultural soil. In addition to agricultural mulch film, the large accumulation of plastic residues and MPs in farmland soils is also due to the result of other sources of inputs, such as municipal waste (Liu et al., 2018; He et al., 2019), sewage sludge application (Long et al., 2019), organic fertilizer and agricultural compost (Weithmann et al., 2018), atmospheric deposition, flooding, littering and runoff (Ng et al., 2018; Yang et al., 2021). However, comparisons between studies should be made with caution, as different studies have used different extraction and detection methods for MPs.

Plastic residues, including MPs, are a threat to the soil ecosystem. Recently, several review studies have emphasized the potential adverse effect of plastic residues, including MPs, on the soil environment (Mbachu et al., 2021; Ng et al., 2018; Qi et al., 2020a; Wang et al., 2022; Wang et al., 2021b; Zhou et al., 2021b). For example, Mbachu et al. (2021) and Wang et al. (2022) revealed that soil MPs can affect plant health and soil fertility. Wang et al. (2021b) highlighted that MPs can cause adverse effects on the growth, lifespan, reproduction, and survival of soil fauna, via diverse toxicity mechanisms, particularly for earthworms and nematodes. The effect of MPs and plastic residues on soil properties and terrestrial biota depends on its chemical composition, concentration, and shape (Mbachu et al., 2021). Specifically, polyester (PES, 0.4%, w/w) fibers could increase the water holding capacity of a loamy sand soil, but at the same time, decrease the soil microbial activity (de Souza Machado et al., 2018). However, high-density polyethylene (HDPE) (2%, w/w) fragments had no significant impact on these soil-related indicators (de Souza Machado et al., 2018). Moreover, PES fibers could increase the ratio of dry biomass between root and leaf, while polyamide (PA) beads had an inverse impact. PA beads in the soil could increase the nitrogen content and total biomass of plant leaves, indicating that PA beads would have a similar effect on plant leaves as nitrogen fertilizer in respect of nitrogen content and biomass (de Souza Machado et al., 2019). Furthermore, several studies reported that plastic particles with the size of 0.08–1.00 μm can penetrate the stele of rice, cucumber, wheat and lettuce, leading to efficient uptake of smaller microplastic (Li et al., 2020; Li et al., 2021b; Liu et al., 2022). It indicates that MPs can be transferred to the human body through the food chain, causing a potential threat to human health (Lwanga et al., 2017; Zhou et al., 2021a). Furthermore, exposure to MPs could affect the growth and reproduction of soil animals (Kwak and An, 2021), causing intestinal damage and neurotoxicity (Lei et al., 2018). In addition, MPs could impact microbial activity, as they can increase the abundance of specific microbial communities, such as dominant phyla (*α-proteobacteria* and *acidobacteria*) (Lu et al., 2018; Liu et al., 2021).

To tackle the pollution caused by the wide use of conventional polymers (e.g. polyethylene, PE), the application of biodegradable plastic mulches (BDMs) has been regarded as a promising solution (Kasirajan and Ngouajio, 2012). BDMs degrade at rates faster than conventional PE film (Chamas et al., 2020), and their agricultural benefits are comparable with conventional PE films (Yin et al., 2019). However, the widespread use of BDMs has been hindered due to the high cost and poor suitability in different geographical and climatic conditions (Liu et al., 2021). Moreover, there are uncertainty about short- and long-term ecological impacts of BDMs on soil ecosystems (Liu et al., 2021; Qi et al., 2020b; Qi et al., 2018).

At present, the study of the impact of plastic residues and MPs on soil ecosystem functioning is still in its infancy. To better understand the effect of plastic residues and MPs on global soil ecosystem function (as indicated by soil physicochemical properties, plant and soil animal health, and soil microorganisms), we conducted a systematic study of available data. Meta-analysis is often used as a statistical method to compare and integrate the results of multiple studies. It can elicit general patterns on regional and global scales (Zheng and Peng, 2001). For example, Gao et al. (2019) and Zhang et al. (2020) explored the effects of plastic mulch film and plastic residues on crop yield and water use efficiency (WUE) in China by using a meta-analysis. To our knowledge, this is the first time a meta-analysis has been used to systematically quantify the effect of plastic residues and MPs on global soil ecosystem function.

2. Materials and methods

2.1. Literature search and data collection

We used the three literature databases, Web of Science (WOS), EI Compendex, and China Knowledge Resource Integrated Database (CKRI), with the keywords "plastic residue" or "plastic debris" or "macroplastic" or "microplastic" or "nanoplastic" and "soil or terrestrial" to identify papers published from January 1, 2000, to January 31, 2021. These keywords aimed to generate data to answer our main questions about the effects of plastic residues and MPs on the global soil ecosystem. All the keywords associated with plastics were linked by the Boolean operator "OR", and synonymous relevant to edaphic were connected with operator "AND". By searching using these keywords, we obtained 5212 scientific papers (WOS 3381, CKRI 1211, and EI 620), excluding reviews and conference articles. Details of search strings and the process of literature collection are presented in Table S1 and Fig. S1 in Supporting Information (SI).

To explore the effects of plastic residues and MPs on soil ecosystems, we divided the research subjects into soil properties, plants, soil animals and soil microorganisms. In summary, these papers were chosen according to the following selection criteria: (a) the study must have compared experimental treatments against controls, with three or more replicates; (b) the experimental groups must have the addition of MPs or plastic residues solely without extra addition of heavy metals and/or plasticizers; (c) the number of replications and average value had to be presented in the article. By applying these selection criteria, we finally selected 105 valid articles for our analysis (Table S2), of which 48, 38, 35, and 23 were related to soil properties, plants, soil animals, and soil microorganisms, respectively. Then, a total of 6223 observations were extracted for meta-analysis, of which 3325, 1240, 799 and 859 were related to soil properties, plants, soil animals and soil microorganisms, respectively.

2.2. Global meta-analysis

The suitability of using either a fixed effect or a random effect model for the meta-analysis was determined using Akechi Information Criterion (AIC). The smaller value for the AIC was observed when the random effect model was applied, meaning that the goodness-of-fit of the random effect model was better than that of the fixed effect model.

Three essential factors were extracted from the papers: the mean (*M*), the number of replicates (*N*) and standard deviation (*SD*) of the selected variables. If *SD* was not provided directly in the paper, it was calculated from the standard error *(SE)* (Hao and Yu, 2005). The conversion formula is as follows:

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

where *N* is the sample size and *SD* is the standard deviation of the treated or control group. A significant number (43.7%) of articles did not provide the *SD* or *SE* values, therefore, we used the average coefficient of variation of all data to calculate the *SD* and multiplied it by the reported mean (M_r) (Zhang et al., 2020). The formula is as follows:

$$SD_i = m_r \times M_i \tag{2}$$

$$m_r = \frac{\sum \frac{SD_r}{M_r}}{n_r} \tag{3}$$

where m_r refers to the average coefficient of variation of the reported, which comes from the sum of the ratio of each known SD (SD_r) and mean (M_r), divided by the number of known data (n_r). SD_i is calculated by the data of articles that did not report the SD and is derived from the sum of m_r and the mean of the literature (M_i).

The effect value is the combined statistics in the quantitative meta-analysis, whose calculation method mainly depends on the acquisition of data from the original literature. We used a natural log-transformed response ratio (ln RR) as a metric of the effects of different sizes of MPs or plastic residues on a response variable relative to the control where plastic residue was not used.

$$\text{logRR} = \text{In}\left(\frac{\overline{X_E}}{\overline{X_C}}\right) \tag{4}$$

$$V_{\text{lnRR}} = SD_p{}^2\left(\frac{1}{N_E\overline{X_E}^2} + \frac{1}{N_C\overline{X_C}^2}\right) \tag{5}$$

$$SD_p = \sqrt{\frac{(N_E - 1)SD_E^2 + (N_C - 1)SD_C^2}{N_E + N_C - 2}} \tag{6}$$

where $\overline{X_i}$, SD_i, and N_i denotes the mean, standard deviation, and number of replicates, respectively, and the subindices *E* and *C* refer to experimental treatments and the control group, respectively. SD_p is the pooled standard deviation, and *X* includes varieties of different indicators that affect soil ecosystems.

