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Microplastics alter microbial structure and assembly processes in different soil types: Driving effects of environmental factors

Qingjie Li [a], Xiaoxing Wang [a,b], Jiaqi Zhang [c], Xueqi Guo [a], Yanli Li [a], Okbagaber Andom [a], Zhaojun Li [a,*]

[a] State Key Laboratory of Efficient Utilization of Arid and Semi-arid Arable Land in Northern China, China-New Zealand Joint Laboratory for Soil Molecular Ecology, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, 100081, China

[b] College of Biological Sciences and Technology, Yili Normal University, Yili, 835000, Xinjiang, China

[c] College of Life Sciences, Hebei University, Baoding, 071002, Hebei, China

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ABSTRACT

Microplastics (MPs) are emerging pollutants with potential impacts on soil ecosystems. However, it is unclear how MPs-induced changes in the soil environment drive microbial structure and assembly in different soils. Here we investigated the responses of microbial structure, enzyme activities and soil properties to biodegradable polylactic acid (PLA) and conventional polythene (PE) with different doses in different soil types. Results showed that PLA generally decreased soil NH_4^+-N and NO_3^--N levels but increased dissolved organic carbon (DOC) and pH, whereas PE exhibited contrasting effects depending on soil type. MPs significantly stimulated soil urease, sucrase, catalase and phosphatase activities, with dose-dependent responses observed under PLA treatments in fluvo-aquic soil. Additionally, MPs altered microbial composition and colonized specific bacterial taxa in different soils. In microbial assemblies dominated by stochastic processes, MPs, especially PE promoted the deterministic processes. Co-occurrence patterns showed lower microbial complexity under PLA treatments compared to PE. Notably, we revealed soil-type-specific response patterns: DOC emerged as the primary driver in red soil ecosystems, while pH exerted dominant control in fluvo-aquic soil systems. Furthermore, perturbation of microbial communities by MPs affected functions related to metabolism. These findings highlight that MPs-induced shifts in microbial communities and assembly processes are soil-type-specific and mediated by soil characteristics changes, providing critical insights for assessing the ecological risks of MPs in diverse agricultural soils.

1. Introduction

Plastics are widely used in various fields, including medical devices, agriculture and packaging due to their strong plasticity, high flexibility and affordability (Yao et al., 2022). As plastic products continue to increase, more than 10 billion tons of plastic trash will enter the environment by 2050 (Steinmetz et al., 2016). These polymers can gradually decompose into microplastics (MPs) under various external factors (Chen et al., 2022). As the major environmental repository of MPs, soil ecosystems can receive MPs from a diversity of sources, such as atmospheric deposition, sewage irrigation, mulch use and manure application (Fang et al., 2024; Gao et al., 2020). Long-term accumulation of MPs in the soil may have a negative impact on animals and plants, and can enter the human body along the food chain, threatening human health (Li et al., 2024). Consequently, researching how MPs affect soil ecosystems is crucial.

MPs have been demonstrated to change soil physicochemical characteristics and exert impacts on soil systems (Wang et al., 2022a; Chang et al., 2024). For instance, the contents of NH_4^+-N and available phosphorus (AP) in farmland soil were significantly decreased under polylactic acid (PLA) treatments, while no significant change was investigated under polyethylene (PE) treatments (Dong et al., 2024). However, Li et al. (2024) found that PE increased NH_4^+-N in red soil, but had no significant effects on NH_4^+-N and AP in fluvo-aquic soil. Additionally, Meng et al. (2023) found that 2 % PE increased dissolved organic carbon (DOC) in phaeozem, but decreased DOC in fluvo-aquic soil. Furthermore, MPs may have a direct or indirect impact on soil enzyme activities (Wang et al., 2024a). A study showed that polystyrene

* Corresponding author.
E-mail address: lizhaojun@caas.cn (Z. Li).

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(PS) lowered the activities of cellobiohydrolase and β-glucosidase in soil under the soil incubation experiment (Awet et al., 2018). Conversely, another study found that cellobiohydrolase and β-glucosidase activities were not changed in the PE-containing soil (Zang et al., 2020). Dong et al. (2024) found that PLA decreased catalase activity in wetland soil while increasing it in farmland soil and woodland soil. In general, the above conflicting findings may be attributed to differences in MPs types, sizes, doses and soil types. Notably, alterations in soil characteristics can modify the structure and composition of microorganisms.

