



# Field application of biodegradable microplastics has no significant effect on plant and soil health in the short term

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## ABSTRACT

Bioplastics (biodegradable plastics) potentially offer an encouraging alternative to conventional (petroleum-based) plastics. In practice, bioplastics inevitably generate a large number of bio-microplastics (bio-MPs, diameter <5 mm) during the degradation progress. However, the impact of bio-MPs on plant and soil health within agroecosystems remains incomplete. Here, a field study was conducted to investigate the effect of two shapes (fiber and powder) of pure polylactic acid (PLA) bio-MPs on oat (*Avena sativa* L.) and soybean (*Glycine max* (L.) Merr.) growth and soil health. Our results showed that PLA application at a representative soil loading rate of 0.2% (w/w) had no significant effect on soil enzyme activities, soil physicochemical properties (soil water content, pH, etc.), root characteristics, plant biomass, and crop yield. Thus, we conclude that soil quality, plant health, and ecosystem multifunctionality were not affected by PLA over one growing season (5 months) in the presence of either bio-MP shape (fiber and powder) for either crop species (oat and soybean). Overall, PLA based bio-MPs may not pose a significant threat to agroecosystem functions in the short term (days to months) in the field, thus may provide a viable environmentally benign solution to replace traditional non-biodegradable plastics in agroecosystems.

## 1. Introduction

Plastic mulch films provide multiple benefits for crop production (controlling weeds, reducing evaporation and soil erosion, increasing the soil and air temperature), and are thus widely used in agroecosystems all over the world (Gao et al., 2021; Griffin-LaHue et al., 2022). However, improper disposal of agricultural plastic mulch eventually leads to the dispersal of microplastics (MPs, diameter <5 mm) into agricultural soils and the wider environment (Astner et al., 2019; Rillig and Lehmann, 2020). This dispersal poses a considerable threat to food and ecological security (Huang et al., 2020b; Zang et al., 2022; Zhang et al., 2020). Biodegradable plastic mulch is being used as an alternative to reduce plastic pollution in agricultural soils (Flury and Narayan, 2021), as bioplastics can be readily converted into CO<sub>2</sub>, water, nutrient ions, and the formation of microbial biomass (Yu et al., 2021). Since bioplastics are more susceptible to rapid degradation, more biodegradable microplastics (bio-MPs) might be generated, in the short term, than

conventional plastics within the same time frame, probably leading to more severe bio-MPs pollution and associated effects (Liao and Chen, 2021; Shruti and Kutralam-Muniasamy, 2019; Zhou et al., 2023). To date, the potential risks of non-biodegradable MPs to the environment and human health have been widely discussed and lots of evidence has shown their detrimental effects on plant and soil health (Li et al., 2020; Xiao et al., 2022; Yu et al., 2022). By contrast, research on the ecological effects of bio-MPs is still in its infancy (Brown et al., 2023; Wang et al., 2022; Zhou et al., 2021a). Consequently, fundamental and in-depth studies regarding the effects of bio-MPs on agricultural ecosystems are needed.

Given that soils provide the most basic and diverse services to ecosystems, maintaining soil health is key to agricultural sustainability (Brown et al., 2022b; Kopittke et al., 2019). The potential threat of MPs to soil ecosystem functioning and resilience has attracted increasing attention (Rillig, 2012; Zhao et al., 2022). Some studies have reported that bio-MPs increase soil aggregation, pH, and nutrient retention

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(Lozano et al., 2021a; Lozano et al., 2021b); while others have observed no impact on soil biochemical properties (e.g., pH, soil carbon and nitrogen, as well as enzyme activities) (Mazzon et al., 2022; Qi et al., 2020a). The paucity and inconsistency of the available results highlight the need for a comprehensive assessment of how bio-MPs affect soil quality indices (SQI) (Jia et al., 2022; Kuzyakov et al., 2020). Bio-MPs can also provide available C to the microbial biomass and support growth (depending on the native soil microbial communities' carbon use efficiency) and intensify soil N immobilization and thus plant N limitation (Sinsabaugh et al., 2016; Yu et al., 2021; Zhou et al., 2022a). This may potentially aggravate the competition for nutrients between plants and microorganisms and consequently suppress plant growth (Zang et al., 2020).

In addition, plants can also be directly affected by MPs through physical interaction, which can alter root architecture and consequently plant growth (Chen et al., 2022; Lee et al., 2022; Yang and Gao, 2022). The net effect of all these individual functions can alter the overall ecosystem function; however, there is a lack of studies holistically addressing the bio-MPs effect on ecosystem multifunctionality (EMF, the ability of an ecosystem to deliver multiple functions simultaneously) (Jia et al., 2022; Manning et al., 2018). Moreover, most studies are limited to laboratory-based experiments, so it is imperative that studies on the ecological effects of bio-MPs on agroecosystems are undertaken at the field scale (Baho et al., 2021; Zang et al., 2020; Zhou et al., 2023).