Our study included an assessment of publication bias using a funnel plot approach (Fig. S2–5; Borenstein et al., 2021). In general, in the absence of publication bias, the scatter will be due to sampling variation only, and the plot will resemble a symmetrical inverted funnel. It should be noted that when the study size is too small (< 10, see Fig. S3-Body length and Fig. S4-Phyla number), the funnel plot cannot accurately reflect the bias situation (Sterne et al., 2011).

We also conducted a subgroup meta-analysis of the shape and chemical component of plastic residues and MPs to explore the impact of different types of plastics on the indicators of soil ecological environment. According to the specific surface area, plastics are classified into fiber, film, and granule, where shapes of sphere and pellet were regarded as granule. The plastic components in this study included polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and biodegradable (Bio) plastics (including polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT)). In addition, a random effect meta-regression analysis was carried out to assess the relationship between MPs loading rate and the soil eco-environmental indicator.

The "metafor" package (version 3.0–2) and "forestplot" package (version 2.0.1) in R (version 4.1.1) (https://www.r-project.org/) were used for the meta-analysis. We used and modified the codes from Zhang et al. (2020), which are provided from the repository: https://github.com/pablogalaviz/Micro-Plastics-Meta-Analysis.git.

3. Results

In current study, the concentrations of plastic residues and MPs in field experiments were 1–2700 kg ha^{-1} and 90–2700 mg kg^{-1}, respectively, based on 2497 observations. While they were 50–2700 kg ha^{-1} and 0.01–600,000 mg kg^{-1} in the laboratory experiments based on 3726 observations. The detailed information of observation data is presented in the Excel file named Raw data in SI. The results of effects of plastic residues and MPs on soil ecosystems are based on the above concentrations.

3.1. Effects of plastic residues and MPs on soil properties

The response of soil to plastic residues and MPs is mainly reflected in the changes of soil basic properties, i.e., carbon content, nitrogen content, phosphorus content and enzymes activities (Zhang et al., 2020; Zhou et al., 2020b). As shown in Fig. 1a, for soil basic properties, plastic residues and MPs reduced soil pH, porosity, water content and soil water movement ($p < 0.05$) based on the summary effect (represented by the red diamond in Fig. 1a). Plastic residues and MPs decreased pH by 1% with summary effect size of 0.99 [95% CI: 0.99, 1] ($p < 0.05$), while according to the chemical components, PE plastic debris reduced pH by 2% with response size of 0.98 [0.97, 0.99], and Bio plastic increased pH by 3% with response size of 1.03 [1.01, 1.04] ($p < 0.05$). The electrical conductivity (EC) and bulk density of soil were not impacted by plastic residues and MPs with the summary effect size equal to 1. However, according to the chemical component of plastics, Bio plastic residues and MPs decreased EC by 19%, while PE plastic debris had almost no effect on EC. Though the summary effect size of bulk density was equal to1,

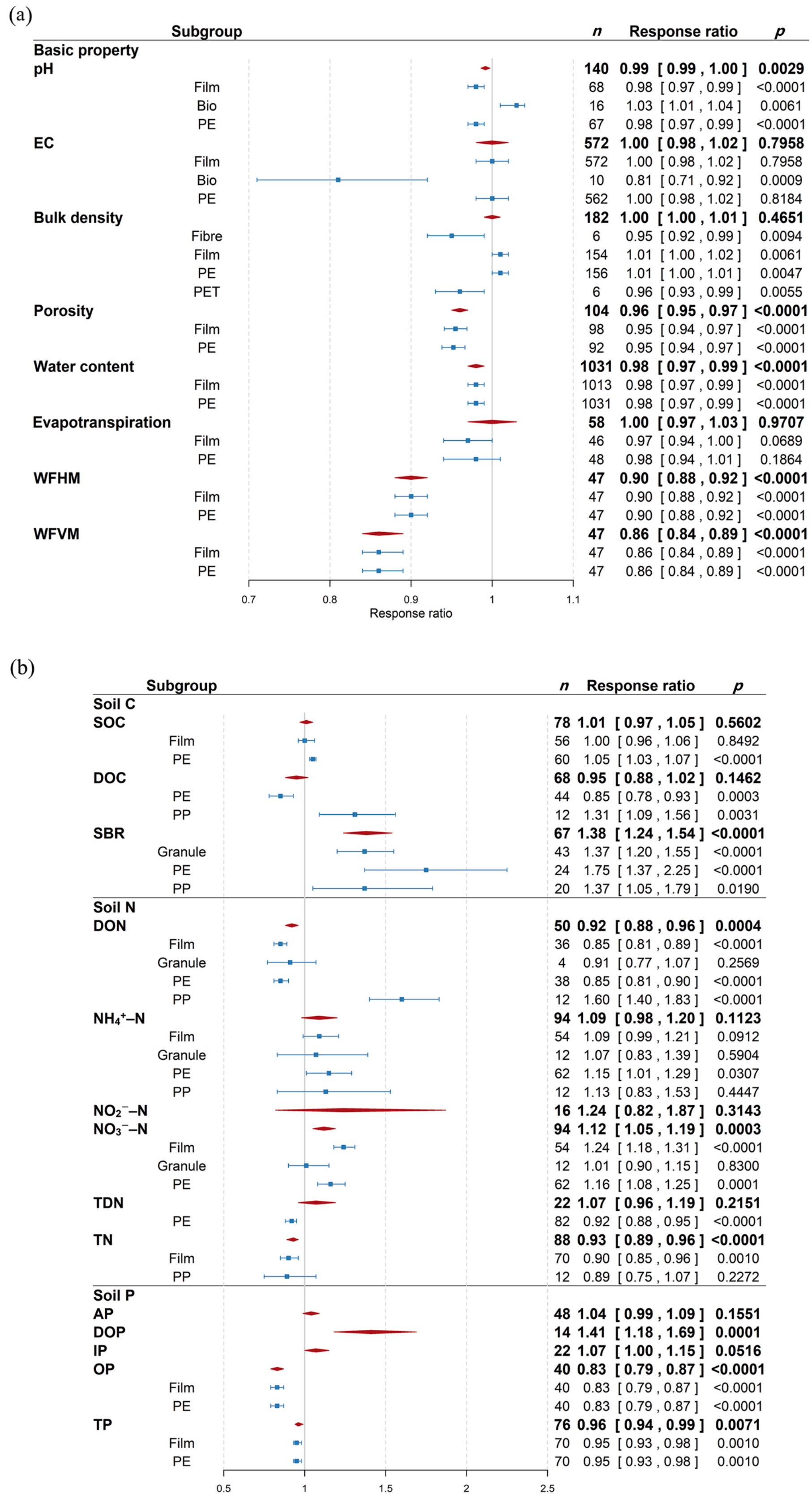

Fig. 1. The effect of plastic residues and MPs on: (a) soil basic properties, (b) soil element content, and (c) soil enzyme activity, based on a multilevel random effect meta-analysis. The red diamond represents the summary effect. The blue square symbols show the average value of response ratio for each type of plastic residue and MPs with error bars representing 95% confidence interval. A ratio > 1 indicates that the response from the treatment is higher compared to the control group. *n* refers to sample size and *p* means the *p*-value of the Q test, with $p < 0.05$ indicating a significant difference. EC, electrical conductivity; WFHM, wetting front horizontal movement; WFVM, wetting front vertical movement; SOC, soil organic carbon; DOC, dissolved organic carbon; SBR, soil basal respiration; DON, dissolved organic

nitrogen; NH_4^+–N, ammonium nitrogen; NO_2^-–N, nitrite nitrogen; NO_3^-–N, nitrate nitrogen; TDN, total dissolved nitrogen; TN, total nitrogen; AP, available phosphorus; DOP, dissolved organic phosphorus; IP, inorganic phosphorus; OP, organic phosphorus; TP, total phosphorus; ACP, acid phosphatase; AKP, alkaline phosphatase; CAT, catalase; CBH, cellobiohydrolase; FDAse, fluorescein diacetate hydrolase hydrolase; GLU, glucosidase; Bio, biodegradable; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene.