Ecological equilibrium can be maintained by soil microorganisms, which are a vital part of the soil ecosystem (Coban et al., 2022). MPs can provide new ecological niches for microorganisms after they enter the soil, thereby altering the diversity and composition of microbial communities (Miao et al., 2019). One study found that 0.02 % PBAT (polyadipate/butylene terephthalate) increased soil bacterial diversity and significantly enriched *Mesorhizobium*, *TM7a* and *Azotobacter* (Li et al., 2022a). Another study found that PS and polypropylene (PP) promoted the abundance of some bacterial genera such as *Bacillus, Roseiflexaceae* and *Sphingomonas*, although they didn't alter the soil bacterial diversity (Zhao et al., 2023). Additionally, microbial assembly, co-occurrence and function presented different trends under MPs stress. For example, PS altered the structure of autotrophic microbial communities, resulting in more stochastically dominated assembly and more fragile co-occurrence networks than the control group (Fang et al., 2024). PE boosted the influence of stochastic processes and reduced network complexity and stability in a soil microcosm experiment (Shi et al., 2022). MP-induced alterations in soil microbial communities may further affect microbial functions, such as nitrogen fixation, organic carbon decomposition and nitrate reduction (Qin et al., 2023). However, most studies have only considered the specific effects of MPs on soil properties and microbial communities, the effects of MPs on soil microbial assembly and function have not been elucidated, especially in different soils.

In recent decades, research has focused on the environmental contamination caused by conventional plastics like PE and PP, which are difficult to breakdown (Chang et al., 2024). As an alternative to traditional plastics, biodegradable plastics like PLA and PBAT are currently widely employed in agriculture (Chen et al., 2020). However, if biodegradable plastics don't break down completely, it could disrupt soil ecosystems and cause more damage (Xie et al., 2023). According to Liu et al. (2023), the biodegradable PLA (2 %) had a greater influence on the microbial community than other MPs and severely decreased the shoot biomass of rice by 28 %. Similarly, PLA (1 %) impeded pakchoi growth and dramatically decreased its biomass and chlorophyll content, according to Li et al. (2024). Although extensive reporting on the impacts of MPs on soil systems, little is known about the precise mechanisms via which MPs alter the microbial communities and soil characteristics (Zhang et al., 2023b). Furthermore, it is indistinct what the main elements influencing microbial structure and assembly are, as well as how different doses of conventional and biodegradable plastics affect these processes in different soil types.

PE and PLA are conventional plastic and biodegradable plastic that are widely studied in farmland soils, respectively. This study investigated the effects of PE and PLA at different doses on microbial structure, enzyme activities and soil properties in different soil types. Particularly, alterations in the microbial community's diversity, composition, assembly process, and function were described. More importantly, we examined how microbial communities were impacted by MPs-induced modifications to soil biogeochemical characteristics. The comparison of the environmental effects of PE and PLA in various soil types was the main goal of this study. We aimed to reveal the mechanisms by which MPs alter microbial structure and assembly in different soils and elucidate the key driving effects. The findings can help to assess the environmental threats that MPs present to different soil ecosystems.

2. Materials and methods

2.1. MPs sources and soil collection

PE and PLA, two common MPs widely detected in environments in the world, were selected in this experiment. These two types of MPs were procured from Guangdong Ruixiang Plastic Chemical Co., Ltd., China. PE and PLA had densities of 0.92 and 1.24 g/cm^3, respectively, with the average particle size was 25 μm. The shape of PE and PLA were characterized using scanning electron microscope (Fig. S1). To avoid introducing other contaminants into the soils, MPs were cleaned with methanol prior to use.

Red soil (Hengyang, Hunan) and fluvo-aquic soil (Zhangjiakou, Hebei) were used in our experiment, denoted by R and F, respectively. The soils were collected from 0 to 20 cm of topsoil in farmland soils with no history of plastic cover, and then air-dried. The selected parameters of soils were shown in Table S1. Both types of soil were incubated at 25 °C in the dark for a week to reduce the impact of environmental changes prior to the experiments.

2.2. Experimental design and soil sampling

Five treatments with three replicates were set up in each soil for soil incubation experiment: (1) CK, control, soils without MPs addition; (2) PE0.1, soils with 0.1 % PE (w/w) addition; (3) PE1, soils with 1 % PE (w/w) addition; (4) PLA0.1, soils with 0.1 % PLA (w/w) addition; (5) PLA1, soils with 1 % PLA (w/w) addition. The dose of MPs was determined based on the residual contents of MPs in farmland soils (Huang et al., 2019).