Briefly, the formation of bio-MPs in soil may induce negative effects on soil properties, plant growth, and EMF in drylands, through the addition of a potentially labile/semi-labile carbon source that may alleviate the carbon limitations of the soil microbial community (Brown et al., 2022). However, the majority of current research has been conducted in the laboratory or greenhouse over short periods (<30 days), which may hamper the in-depth understanding of the impact of bio-MPs on soil quality and ecosystem functions in the long-term. Here, as two typical grain crops in the semi-arid region of China (an area with a long history of plastic mulching), oat and soybean have been selected to evaluate the effects of bio-MPs on plant-soil health (Huang et al., 2020b). Polylactic acid (PLA) is one of the most well-known bioplastics, and it has proved to be an effective substitute for petroleum-based counterparts (Ainali et al., 2022). Equally, plastic fiber and powder are two ubiquitous forms of MPs in soil, and they often have different effects on soil functions. For example, soil microbial activity associated with MPs powder is lower compared to fiber (Lozano et al., 2021b). Herein, two shapes of PLA (i.e., powder and fiber) at a realistic field level of agricultural soil pollution of 0.2% (w/w) was used to explore the effect on soil biochemical properties and plant growth (de Souza Machado et al., 2018; Huang et al., 2020b). We hypothesize that bio-MPs would profoundly change soil quality and plant growth, thereby the *in situ* EMF would be altered by bio-MPs regardless of microplastic shapes and crop species.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was carried out at Ertai Town, Zhangbei County (41°21'N, 114°54'E), located northwest of Hebei Province, with a temperate continental monsoon climate. The mean temperature was 16.6 °C and the mean rainfall was 373.8 mm (mainly concentrated in July and August) during the growth period (from May to September) of the past five years. The experiment site has no previous history of plastic mulching or organic waste application, thus the soil is unlikely to contain plastics from compost or sludge. The soil is classified as a Haplic Kastanozem (IUSS Working Group WRB, 2015) with initial properties as follows: soil organic carbon, 7.5 g kg<sup>-1</sup>; total nitrogen, 0.97 g kg<sup>-1</sup>; mineral nitrogen, 2.0 mg kg<sup>-1</sup>; available phosphorus, 5.0 mg kg<sup>-1</sup>; and pH (H<sub>2</sub>O), 8.0.

### 2.2. Experimental design and soil sampling

The pure non-additive PLA plastic material (Zhonglian Plastics Technology Co. Ltd. Fujian Province, China) was used to produce particles with a pulverizer, and then sieved through a 100-mesh filter to produce the bio-MPs powder; the bio-MP fiber was produced using shears to a length of <5 mm and a diameter of 90 μm. Bio-MPs were rinsed with deionized water 3 times and freeze-dried prior to use. Here, bio-MPs were classified into powder (spherical particles) and fiber according to the specific surface area. Fibers represented those found in agricultural fertilizers such as biosolids (Piehl et al., 2018) while powders were spherical particles or fragments, similar in shape to many intrinsic soil particles.

In mid-May 2021, a completely randomized design was established with four replicates ( $n = 4$ ) for each treatment. Each experimental plot (2.0 × 2.0 m) was then treated with bio-MPs powder or fiber. Each plot was divided into 16 equal areas of 0.5 m × 0.5 m grids, from which the top 20 cm of soil from each grid was dug out and thoroughly mixed by hand with bio-MPs at a rate of 4800 kg ha<sup>-1</sup>. This corresponds to about 0.2% of the soil weight (with a depth of 20 cm and bulk density of 1.20 g cm<sup>-3</sup>). After homogenizing the bio-MPs, the mixed soil was backfilled into the corresponding grid. This resulted in three treatments in this study: 1) Powder (PLA microplastic powder addition), 2) Fiber (PLA microplastic fiber addition), and 3) Control (without microplastic addition). The control plots were also mixed in the same way as the treated plots without adding any plastic. Subsequently, oat (*Avena sativa* L. cv. Bayou 14) and soybean (*Glycine max* (L.) Merr. cv. Jizhangdou 2) were planted. The field experiment followed the common practice of local farmers with regular manual weeding, and no irrigation and fertilization during the growing season of oat and soybean.

After crop harvest in mid-September 2021, soils were sampled from each plot at 0–20 cm. Two sub-samples were pooled to form a mixed soil sample in each of the four field replicates. The samples were passed through a 2-mm sieve after removing the roots, litter, debris, and stones. Each soil sample was then stored at 4 °C for soil enzyme activities and chemical properties analysis which were performed within 5 days.

Oat and soybean were destructively sampled from each plot, and plants per plot were cut at the base and divided into aboveground (shoot) and belowground (root) components. With the position of the stem as the center of the core, we manually excavated the root system from the surrounding soil in the 0–20 cm soil layer (more than 50% of the root biomass was located in this soil layer) with a hand trowel. The plant samples were subsequently used for the determination of dry biomass and root characteristic parameters.