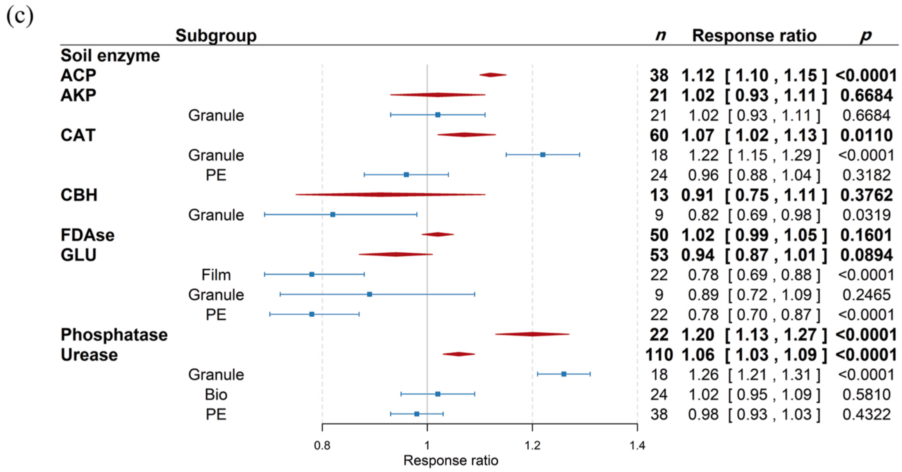

Fig. 1. (*continued*).

fibrous plastic debris decreased the bulk density by 5%, while film plastic debris increased the bulk density by 1% ($p < 0.05$). The PE plastic debris increased the bulk density by 1%, while the PET plastic debris decreased the bulk density by 4% ($p < 0.05$). The summary effect sizes of wetting front horizontal movement (WFHM) and wetting front vertical movement (WFVM) were 0.9 [0.88, 0.92] and 0.86 [0.84, 0.89] ($p < 0.05$) with the plastic residues addition of 80–1280 kg ha^{-1}.

As shown in Fig. 1b, the content of soil organic carbon (SOC) and dissolved organic carbon (DOC) were not significantly affected by the plastic residues (80–2700 kg ha^{-1}) and MPs (1000–280,000 mg kg^{-1}) with the summary effect sizes of 1.01 [0.97, 1.05] and 0.95 [0.88, 1.02] ($p > 0.05$), although PE plastic debris increased SOC content by 5%, and decreased DOC by 15% ($p < 0.05$). All types of plastic residues promoted soil basal respiration (SBR) with summary effect size of 1.38 [1.24, 1.54] ($p < 0.05$). Dissolved organic nitrogen (DON) and total nitrogen (TN) were reduced by most types of plastic residues (450–2700 kg ha^{-1}) and MPs (20–280,000 mg kg^{-1}) with summary effect size of 0.92 [0.88, 0.96] and 0.93[0.89, 0.96] ($p < 0.05$), except for PP plastic debris that promoted DON by 60% ($p < 0.05$). In contrast, nitrate nitrogen (NO_3^-–N) in soil was increased by 12% ($p < 0.05$), while the changes of ammonium nitrogen (NH_4^+–N) and nitrite nitrogen (NO_2^-–N) were not significant ($p > 0.05$). The dissolved organophosphorus (DOP) content was increased by 41% by plastic residues and MPs ($p < 0.05$), while the total organophosphorus (OP) and total phosphorus (TP) content were decreased by 17% and 4% ($p < 0.05$). In general, the effects of plastic residues and MPs on soil carbon, nitrogen and phosphorus varied with the forms of the elements as well as chemical component and shape of plastics. However, the total contents of these elements (i.e., SOC, TN and TP) in soils decreased in the presence of plastic residues and MPs.

The activity of acid phosphatase (ACP), catalase (CAT), phosphatase and urease were enhanced by plastic residues and MPs with summary effect sizes of 1.12 [1.1, 1.15], 1.07 [1.02, 1.13], 1.2 [1.13, 1.27] and 1.06 [1.03, 1.09], respectively ($p < 0.05$; Fig. 1c). Among all plastic types, granular plastic residues and MPs show the greatest effect, increasing the activity of CAT and urease by 22% and 26% ($p < 0.05$). However, other enzymes (AKP, CHB and FDAse) had almost no response to plastic residues and MPs with the summary effect size of 1.02 [0.93, 1.11], 0.91 [0.75, 1.11] and 0.94 [0.87, 1.01], respectively ($p > 0.05$).

3.2. Effects of plastic residues and MPs on plants

The effects of plastic residues and MPs on plants are mainly reflected in plant growth and the indicators of oxidative stress of plants (Pignattelli et al., 2020; Qi et al., 2020a). As shown in Fig. 2a, plastic residues and MPs significantly reduced plant height, total biomass, shoot biomass and root biomass by 13%, 12%, 12% and 14%, respectively ($p < 0.0001$). All types of plastic residues and MPs (film, granule, Bio, PE, PS, and PVC) inhibited plant growth with the summary effect size from 0.59 [0.55, 0.63] to 1 [0.9, 1.21], and the response of shoot biomass to granular plastic was greatest with the response ratio of 0.59 [0.55, 0.63].

In this study, the oxidative stress indicators in plant response to plastic residues and MPs include antioxidant enzymes (ascorbate peroxidase (APX), CAT, peroxidase (POD), superoxide dismutase (SOD)), corresponding substrates and products (ascorbic acid (AsA), glutathione (GSH), hydrogen peroxide (H_2O_2), malonaldehyde, proline (Pro)). As shown in Fig. 2b, the contents of APX, CAT, AsA, H_2O_2, MDA and Pro were increased markedly by plastic residues and MPs ($p < 0.0001$), and APX had the greatest response with summary effect size of 1.46 [1.31, 1.64]. Among all types of plastic, the effect of PET plastic debris to GSH was greatest with the response ratio of 4.74 [3.96, 5.67]. The summary effect of plastic residues and MPs to GSH was not significant ($p > 0.05$), although GSH was decreased by 37% by PE plastic debris, and increased by 3.74 times by PET plastic debris ($p < 0.0001$) according to the chemical component of plastics. However, the contents of POD and SOD were not altered by most types of plastics ($p > 0.05$) with the exception of PVC plastic debris that increased SOD by 27% ($p < 0.05$).

3.3. Effects of plastic residues and MPs on soil animals

The meta-analysis results show that plastic residues and MPs have different degrees of impact on growth, behavior, feeding, reproduction, survival, energy metabolism and oxidative stress response of soil animals (e.g. mice, earthworm, snail, nematode, springtail, Isopods, and honey bee) as shown in Fig. 3.

Plastic residues and MPs can inhibit animal growth. This is reflected in Fig. 3a, where body length, body weight, growth rate, liver organ weight and relative liver weight of animals were reduced by 7%, 5%, 19%, 8% and 6% ($p < 0.05$), respectively. Life span was also shortened by 8% ($p < 0.05$) with the adding of plastic. Moreover, all types of plastics inhibited animal growth to different degrees, e.g. PS plastic debris reducing the body weight, liver weight, relative liver weight and life span of animals with the response ratios of 0.97 [0.95, 0.99], 0.92