Exactly 300 g soil were weighed into a 500-mL glass bottle. Subsequently, PE or PLA with different doses were added to the bottles with constant stirring until well mixed with the soils. Soil moisture was kept at 60 % of the maximum field capacity and ultrapure water was added every three days during the incubation experiment. Finally, all the sealed bottles were randomly placed in an incubator at 25 °C under the dark conditions. Soil samples were collected for biological and chemical analysis after 120 days of incubation.

2.3. Determination of soil characteristics

Soil properties were detected according to our previous method (Li et al., 2024). Soil ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were extracted by 2M KCl, soil available phosphorus (AP) was extracted by 0.5M $NaHCO_3$, and then measured by ultraviolet spectrophotometer (UV-2600, Shimadzu, Japan). Soil dissolved organic carbon (DOC) was extracted with ultrapure water and measured by total organic carbon automatic analyzer (TOC-L CPH, Japan). Soil pH and electrical conductivity (EC) were determined with a PT-11 pH meter and a DDS-11A conductivity meter (Shanghai Leici Instrumentation, China), respectively. Soil urease, sucrase, phosphatase and catalase activities were determined by respective kits from Jiangsu Meimian Industrial Co., Ltd (Jiangsu, China), through the double antibody sandwich method to determine enzyme activity levels in soil samples. In order to reduce the experimental error, standard, blank and sample holes were set respectively during the measurement process. The enzyme activities of soil samples were determined by enzyme-labeled apparatus after incubation, washing, color development and termination.

2.4. Soil microbial community

Soil DNA was extracted to evaluate the impacts of MPs on soil microbes. Bacterial 16S rRNA were amplified using primer 338F and 806R based on the extracted DNA samples as template. Amplicons were recovered, purified and quantified for high-throughput sequencing. The double-ended raw sequences were processed for quality control (fastp, version 0.196), splicing (FLASH, version 1.2.11), and noise reduction

(QIIME, version 1.9.1) to obtain amplicon sequence variants (ASVs) that could be used for analysis. In addition, sequences annotated as chloroplasts or mitochondria and their splice fragments were removed according to the annotation results. The species taxonomy and composition of ASVs were analyzed based on Sliva database (version 138).

2.5. Statistical analysis

The effects of MPs on soil characteristics were evaluated using Duncan's multiple range test combined with one-way analysis of variance (ANOVA). The main effects of soil type, MPs type and MPs dose on soil environmental factors were investigated using three-way ANOVA with the least significant difference (LSD) post hoc test. All statistical analysis were completed in SPSS 20.0 software, with data in the form of mean values and standard deviations (SD). Principal coordinate analysis (PCoA) plots showed how the architecture of the soil bacterial communities were comparable. Furthermore, adonis (PERMANOVA) was used to test dissimilarity among groups. Bacterial phyla with significant differences among treatments were assessed using the Kruskal-Wallis H test. In addition, R software (v 3.3.1) was used to screen the top 50 bacterial genera with relative abundance and identified the ten key categories of bacterial genera that are most important for the response to MPs using a random forest model.

β-nearest taxon index (βNTI) was used to determine the microbial assembly process. $|\beta NTI| < 2$ means that stochastic processes predominate, whereas deterministic processes are the opposite. To investigate microbial interactions, co-occurrence networks for the 50 most prevalent bacterial genera in the soil were created using R software. Gephi software (v 0.10) was used to visualize and obtain network topology parameters. Functional Annotation of Prokaryotic Taxa (FAPROTAX) was used for functional annotation prediction of metabolic and biogeochemical cycles of soil microorganisms. Distance-based redundancy analysis (db-RDA) and variance partitioning analysis (VPA) were used to evaluate the effects of environmental factors on microbial communities. Heat maps of the correlation between microbial composition and assembly processes and environmental factors were done using Origin 2022 software.