### 2.3. Soil quality assessment

Soil bulk density (BD) was determined on an oven-dry basis by the cutting ring method. Soil water content (SWC) was analyzed by drying at 105 °C until the weight remained stable. Soil pH and electrical conductivity (EC) were measured using a pH meter and conductivity meter (DDS-307, Rex Electric Chemical, China), respectively, in a soil suspension with a soil-water ratio of 1:2.5 (w/v). Total nitrogen (TN) content was analyzed by the semi-micro Kjeldahl method (Bao, 2000). Ammonium (NH<sub>4</sub><sup>+</sup>-N) and nitrate (NO<sub>3</sub><sup>-</sup>-N) were both determined using a spectrophotometer (1510, ThermoFisher, USA) after extraction of 5.0 g fresh soil with 20 mL 0.05 M K<sub>2</sub>SO<sub>4</sub>. Available phosphorus (Olsen-P) was analyzed by the Olsen method (Olsen et al., 1982) via extracting soil samples with 0.5 M NaHCO<sub>3</sub>.

The activities of six hydrolases enzymes: C-related (β-glucosidase, BG; β-xylosidase, BX; β-cellobiosidase, CBH), N-related (leucine aminopeptidase, LAP; β-1,4-N-acetyl-glucosaminidase, NAG), and P-related (alkaline phosphatase, ALP) cycling were fluorogenically measured using labeled substrates (Zang et al., 2020). Briefly, 50 mL sterile water was added to 1.0 g of fresh soil and suspended by shaking for 30 min at a speed of 200 rev min<sup>-1</sup>. An equal amount of 50 μL soil suspension was

pipetted into 96-well microplates, and then 50  $\mu\text{L}$  buffer and 100  $\mu\text{L}$  of the substrate at a concentration of 400  $\mu\text{M}$  were added (the enzyme substrates are shown in Table S1). At 60 and 120 min after substrate addition, the microplates were fluorometrically determined at an excitation wavelength of 355 nm and an emission wavelength of 460 nm. Phenoloxidase (POX) and peroxidase (PER) activities were spectrophotometrically assayed with 96-well microplates and the substrate of L-DOPA (DeForest, 2009). The enzyme activities were expressed as  $\text{nmol g}^{-1}$  dry soil  $\text{h}^{-1}$ .

Here, we further combined enzyme activities as indicators of specific substrates or nutrient acquisition, which divided into four parts: C acquisition (C-acq), N acquisition (N-acq), P acquisition (P-acq), and oxidative decomposition (OX). They were calculated as the average value of multiple enzyme activities as follows (Luo et al., 2018):

$$\text{C-acq} = (\text{BG} + \text{BX} + \text{CBH}) / 3 \quad (1)$$

$$\text{N-acq} = (\text{LAP} + \text{NAG}) / 2 \quad (2)$$

$$\text{P-acq} = \text{ALP} / 1 \quad (3)$$

$$\text{OX} = (\text{POX} + \text{PER}) / 2 \quad (4)$$

#### 2.4. Plant quality assessment

At the physiological maturity stage, grain yield for each plot was determined by collecting the plants from a full length of a middle row, dried, and corrected to 13% grain moisture content to calculate grain yield ( $\text{t ha}^{-1}$ ). The root samples were washed with running water to obtain the root system for each plant. WinRHIZO software (Regent Instruments Inc. Canada) was used to analyze scanned images of the roots to determine the root length, root surface area, and root volume. The scanned roots were then collected and dried to constant weight before recording their weights (root biomass). Also, aboveground plant samples were dried at 80  $^{\circ}\text{C}$  for 72 h to determine shoot biomass after the height was recorded.

#### 2.5. Quantification of plant growth, soil quality, and ecosystem multifunctionality

Soil quality index (SQI) was calculated using an SQI-area approach by comparing the area on a radar graph comprising all soil parameters that equal to the sum of individual triangles comprising the whole figure (Jia et al., 2022; Kuzyakov et al., 2020). The plant growth index (PGI), a single comprehensive index reflecting plant growth, was determined in a similar way to the SQI calculation (Nayab et al., 2022). Ecosystem multifunctionality (EMF) was calculated based on 19 ecosystem functions, which included the majority of soil functions (except for BD, SWC, pH, and EC) and all plant parameters measured in this study (Garland et al., 2021; Lozano et al., 2021a). Detailed calculation methods of PGI, SQI, and EMF are shown in the supplementary material.

#### 2.6. Statistical analysis

The Shapiro-Wilk test was conducted to determine the normality of data distribution within each variable group. Levene's test was used to determine the homogeneity of square differences between the two groups of variables with normal distribution. An independent sample *t*-test was performed once the square differences between the two groups were equal; otherwise, an adjusted *t*-test (i.e., Welch's *t*-test) was performed. A Mann-Whitney *U* test was used for comparison between groups with non-normal distribution. All data were analyzed using IBM SPSS Statistics 26 (IBM, USA). The histograms were drawn by SigmaPlot 14.0 (Systat Software Inc. USA), and the radar graphs, as well as the heatmap, were drawn by Origin 2021 (OriginLab Corp. USA). A combination graph of correlation heat map of soil and plant parameters and

mantel test line was drawn using the R package ("ggcor") with the R 4.1.2 (Huang et al., 2020a; R Core Team, 2021).