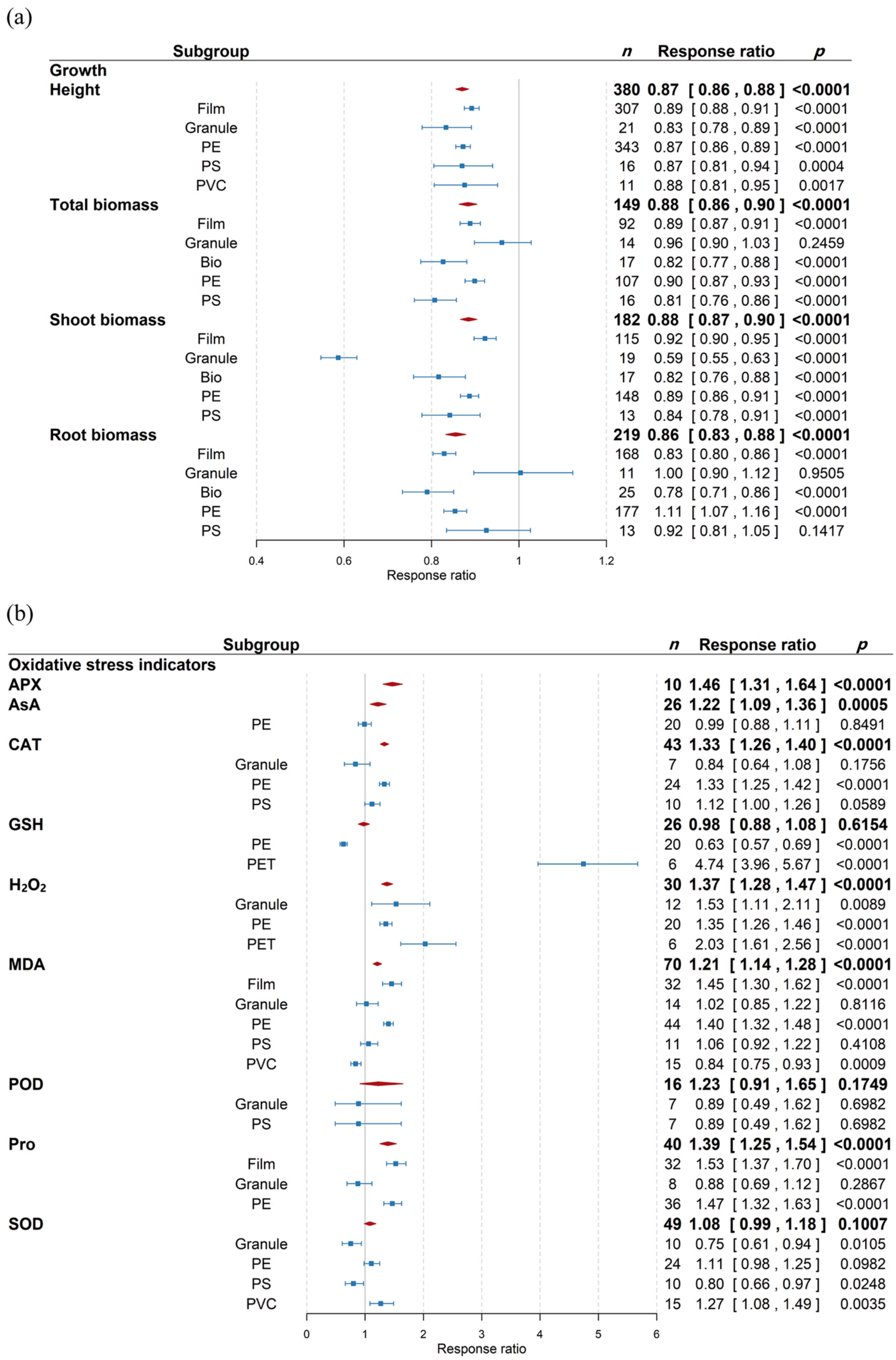

Fig. 2. The effect of plastic residues and MPs on: (a) plant growth and (b) plant oxidative stress indicators based on a multilevel random effect meta-analysis. The red diamond represents the summary effect. The blue square symbols show the average value of response ratio for each type of plastic residue and MPs with error bars representing 95% confidence interval. A ratio > 1 indicates that the response from the treatment is higher compared to the control group. *n* refers to sample size and *p* means the *p*-value of the Q test, with $p < 0.05$ indicating a significant difference. SOD, superoxide dismutase; POD, peroxidase; MDA, malondialdehyde; APX, ascorbate peroxidase; Pro, proline; GSH, glutathione; AsA, ascorbic acid; PS, polystyrene; PVC, polyvinyl chloride.

[0.87, 0.96], 0.94 [0.92, 0.97] and 0.81 [0.74, 0.88], respectively ($p < 0.05$). Behaviors of soil animals was also affected by plastic residues and MPs, with body bending and head thrash frequency decreased by 9% and 19% ($p < 0.0001$), respectively. The response of animal's head thrash to granular plastic was greatest with the response ratio of 0.65 [0.6, 0.7]. However, the locomotion speed of animals increased slightly, although not significantly ($p > 0.05$). In addition, animal feeding rate was slightly reduced by plastic residues and MPs ($p > 0.05$), although it was increased by 24% by the PE plastic residues and MPs ($p < 0.05$).

As shown in Fig. 3b, plastic residues and MPs had a marked negative effects on animals reproduction and survival, reducing the reproduction rate, sperm count and vitality, the contents of succinate dehydrogenase (SDH) and testosterone and survival rate by 11%, 34%, 26%, 47%, 47% and 3%, respectively ($p < 0.0001$), and increasing the rate of sperm deformity by 1.37 times ($p < 0.0001$). The effects of all types of plastic residues and MPs on animal reproduction are similar to the summary effects, such as PS plastic debris decreasing reproduction rate, sperm count and vitality by 7%, 35% and 47%, respectively ($p < 0.05$). In addition, plastic residues and MPs significantly changed the energy metabolism of animals, decreasing the contents of lipids, proteins and total cholesterol (TCH) and energy available by 10%, 9%, 30% and 13%, respectively ($p < 0.05$), but increasing lactate dehydrogenase (LDH) by 25% ($p < 0.0001$).

Similar to the effects on plants, plastic residues and MPs also caused oxidative stress in animals, increasing the ROS and MDA concentration by 63% and 2% with the summary effect sizes of 1.78 [1.39, 2.29] and 1.02 [1.01, 1.03], respectively ($p < 0.0001$; Fig. 3c). Correspondingly,