3. Results

3.1. Soil basic properties

After 120 days of soil incubation, MPs generally reduced the content of NH_4^+-N (Fig. 1A). In red soil, PLA treatments significantly decreased NH_4^+-N content by 16.78 %–49.28 %. In fluvo-aquic soil, PE and PLA at the low dose significantly decreased NH_4^+-N by 13.75 % and 15.26 %, respectively. Soil NO_3^--N was lowed under PLA treatments in two soils, with the highest decrement at high-dose PLA treatments (50.40 %–69.00 %) (Fig. 1B). The effects of PE on NO_3^--N varied in different soils. NO_3^--N content was significantly decreased by 20.89 % under PE0.1 treatment in red soil, however increased by 4.71 %–12.09 % under PE treatments in fluvo-aquic soil. MPs had no significant effect on AP, except for the PLA1 treatment at which the content of AP reached the lowest in fluvo-aquic soil (Fig. 1C). Additionally, MPs caused increases in DOC content to varying extent in red soil, with an opposite trend to the changes in NO_3^--N content (Fig. 1D). It was interestingly found that in fluvo-aquic soil, DOC was significantly decreased by 26.28 % by PE1, whereas significantly increased by 22.65 % under PLA1 treatments. MPs promoted the significant rise of pH in red soil (Fig. 1E). However, PE significantly decreased pH in fluvo-aquic soil. Soil EC didn't change significantly under MPs treatment (except for PE0.1 treatment in red soil) (Fig. 1F). The primary elements influencing soil characteristics were soil type and MPs type (Table S2).

3.2. Soil enzymatic activities

Broadly, MPs promoted the elevation of four soil enzyme activities (Fig. 2). In red soil, PE treatments significantly increased soil urease activity by 19.75 %–40.11 % compared to CK (Fig. 2A). The activities of soil sucrase (Fig. 2B) and catalase (Fig. 2C) were significantly increased by 41.65 % and 24.54 % under PE0.1 treatment, respectively. In contrast, MPs presence did not significantly alter the activity of soil phosphatase (Fig. 2D). Additionally, soil enzyme activities under PE0.1 treatment were the highest. In fluvo-aquic soil, MPs significantly increased the activities of urease (25.37 %–44.98 %), sucrase (30.82 %–55.32 %), catalase (21.20 %–44.02 %) and phosphatase (13.92 %–33.21

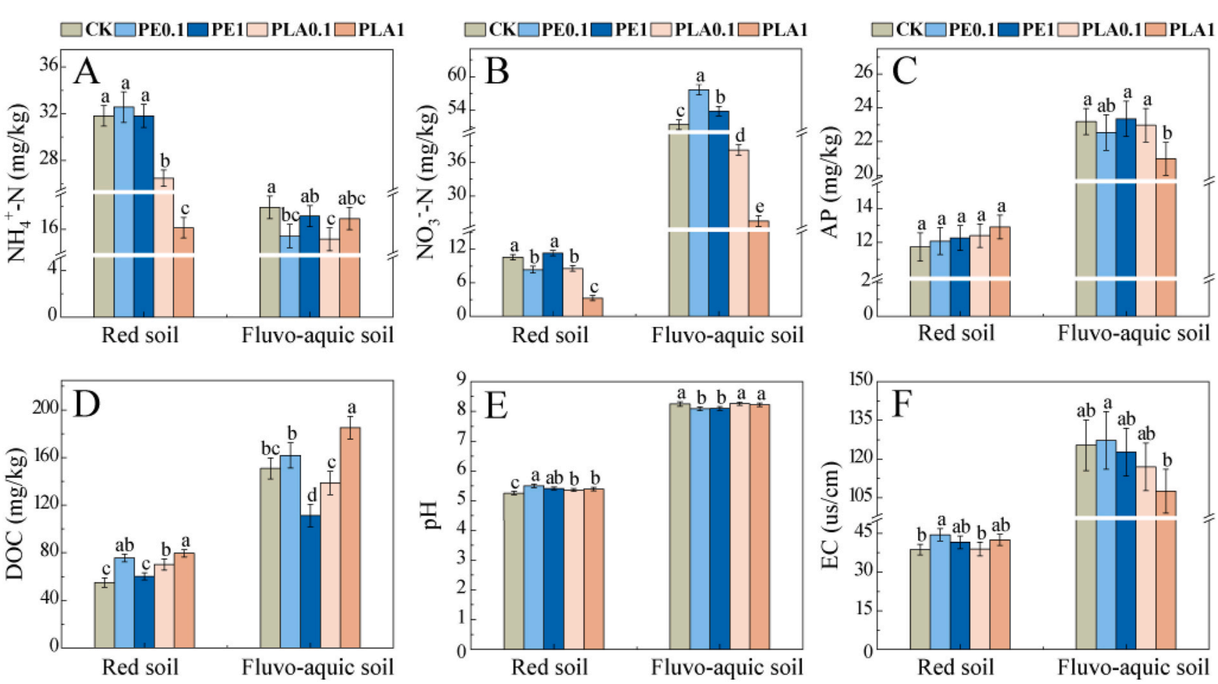

Fig. 1. Soil properties exposed to MPs under different soil types (A: NH_4^+-N, B: NO_3^--N, C: AP, D: DOC, E: pH, F: EC). Different lowercase letters indicate statistical differences between treatments ($P < 0.05$).