### 3. Results

#### 3.1. Soil enzyme activity

PLA fiber significantly improved the soil N-acq (the sum of NAG and LAP) activity by 37% compared to Control with oat ( $P < 0.01$ ; Fig. 1c), whilst it had no appreciable effect in the soybean treatments ( $P = 0.77$ ; Fig. 1g). Moreover, bio-MPs shapes (i.e., powder and fiber) did not impact the C-acq, P-acq, and OX activities in soil planted with oat and soybean compared with the Control treatment ( $P = 0.06$ – $0.89$ ; Fig. 1).

#### 3.2. Soil quality and plant growth

In soil planted with oat, similar SQI scores were observed between bio-MPs powder and fiber ( $P = 0.96$ ; Fig. 2b), although they marginally increased SQI compared with Control ( $P = 0.11$ ). In soil planted with soybean, bio-MPs powder slightly decreased the SQI compared with Control ( $P = 0.12$ ), while there was no difference in SQI between bio-MPs fiber and Control ( $P = 0.70$ ; Fig. 2d).

Bio-MPs powder and fiber marginally increased the PGI score of oat by 18% ( $P = 0.44$ ) and 47% ( $P = 0.06$ ; Fig. 3b) compared with the Control. Also, the PGI of soybean did not show a difference in response to bio-MPs, regardless of fiber and powder ( $P = 0.87$ ; Fig. 3d).

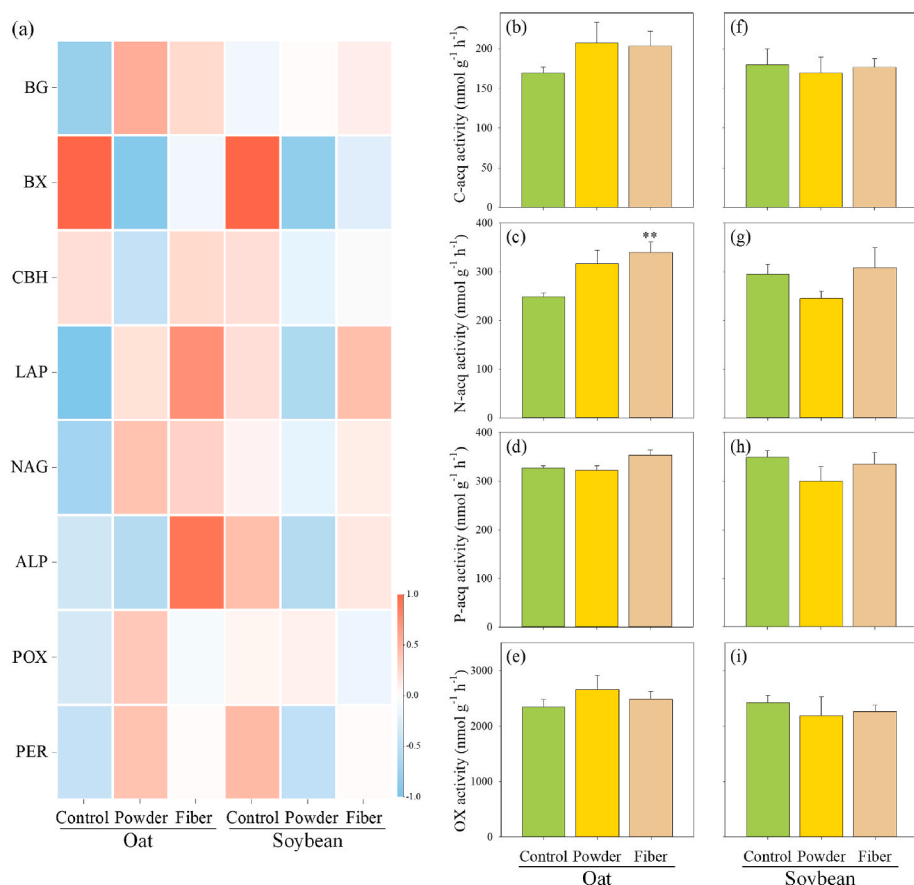
#### 3.3. Ecosystem multifunctionality

EMF was marginally increased by bio-MPs fiber in soil planted with oat by 69% ( $P = 0.17$ ) and 89% ( $P = 0.15$ ) compared with Control and bio-MPs powder, whilst there was no significant difference in EMF under oat between bio-MPs powder and Control ( $P = 0.74$ ; Fig. 4a). By contrast, both bio-MPs shapes slightly decreased EMF under soybean by 14–29% compared with Control ( $P = 0.29$ – $0.61$ ; Fig. 4b). The EMF score was mainly influenced by SWC ( $r > 0.4$ ) and plant growth parameters (also known as PGI) ( $r > 0.2$ ,  $P < 0.05$ ; Fig. 4c).