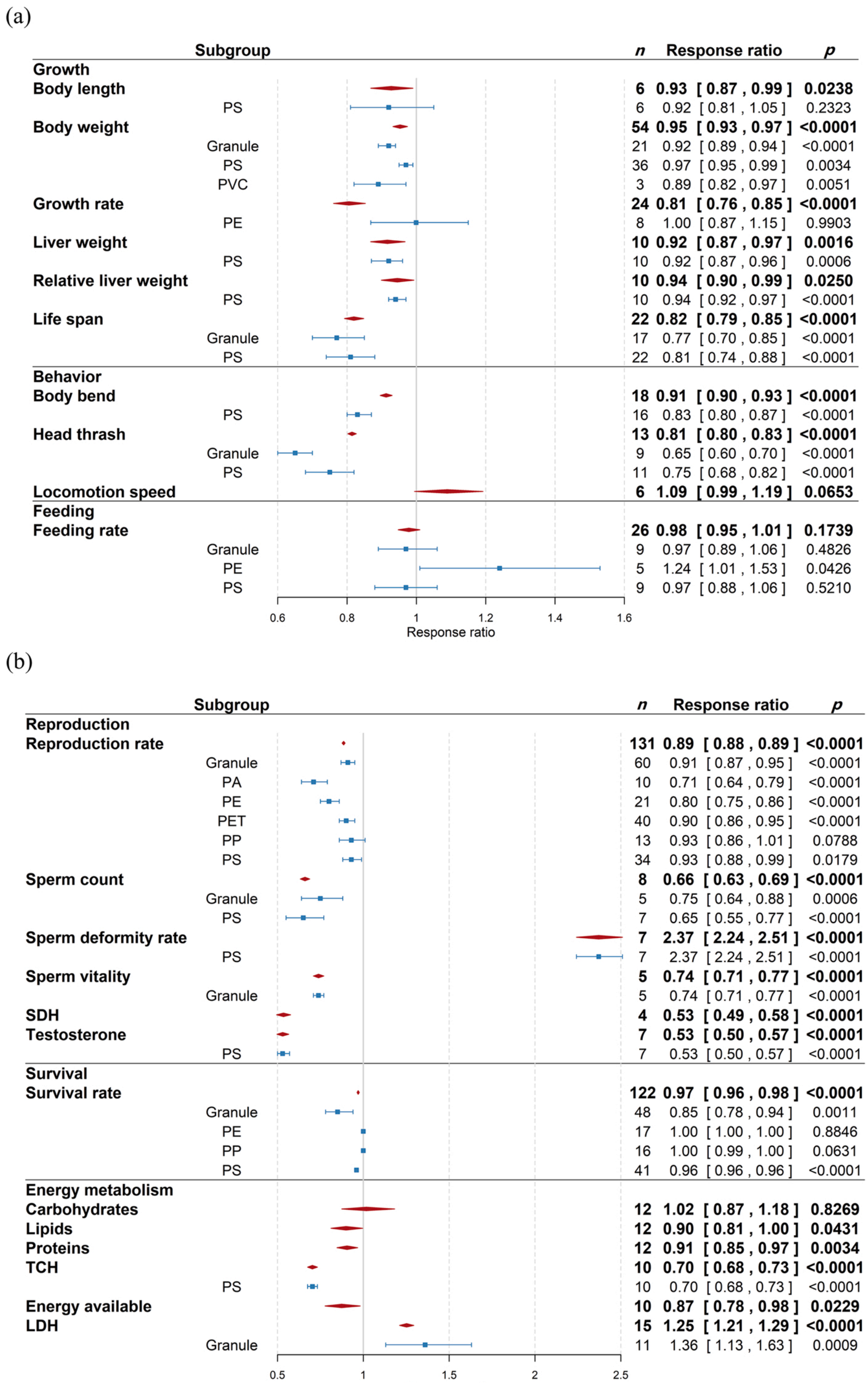

Fig. 3. The effect of plastic residues and MPs on: (a) soil animal growth, behavior and feeding, (b) soil animal reproduction, survival and energy metabolism, and (c) soil animal oxidative stress indicators based on a multilevel random effect meta-analysis. The red diamond represents the summary effect. The blue square symbols show the average value of response ratio for each type of plastic residues and MPs with error bars representing 95% confidence interval. A ratio > 1 indicates that the response from the treatment is higher compared to the control group. *n* refers to sample size and *p* means the *p*-value of the Q test, with $p < 0.05$ indicating a significant difference. SDH, succinate dehydrogenase; LDH, lactate dehydrogenase; TCH, total cholesterol; AchE, acetylcholinesterase; GSH-Px, glutathione peroxidase; GST, glutathione s-transferase; TBARS, thiobarbituric acid reactive substances; ROS, reactive oxygen species; PA, polyamide.

the activities of acetylcholinesterase (AChE), glutathione peroxidase (GSH-Px), SOD and the content of GSH increased by 26%, 441%, 15% and 10%, respectively ($p < 0.0001$), in response to the oxidative stress caused by plastic residues and MPs. However, the activities of anti-oxidative enzymes CAT and GST were inhibited by 5% and 19%, respectively ($p < 0.0001$). The change in thiobarbituric acid reactants (TBARS) was not significant ($p > 0.05$). Furthermore, the effects of various plastic residues and MPs on the antioxidative system of animals was similar to the summary effect, such as the granular and PS plastic debris increasing the content of ROS.

(c)

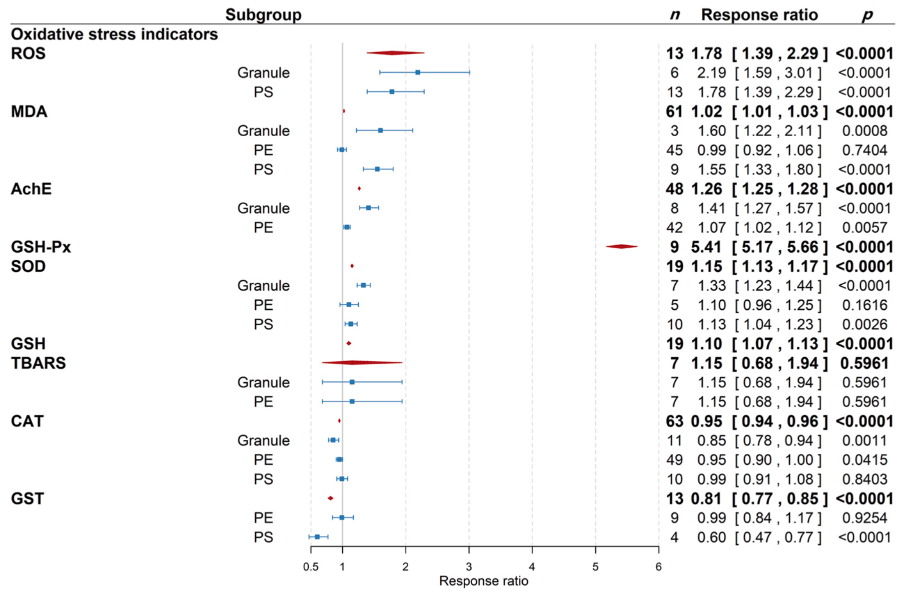

Fig. 3. (*continued*).

3.4. Effects of plastic residues and MPs on soil microorganisms

There are fewer studies about the effects of plastic residues and MPs on soil microorganisms compared to that of soil properties and plants. The sample size of microbial meta-analysis in this study is 859, which is smaller than that for soil properties ($n = 3325$) plants ($n = 1240$). Published research has mainly focused on microorganisms at phylum and family level, and the abundance of different microorganisms varies greatly with the influence of plastic residues and MPs.

Specifically, plastic residues and MPs significantly reduced the abundance of *Bacteroidetes*, *Cyanobacteria*, *Fimicutes*, and *Planctomycetes* by 9%, 41%, 15% and 9%, respectively, while the abundance of *Nitrospirae* increased by 33% at the phylum level ($p < 0.05$; Fig. 4a). Bio plastic residues and MPs also reduced the abundance of *Cyanobacteria* with the response ratios of 0.8 [0.67, 0.96] ($p < 0.05$). However, most types of plastic residues and MPs had no significant effect on bacterial phylum abundance.

In addition, at the family level, plastic residues and MPs decreased the proliferation of *Bradyrhizobiaceae*, *Nocardioidaceae*, *Paenibacillaceae*, *Sphingobacteriaceae* and *Xanthobacteraceae* with response ratios of 0.77 [0.64, 0.93], 0.59 [0.49, 0.71], 0.69 [0.57, 0.84], 0.69 [0.52, 0.91] and 0.8 [0.67, 0.96], while the abundance of *Chitinophagaceae* and *Comamonadaceae* were promoted by 34% and 67%, respectively ($p < 0.05$; Fig. 4b). The effects of all types of plastic were similar to the summary effect sizes, such as PVC plastic debris decreasing the abundance of *Bradyrhizobiaceae*, *Nocardioidaceae* and *Paenibacillaceae* by 35%, 37% and 26% ($p < 0.05$). Furthermore, the effect of plastic residues and MPs on microbial biomass carbon (C) and nitrogen (N) was not significant compared to those without adding plastic ($p > 0.05$). In addition, plastic residues and MPs reduced the number of observed species by 18% ($p < 0.05$), but had no significant effect on other alpha diversity indexes (such as AEC, Chao1, Coverage, Shannon and Simpson) of the bacterial community with $p > 0.05$ (Fig. 4c).

4. Discussion

4.1. Response of soil properties to plastic residues and MPs

According to the results of this first meta-analysis to determine the effects of plastic residues and MPs on soil ecosystem functioning, we found that plastic residues and MPs significantly inhibited the horizontal and vertical migration of soil water and slightly reduced soil water content by 2% (Fig. 1a). Li et al. (2013) found that plastic residues would hinder soil water migration and infiltration, and reduce soil moisture, which is consistent with our meta-analysis result. In contrast, Hu (2020) suggested that residual film accelerates water migration in both vertical and horizontal directions. These differences could be due to the different quantity of plastic residues and MPs. Li et al. (2015) reported that when the loading rate of plastic residues is very large (> 720 kg ha^{-1}), the movement of water through the soil will be facilitated (Franklin et al., 2007), but water evapotranspiration will be hindered (Fig. S6-Evapotranspiration). This means that the effect of plastic residues and MPs on water migration and evapotranspiration can change with the accumulation of plastic residues and MPs in the farmland soil. The effect of Bio plastic on pH and EC is markedly different from PE, which is probably due to their different degradation characteristics, such as the differences in degradation rates and products (Qi et al., 2020b; Wang et al., 2020).

DOC is widely known as the source of soil microbial energy and nutrients (Kaiser and Kalbitz, 2012). Previous studies have found that plastic residues and MPs can increase soil DOC content by reducing the leaching of DOC and stimulating the enhancement of related enzyme activities in soil (Gao et al., 2021; Liu et al., 2017). However, the results of our meta-analysis show that the addition of plastic residues and MPs reduced soil DOC content by 9%. This difference may be because the soil was divided into different aggregates according to the particle size in several studies, and the DOC content is quite different in different aggregate sizes (Fig. S6-DOC; Hou, 2020). Therefore, the effect of plastic residues and MPs on soil DOC dynamics needs further investigation, with a focus on different soil aggregate sizes.

The contents of TDN, DON, TDP and DOP in soil increased, indicating that plastic residues and MPs promote the release of soil nutrients to soil solution and DOM accumulation (Liu et al., 2017). Plastic residues and MPs can stimulate soil microbial activities, thus increasing the activities of some enzymes in the soil. Soil enzymes also decompose organic matter and catalyze important transitions in the C, N, and P cycles (Zhou and Staver, 2019b). Additionally, the decrease of TN, TP and DOC content in soil may provide an explanation for the inhibition of plant growth by plastic residues and MPs. These results indicate the interactions caused by MPs between soil element cycling, soil enzyme

(a)

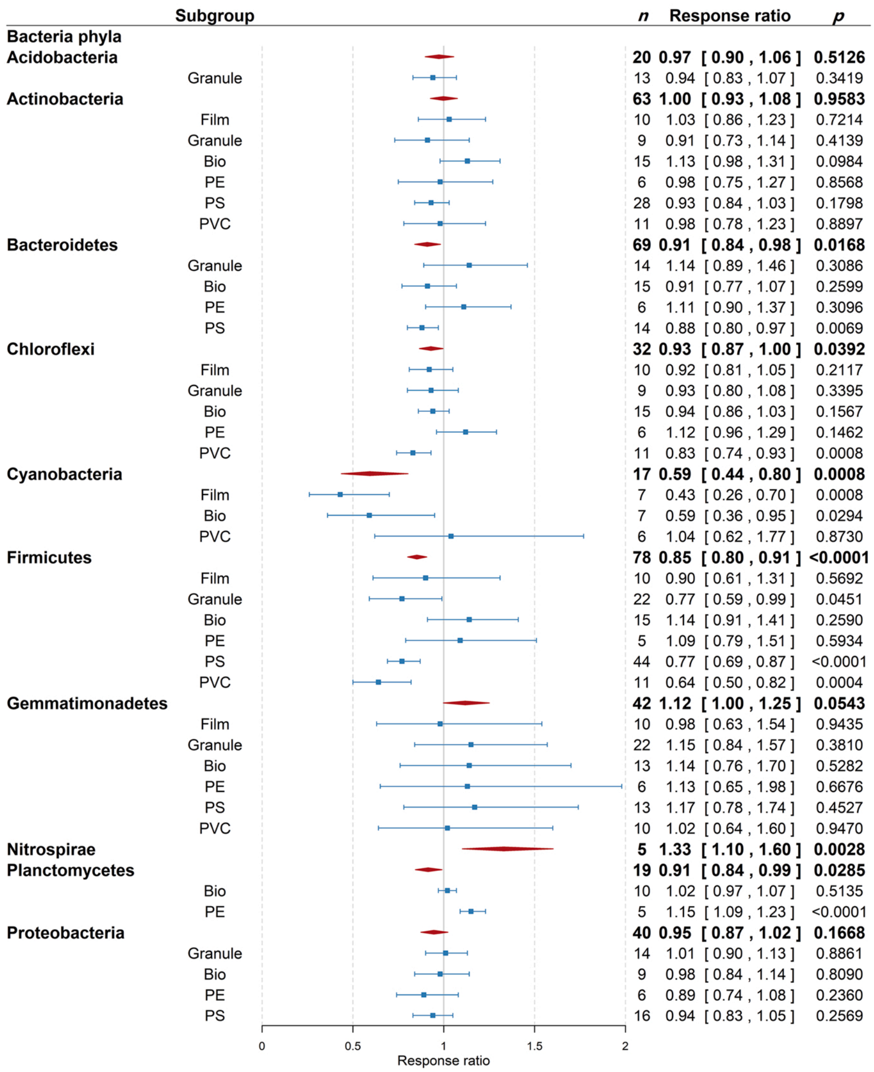

Fig. 4. The effect of plastic residues and MPs on soil microorganisms: (a) phylum abundance, (b) family abundance and microbial biomass, and (c) bacteria alpha diversity based on a multilevel random effect meta-analysis. The red diamond represents the summary effect. The blue square symbols show the average value of response ratio for each type of plastic residue and MPs with error bars representing 95% confidence interval. A ratio > 1 indicates that the response from the treatment is higher compared to the control group. *n* refers to sample size and *p* means the *p*-value of the Q test and $p < 0.05$ indicates significant difference.

activity and plant growth. The interplay of these indicators should be investigated in the future study of effects of plastic residue and MPs on soil ecosystems.

In addition, several parameters (such as water evapotranspiration, DOC, SBR, CAT) show a dose-effect relationship with MPs (Fig. S6), meaning that the effect of MPs on the soil ecological environment could have a cumulative effect. In general, plastic residues and MPs could hinder soil water transport, reduce the total soil nutrient content, and increase the soil enzyme activities. These findings are helpful for the exploration of the ecological threshold of plastic residues and MPs in farmland soils.

4.2. Response of plants to plastic residues and MPs

Plastic residues and MPs in soil have a negative impact on plant growth (Boots et al., 2019; de Souza Machado et al., 2019; Qi et al., 2020a; Zhang et al., 2022a), and these negative effects show a dose-effect with MPs, i.e., SOD enzyme activity, MDA and biomass decreased with the increase of MPs content (Fig. S7).

In this meta-analysis, we found plastic residues and MPs reduced plant height and biomass by 11% and 12%, respectively (Fig. 2a). Dong et al. (2015) suggested that boll weight, yield and biomass of cotton decreased with increasing plastic residues content in soil. Pignattelli et al. (2020) found that MPs produced acute and chronic toxicity to *Lepidium sativum*, reducing plant height and aboveground biomass at different exposure durations (6 and 21 days). Similar conclusions can be found in studies on the response of maize, wheat and rice to plastic residues and MPs (Qi et al., 2018; Urbina et al., 2020; Zhou et al., 2021a). These effects could be explained that plastic residues and MPs can hinder the movement of water and nutrients in soil and the activities of plant roots (Zhao et al., 2021), thus limiting the absorption and utilization of water and nutrients by plants. In addition, MPs can also affect the structure and metabolic process of rhizosphere microbial community, changing the root growth environment and plant vital activities (Qi et al., 2018). Therefore, although the use of plastic film mulching can increase crop yields (Sun et al., 2020), we recommend more research addresses the potential negative effect of plastic residues and MPs on the plant growth and quality.