### 4. Discussion

#### 4.1. Soil enzyme activity response to bio-MPs addition

Soil enzyme activities are vital to a range of soil functions and are considered one of the most sensitive indicators of soil quality (Jaborova et al., 2021; Sheteiyw et al., 2021). The frequent determinations of four combined functional enzyme activities (C-, N-, P-acq, and OX activities) are usually related to soil microbial nutrient limitation and biochemical processes (Khosrozadeh et al., 2022; Lasota et al., 2022). It is generally the case that bio-MPs are C-rich but nutrient-poor (Zhou et al., 2021a, 2021b), which triggers soil microorganisms to respond to a lack of nutrients (e.g., N, P) (Brown et al., 2022a; Zang et al., 2020). However, legume N-fixation could alleviate soil N deficiency caused by the microbial immobilization of N under bio-MPs addition (as a source of relatively labile C) (Song et al., 2020; Wang et al., 2021), thus bio-MPs did not increase the N-acq enzyme activity for the legume planted soils (Fig. 1). Additionally, here we observed no significant differences between C-acq enzyme activities for either plastic shape. These findings are contradictory to the observed significant positive effects on soil C-acq enzyme activities previously shown under 10% poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (Zhou et al., 2021a; Zhou et al., 2023), 1% Mater-Bi (Mazzon et al., 2022), and 2% PLA (Chen et al., 2020) addition. Equally, the discrepancy could be due to the different types of bio-MPs used given that the mineralization of PLA is slow relative to the PHB (15.5% vs. 84.3%) within the first 230 days after application (Schopfer et al., 2022), as well as the distinctly different microbial C partitioning dynamics in the field compared to the laboratory (Oburger



**Fig. 1.** Soil enzyme activities in oat and soybean cropping system. Panel (a) represents Z-Score standard enzyme activities with a color scale, an increase, and a decrease in the activity being indicated by the intensity of red and blue color. Panels (b–i) show four grouped enzyme activities. C-acquiring enzymes include  $\beta$ -glucosidase, BG;  $\beta$ -xylosidase, BX; and  $\beta$ -cellobiosidase, CBH. N-acquiring enzymes contain leucine aminopeptidase, LAP; and  $\beta$ -1,4-N-acetylglucosaminidase, NAG. P-acquiring enzyme refers to alkaline phosphatase, ALP. Oxidative decomposition enzymes involve phenol oxidase, POX; and peroxidase, PER. Values are averages  $\pm$  standard errors ( $n = 4$ ). Asterisk indicates a statistically significant difference from the Control treatment (\*\*,  $P < 0.01$ ). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and Jones, 2009). Therefore, PLA may be likely to become bioavailable as a viable C source over a long period (years to decades) (Chamas et al., 2020), and, as such, did not cause major shifts in enzyme activities in the timescale measured here (months). On the other hand, the effect of bio-MPs on enzyme activity may also be concentration-dependent (Zhou et al., 2022b). For example, one study reported by Bandopadhyay et al. (2018) documented that high concentrations of bio-MPs (i.e., 2.0%, 2.5%, w/w) promoted microbial growth through labile C addition. In short, the type and loading concentration of bio-MPs incorporated into the soil will likely dictate the biological and ecological effects exhibited. It is therefore important to explore the impact of realistic dose rates of bio-MPs rather than the extreme doses used in many previous studies.