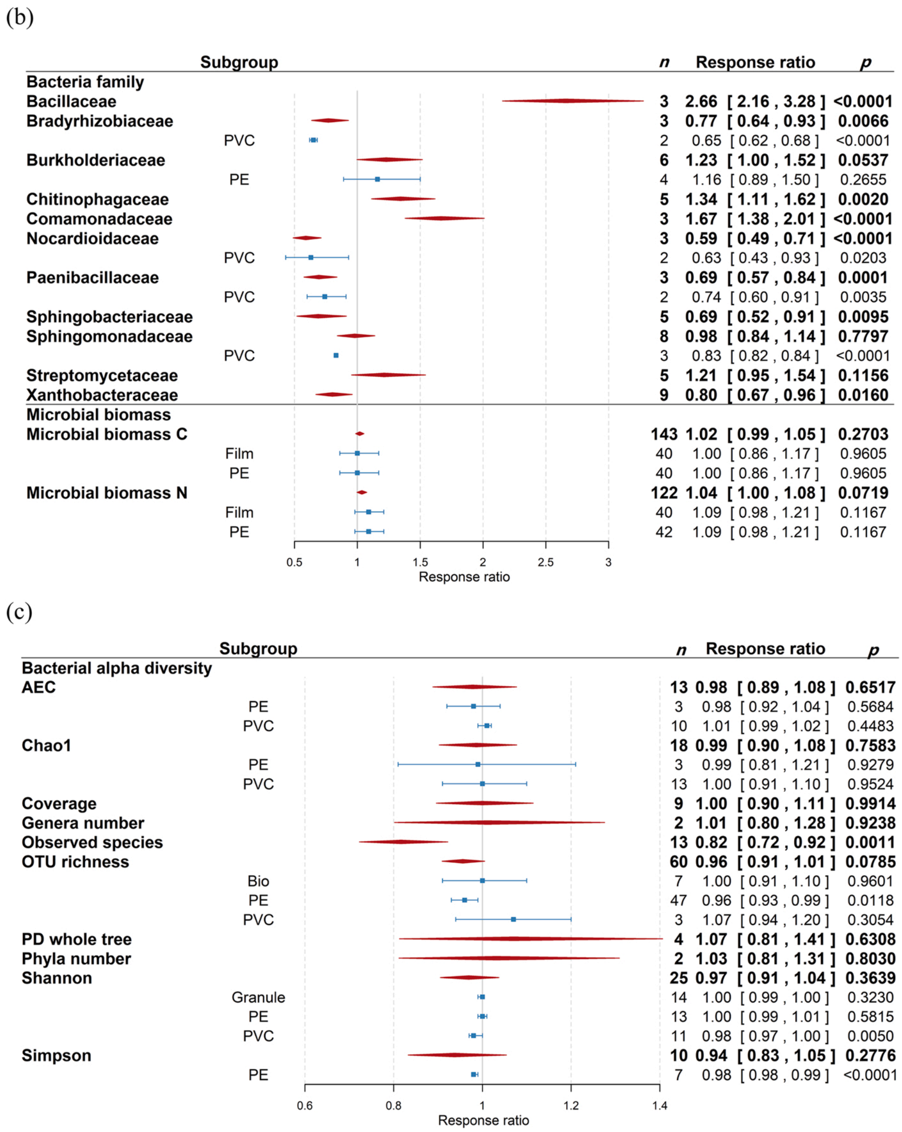

Fig. 4. (*continued*).

Bio plastic residues and MPs inhibited plant growth, which is similar to conventional PE, PS and PVC plastic residues and MPs. However, the effects of Bio plastic residues and MPs on plant growth varied between different studies. A previous study by Qi et al. (2018) reported that starch-based Bio MPs had a stronger negative effect on plant height, leaf number and biomass of wheat than low-density polyethylene MPs. In contrast, Li et al. (2021a) found that adding 0.1% and 0.5% Bio plastic residues increased plant height and leaf area of soybean to different degrees at seedling, flowering and harvesting. The inconsistent results of studies on the ecological effects of Bio plastic residues and MPs in soil may be attributed to different exposure duration. Bio plastics are more easily degraded and utilized by microorganisms, and the plastic residues and MPs formed from Bio plastics can affect the soil biome (such as earthworms) and soil biophysical properties (including bulk density, soil aggregates and water holding capacity), indirectly affecting the soil nutrient cycling and plant growth (Lwanga et al., 2017; Zhao et al., 2021). Bio plastics may produce greater numbers of plastic residues and MPs in the short term, while the increased rates of biodegradation may result in less plastic residues and MPs in the longer term, and thus potentially have a reduced impact on plants compared to conventional plastics (Zhao et al., 2021). However, long-term degradation studies are needed to further assess the effects of Bio plastic residues and MPs on plants and soil processes.

In the current study, the activities of antioxidant enzymes in plants was generally improved in the presence of plastic residues and MPs, which has been verified in previous studies (Gao et al., 2021; Pignattelli et al., 2021, 2020). In organisms, antioxidant enzymes and antioxidants neutralize reactive oxygen species (ROS) to avoid possible oxidative damage (Mates, 2000). In plant cells, SOD enzyme exists in the cytoplasm, chloroplast, mitochondria and peroxisome and can convert $O_2\bullet^-$ to H_2O_2 (Bowler et al., 1992). Excess toxic H_2O_2 can spread rapidly through cell membranes (Foyer et al., 1997), and CAT and GSH-Px can break down H_2O_2 in mitochondria, microsomes and chloroplasts (Kuźniak and Skłodowska, 2001; Thounaojam et al., 2012). Therefore, we call for further research at the cellular level to explore the mechanism of the effects of MPs on plant antioxidant systems. APX is a key enzyme in the ascorbate-glutathione pathway and catalyzes AsA oxidation to remove H_2O_2 (Asada, 1999; Diaz-Vivancos et al., 2006). Therefore, the enhanced activities of antioxidant enzymes and the production of corresponding antioxidant products in plants may be typical responses to the exposure of plastic residues and MPs. However, there was no significant decrease in GSH content in this study, which may be due to the shorter exposure time used in relevant studies. Pignattelli et al. (2020) found that although the GSH content of garden cress increased in the chronic (21 d) toxicological effect experiment due to MPs stimulation, the GSH content decreased substantially in the acute (6 d) toxicological effect experiment. This may be because ROS stimulated by MPs consume the existing GSH in plants, but new GSH has not yet been generated. Therefore, studies of the effects of plastic residues and MPs on plant antioxidant systems should be carried out over long periods of time, e.g. throughout a complete cropping season.

4.3. Response of soil animals to plastic residues and microplastics

Our current study shows that growth parameters, including body length, body weight, growth rate, liver organ weight, relative liver organ weight and life span are markedly reduced by most types of plastic residues and MPs (Fig. 3), indicating plastic residues and MPs inhabit the animal growth. The decreased frequency of body bending and head thrashing reveals the disturbed locomotor behaviors of animals caused by plastic residues and MPs (Kim and An, 2019). Additionally, the slight increase of locomotion speed provides the evidence of excitatory toxicity caused by plastic residues and MPs (Lei et al., 2018). However, similar to the effect of plastic residues and MPs on plant GSH, the movement rate of animals may also be affected by longer-term exposure to plastic residues and MPs, but this needs to be confirmed through appropriate long-term toxicology experiments. Plastic residues and MPs had no significant effect on animal feeding rate, which is due to the large difference in the results of animal feeding studies in this meta-analysis (Fig. 3a). Several studies reported that the feeding rate of honey bee was reduced by MPs (Wang et al., 2021a), but other studies showed the opposite results that MPs improve earthworm (*Lumbricus terrestris*) feeding activities (Lwanga et al., 2016). This difference may be associated with MPs exposure duration, short exposure time may increase animals' food intake, while long exposure time could reduce animal appetite. Plastic residues and MPs are difficult to be digested by animals, diluting and limiting the bioavailability of nutrients in food (Besseling et al., 2013), so animals have to intake more food to meet their physiological needs (Lwanga et al., 2016). However, long-term exposure to MPs may cause gastrointestinal walls damage and decrease the feeding desire of animals (Song et al., 2019). A subgroup meta-analysis of plastic residues and MPs exposure time was not carried out in our current study because of the difficulty of integrating the exposure time of different soil animals, as well as the lack of sufficient data for certain soil animals.

The decline of reproduction rates (i.e. juveniles number), sperm count and vitality and testosterone, as well as the increase in sperm deformity rate suggest that all types of plastic residues and MPs are harmful to animal reproduction (Fig. 3), and these damages are more serious with the increasing MPs (Fig. S8). Both LDH and SDH are sperm-specific enzymes involved in sperm development and energy metabolism (Chen et al., 2015; Zhu et al., 2014, 2019). The decrease of SDH level indicates disordered energy metabolism caused by plastic residues and MPs. However, plastic residues and MPs led to an increase in LDH content, which can be explained by altered in energy metabolism pattern. Rodríguez-Seijo et al. (2018) found that the increase of LDH may alter energy consumption to counteract the effects of oxidative stress imposed by the large addition of MPs. These results are also in agreement with other studies that explored the energy metabolism and LDH levels among mice and earthworm when they were exposed to different content and type of MPs (Deng et al., 2017; Kwak and An, 2021). Therefore, studies on the effects of plastic residues and MPs on animal reproduction should consider the response of the entire reproductive system, including the changes in the number and morphology of germ cells and the level of sex hormones, and disturbances in energy metabolism.

The contents of lipids and proteins in the animal body decreased with the presence of plastic residues and MPs, resulting in a reduction of available energy (Lu et al., 2018). The decrease of total cholesterol (TCH) content also provides evidence of lipid metabolism disorders. The possible reason is that exposure to MPs may cause an inflammatory response, which leads to lipid metabolism disorders in the liver, suppressing feeding activity (Jaeschke et al., 2002; Wright et al., 2013).

Similar to the response of plant antioxidant system to plastic residues and MPs, oxidative stress responses in animals are also intensified by plastic residues and MPs (Chen et al., 2022; Zhou et al., 2020a). Firstly, exposure to MPs increases ROS levels in animals, thereby activating the cellular antioxidant defense system. As a toxic end product of lipid peroxidation, the increase in MDA contents reflects the oxidative stress caused by ROS and lipid peroxidation (Yu et al., 2018). Then AChE, GSH-Px and SOD enzymes activities and GSH content increased to eliminate these oxidative damages. However, CAT and GST enzymes activities decline, which may be related to the MPs exposure duration. Chen et al. (2020) found that the decrease of CAT activity in the first 7 days of MPs exposure may be related to the inactivation of enzyme, the decline of enzyme synthesis rate or the change of enzyme subunit assembly, while the highest CAT activity at 28 days may be due to the stress response of the body to increased H_2O_2 content.

In summary, the meta-analysis results show that plastic residues and MPs have a negative effect on the growth, metabolism, reproduction and survival of soil animals. Most types (granule in shape, and PA, PE, PET, PS, PVC in component) of plastic residues and MPs had similar effects on soil animals. Furthermore, these responses indicators show a dose-effect with MPs (Fig. S8). Given the damage of MPs to animals and the fact that humans can intake MPs through ingestion and inhalation, MPs are also a potential threat to human health (Leslie et al., 2022; Senathirajah et al., 2021). Therefore, toxicity tests of MPs in animals and human tissue cells could be carried out to assess the human health risks of MPs.

4.4. Response of soil microorganisms to plastic residues and MPs

Many studies have shown a dose-response relationship between plastic addition and soil microorganism abundance and diversity (Fig. S9). Zhang et al. (2017) found that a low amount of plastic residues could improve soil microbial activity, but the microbial biomass, microbial community abundance and soil enzyme activity decreased significantly in the soil with plastic residues amount > 450 kg ha^{-1}. Lu et al. (2018) showed that PS-based MPs can induce intestinal microflora disorders in mice. Although some family-level bacteria had significant responses to plastic addition, the study sample is too small, with < 10 observations for each bacteria family. Most types of plastics had small effect on bacterial abundance at the phylum level. Therefore, more studies are needed to assess the effects of MPs on microbial genus and species abundance levels.

Currently, the mechanism of the effect of plastic residues and MPs on soil microorganisms is still unclear. Soil habitat changes caused by plastic residues and MPs are thought to be a possible cause of microorganisms' change (Naveed et al., 2016; Ng et al., 2021; Qi et al., 2020b). Changes of soil aggregate structure, porosity, water and oxygen concentration caused by plastic residues and MPs may affect microhabitats and change local microbial community structure (Boots et al., 2019; Rillig and Bonkowski, 2018; Veresoglou et al., 2015; Zhang et al., 2019). However, the responses of most indicators of bacterial alpha diversity and microbial biomass to plastic residues and MPs were not significant. This also indicates that conventional plastics (PE and PVC) are not easily utilized by microorganisms and do not result in changes in the microbial community structure in the short term. There have been few studies on the effect of Bio plastics on microorganisms, so, further studies should focus on the response of soil microbial abundance and community structure to Bio plastic residues and MPs.

4.5. Limitations

The effect of plastic residues and MPs on global soil ecosystem functioning (as indicated by soil physicochemical properties, plants and soil animal health, and the abundance and diversity of soil microorganisms) has been quantified by using a meta-analysis in this study.

However, most of these quantitative results are based on laboratory or plot experiments, where very high rates of plastic debris including MPs were added to the soil in experimental treatments. For example, the additive amount of plastic residues in several studies was up to 800 kg ha^{-1} (Hu, 2020), and the MPs addition was 140,000 mg kg^{-1} (Liu et al., 2017). In practice, the maximum concentration of plastic residues and MPs in the soil worldwide can be as high as 411.1 kg ha^{-1} and 67,500 mg kg^{-1} (Fuller and Gautam, 2016; Scheurer and Bigalke, 2018), respectively. In this meta-analysis study, 36% of the 2940 experiments that included a macroplastics treatment, applied the macroplastics at a rate of > 411.1 kg ha^{-1}, while 22% of the 2405 experiments with MPs treatments, applied MPs at > 67,500 mg kg^{-1}. Therefore, uncertainties exist when extrapolating the results of this meta-analysis to the typical levels of plastic residues and MPs found in typical agricultural systems. In addition, studies on the effect of degradable plastic residues on soil ecosystem functioning are rare, with only 51 observations in our meta-analysis (out of 6223). Therefore, there is still a large knowledge gap in understanding the effects of degradable plastics on the soil environment.

5. Conclusion

For the first time, we quantified the effect of different shapes and components of plastic residues and MPs on indicators of global soil ecosystem functioning (i.e. soil physicochemical properties, plant and soil animal health and abundance and diversity of microorganisms) by a meta-analysis with 6223 observations. Plastic residues and MPs changed 30 key soil physiochemical property indexes with summary effect sizes of 0.83–1.41, 13 key plant-related indexes with summary effect sizes of 0.86–1.46, 32 soil animal-related indexes with summary effect sizes of 0.53–5.41, and 33 soil microbial-related indexes with summary effect sizes of 0.59–2.66. This study demonstrates that plastic residues and MPs pose a threat to soil ecosystems by altering the physicochemical properties of soils, hindering the growth and development of plants and soil animals, and producing oxidative stress damage. However, the effects of plastic residues and MPs on the abundance and diversity of different phylum and family microorganism vary between different bacteria.

This work gives an important insight into the abundance of plastic residues and MPs in farmland soils of China and their effect on the global soil ecosystem, enhancing our understanding of the potential effects of plastic pollution on ecosystem functioning in agricultural soils. Finally, we call for more long-term positioning experiments conducted in field conditions using realistic concentrations of conventional and degradable macroplastics and/or MPs to provide a more realistic understanding of the impact of plastic debris on soil ecosystems.

CRediT authorship contribution statement

Jinrui Zhang (First author): Conceptualization, Methodology, Data Curation, Formal analysis, Writing – original draft, Visualization. **Siyang Ren (Co-first author):** Conceptualization, Methodology, Data Curation, Formal analysis, Writing – original draft, Visualization. **Wen Xu:** Conceptualization, Writing – review & editing. **Ce Liang:** Data Curation, Formal analysis. **Jingjing Li:** Data Curation, Formal analysis. **Hanyue Zhang:** Writing – review & editing. **Yanan Li:** Writing – review & editing. **Xuejun Liu:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Davey L. Jones:** Writing – review & editing, Funding acquisition. **Dave Chadwick:** Writing – review & editing, Funding acquisition. **Fusuo Zhang:** Conceptualization, Funding acquisition. **Kai Wang:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2022.129065.

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