#### 4.2. Effect of bio-MPs on soil quality and plant health

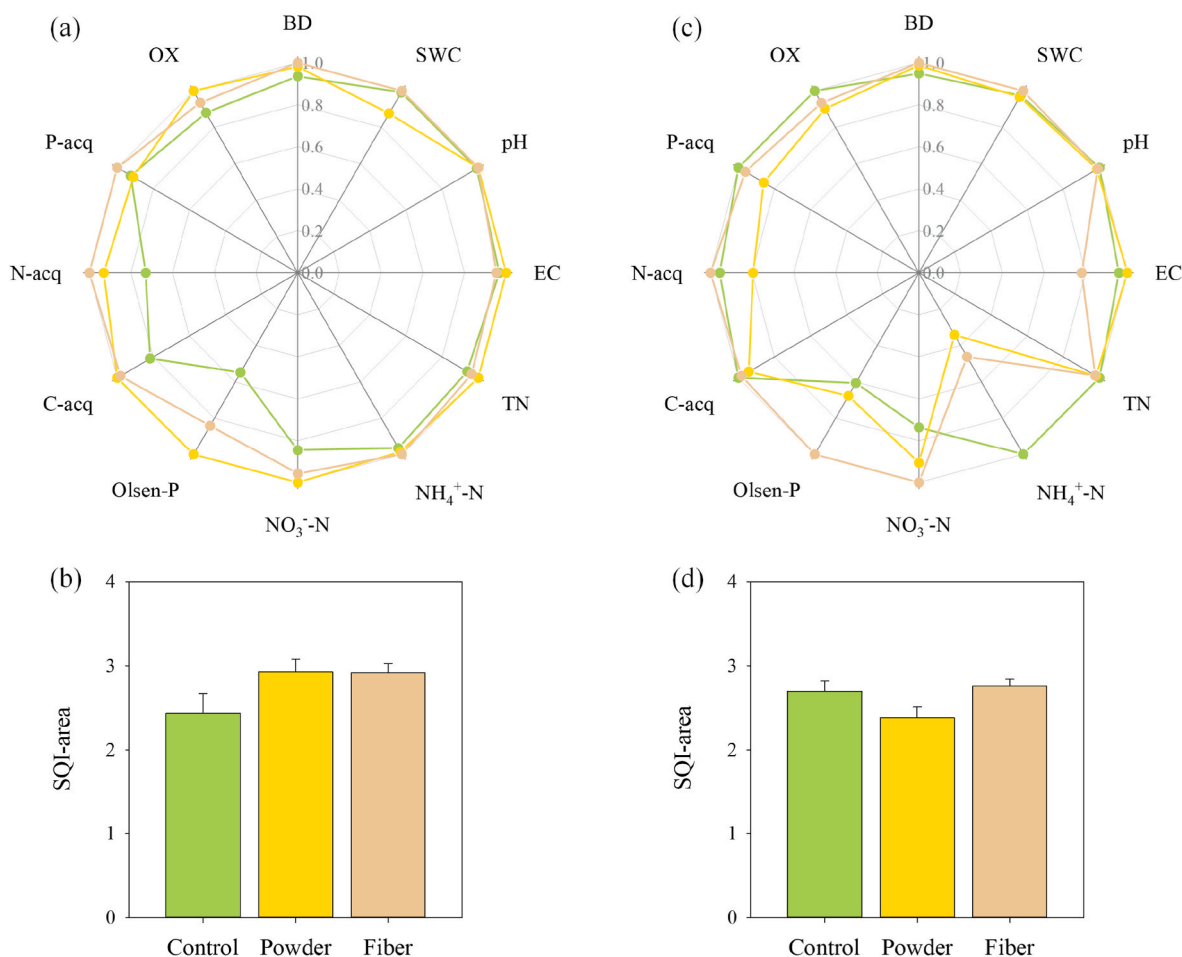
Soil is a fundamental part of the ecosystem and contributes essentially to the cycles of all elements that are critical to crop growth and food production (Bunemann et al., 2018; Kuzyakov et al., 2020). We found bio-MPs had no significant effect on SQI based on many soil indicators (as shown in Fig. 2), which indicated that key soil properties were not fundamentally affected by PLA addition. Specifically, contrary to the common expectation that the degradation of PLA would decrease soil pH due to the generation of lactic acid (Karamanlioglu and Robson, 2013), we observed that the soil exposed to 0.2% PLA did not affect pH in the field (Fig. 2). This could be ascribed to the natural field environment having a stronger buffering capacity and a higher tolerance for bio-MPs addition, which was not reflected in the limited space and controlled temperature and moisture conditions under laboratory conditions (Qi et al., 2020a) and the rapid microbial consumption of any lactic acid monomers released (Gunina et al., 2017). Realistically, bioplastic may accumulate in the soil, particularly in colder and drier climates (Satti et al., 2018), as application rates may exceed biotic and

abiotic degradation rates (e.g., repeated use over several years) (Nandakumar et al., 2021). As such, the effect of bio-MPs on soil properties may be concentration-dependent and temporally variable, potentially increasing over time. In the short term, the lower dose (0.2%) of PLA bio-MPs was unlikely to cause a significant shift in soil C/N ratio and induce N deficiency (Fig. 2), whereas higher doses (hotspots or longer term accumulation) of bio-MPs might affect the C/N ratio of the soil (Qi et al., 2020b) and are more likely to have a larger impact on soil stoichiometry and associated soil microbial function (Aanderud et al., 2018). Analogously, we found that both bio-MPs shapes had no significant effect on root characteristics and the productivity of either oat or soybean (Fig. 3). This was contrary to a previous greenhouse study undertaken with constant soil moisture under highly controlled conditions (i.e., temperature, light, and nutrient availability) (Yang et al., 2021; Zeb et al., 2022; Zhou et al., 2021a). A previous review also confirmed that the effects of bio-MPs on plant growth were highly dependent on types and concentrations (Zhou et al., 2021b). However, we note that longer term monitoring is required to better understand the full extent of the impact of bioplastics and subsequent bio-MPs on the agroecosystem.

#### 4.3. Ecosystem multifunctionality as affected by bio-MPs

Ecosystems have the ability to simultaneously provide multiple functions (Jia et al., 2022; Ma et al., 2022; Manning et al., 2018), as the biotic and abiotic processes that occur and contribute to ecosystem services either directly or indirectly (Garland et al., 2021), thereby uniformly called EMF. Our results found that bio-MPs incorporation did not affect EMF for both oat and soybean cropping systems (Fig. 4a and b). The non-significant differences in plant growth and soil moisture largely determined the absence of EMF alteration by bio-MPs, confirmed by the significant correlation between PGI, SWC, and EMF (Fig. 4c).





**Fig. 2.** Soil quality index (SQI) area (b, d) and radar chart of the relative response of soil parameters (a, c) in oat (a, b) and soybean (c, d) cropping system. BD, bulk density; SWC, soil water content; EC, electrical conductivity; TN, total nitrogen;  $\text{NH}_4^+\text{-N}$ , ammonium nitrogen;  $\text{NO}_3^-\text{-N}$ , nitrate nitrogen; Olsen-P, available phosphorus; C-acq, carbon acquisition enzyme activity; N-acq, nitrogen acquisition enzyme activity; P-acq, phosphorus acquisition enzyme activity; OX, oxidative decomposition enzyme activity. Values are averages  $\pm$  standard errors ( $n = 4$ ). No statistically significant differences are observed between the polylactic acid microplastics treatments and the Control ( $P > 0.05$ ).

Moisture increases the likelihood of hydrolytic breakdown of the ester linkages in PLA polymer; consequently, PLA can be hydrolyzed and form water-soluble low molecular weight oligomers, which may act as additional C sources for microbial assimilation and subsequently affect SQI, PGI, and EMF (Elsawy et al., 2017; Nayab et al., 2022). However, soil moisture was relatively low in our field site due to limited precipitation (374 mm) in the semi-arid region, which may have hindered the decomposition of bio-MPs and its subsequent effect on EMF. This is supported by Lozano et al. (2021a) who found that bio-MPs fibers reduced soil functions only under well-watered conditions.

#### 4.4. Implications and future research direction

Although the effects of bio-MPs on soil and plant were studied over one cropping cycle, their impact on agricultural ecosystems is still not fully understood. Clearly, the multi-site experimental data and further microbial analysis are needed in the future, in order to better understand the long-term ecological impact of purportedly harmless bio-MPs on the soil environment (Fan et al., 2022; Zhou et al., 2023). Equally, the degradation rates of bioplastics and bio-MPs in the field should be monitored over longer time periods (e.g., 10 years) to understand the impact of climate and soil type on the accumulation rates over multiple cropping cycles and the subsequent effect on soil and plant health and EMF. Further, depending on how they were produced, bio-MPs can be divided into natural polymers and synthetic polymers (Pellis et al.,

2021). However, research has focused on a limited selection of bio-MPs (i.e., PLA and PHB) that have mainly been used for determination in the greenhouse or field (Liao and Chen, 2021), calling for an expansion of the types and concentrations of bio-MPs.

## 5. Conclusions

This study showed that the field application of PLA had no significant effect on soil biochemical properties, root characteristics, plant biomass, and ecosystem multifunctionality over one growing season (5 months), regardless of bio-MPs shapes (fiber and powder) and crop species (oat and soybean). Although bio-MPs themselves may not be beneficial to plant-soil health, they do not appear to pose a significant threat to agroecosystem functioning. Our evidence therefore suggests that biodegradable plastics may provide a viable alternative to replace conventional non-biodegradable plastics. Further work should be conducted focusing on the effects of bio-MPs types and concentrations on ecosystem multifunctionality in the multi-site field trials over longer time scales (years to decades).

#### Credit author statement

**Juncong Chu:** Conceptualization, Data curation, Methodology, Visualization, Writing - original draft. **Jie Zhou:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Yue Wang:**

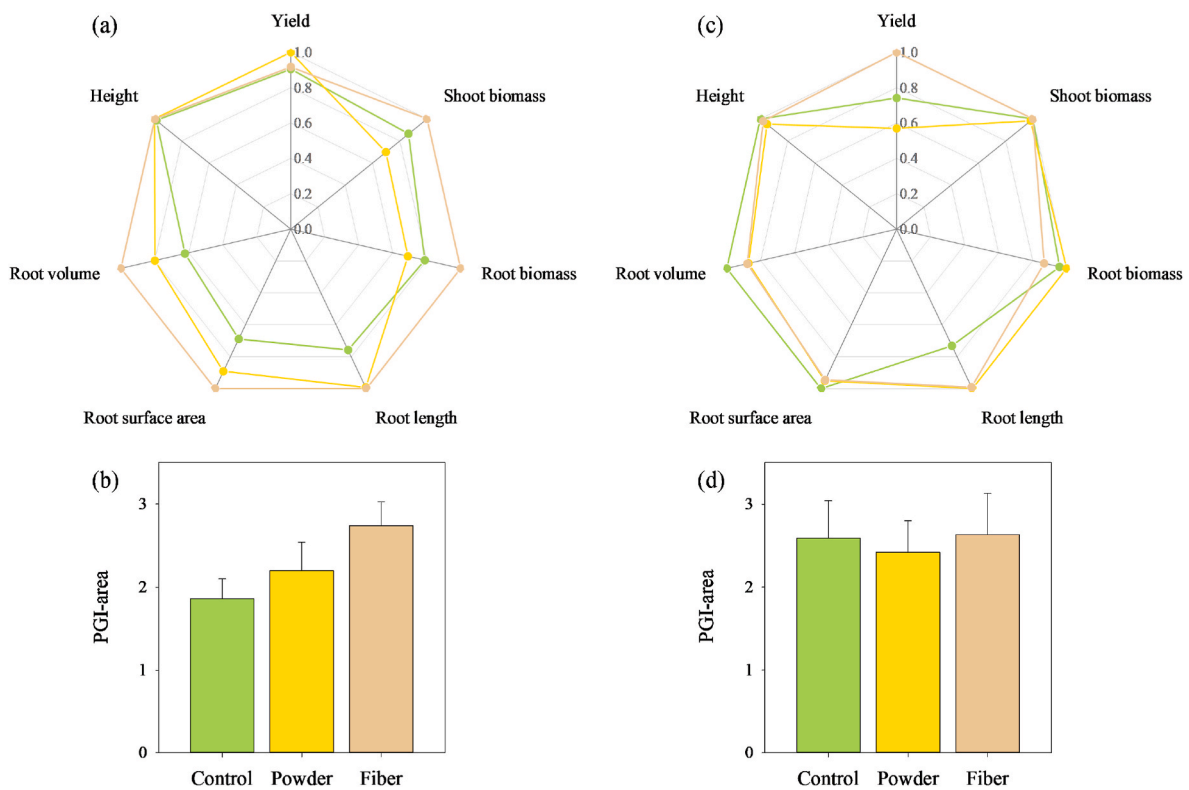


Fig. 3. Plant growth index (PGI) area (b, d) and radar chart of the relative response of plant parameters (a, c) in oat (a, b) and soybean (c, d) cropping system. Values are averages  $\pm$  standard errors ( $n = 4$ ). No statistically significant differences are present between the polylactic acid microplastics treatments and the Control ( $P > 0.05$ ).

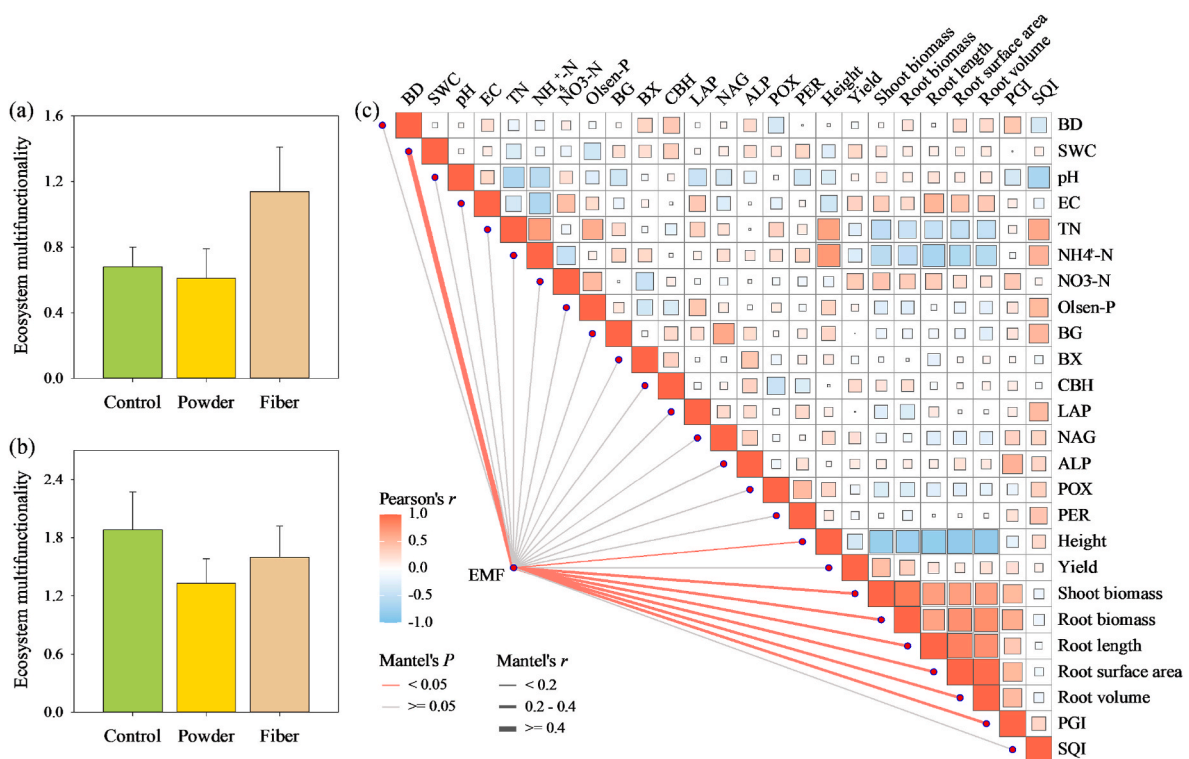


Fig. 4. Ecosystem multifunctionality (EMF) in oat (a) and soybean (b) cropping system and its correlation with plant and soil parameters (c). Pairwise comparisons of environmental factors are shown in the upper right corner, with a color gradient denoting Pearson's correlation coefficients. Ecosystem multifunctionality is related to each soil environmental factor by Mantel test. Edge width corresponds to the Mantel's  $r$  statistic for the corresponding distance correlations, and edge color denotes the statistical significance. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Investigation, Writing - review & editing. **Davey L. Jones:** Funding acquisition, Writing - review & editing. **Junyong Ge:** Writing - review & editing. **Yadong Yang:** Writing - review & editing. **Robert W. Brown:** Funding acquisition, Writing - review & editing. **Huadong Zang:** Conceptualization, Methodology, Project administration, Supervision, Writing - review & editing. **Zhaohai Zeng:** Funding acquisition, 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.

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2022.120556>.

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