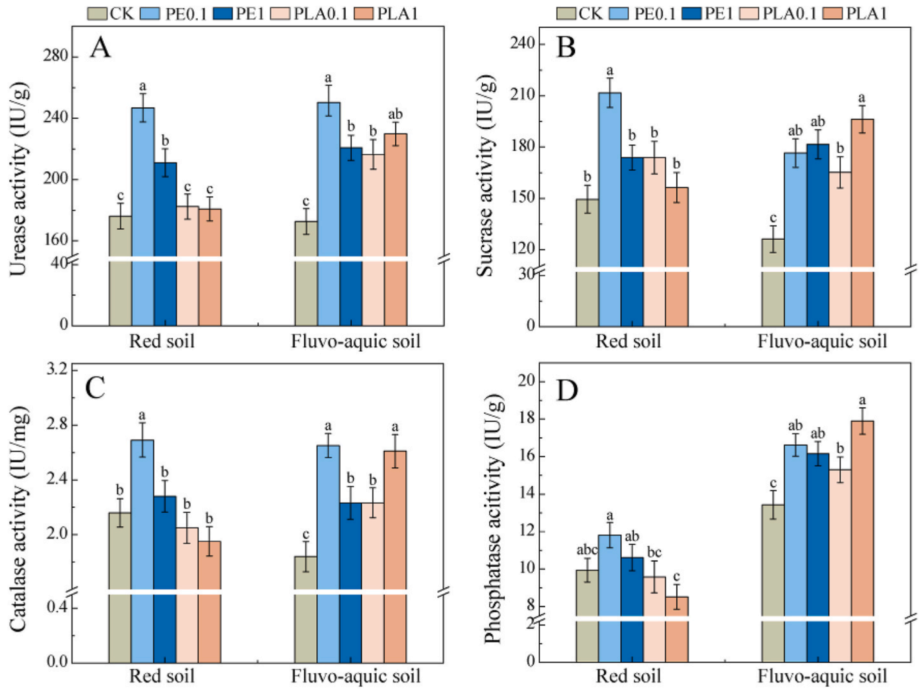

Fig. 2. Soil urease (A), sucrase (B), catalase (C) and phosphatase (D) activities exposed to MPs under different soil types. Different lowercase letters indicate statistical differences between treatments (P < 0.05).

%) in soils. Compared to high-dose PE treatments, the activities of soil urease and catalase were significantly higher in low-dose PE treatments. In contrast, soil enzyme activities increased with the increasing PLA dose.

The primary elements influencing soil enzyme activities were MPs type and dose (Table S2, Table S4).

3.3. Diversity and composition of soil microbes

MPs significantly decreased bacterial community diversity in red soil, and lower bacterial diversity was observed in PLA treatments compared to PE treatments (Fig. S2). However, MPs treatments didn't significantly affect the bacterial diversity in fluvo-aquic soil. PCoA plots showed the variance in bacterial community structure among different MPs types and different MPs doses in both soils (Fig. 3A and B). MPs caused a large separation of bacterial communities, especially the farthest distance between the PLA and the CK treatments. In addition, bacterial communities at different doses of PE treatments were clustered together, while those of different doses of PLA treatments were separated from each other. It indicated that PLA had greater effects on bacterial communities than PE.

Chloroflexi (8.17 %–57.65 %) and Firmicutes (24.86 %–40.25 %) were the most dominant bacteria phyla in red soil and fluvo-aquic soil, respectively, followed by Proteobacteria (17.21 %–57.12 %) and Actinobacteria (4.75 %–48.59 %) (Fig. 3C and D). MPs significantly increased the abundance of Chloroflexi in red soil and decreased the abundance of Firmicutes in fluvo-aquic soil (Fig. S3). The abundance of Proteobacteria increased significantly under MPs treatments in two soils, except that it was significantly lower in red soil under PE treatments compared to CK. By contrast, the abundance of Actinobacteria in both soils decreased significantly under MPs treatments (except PLA0.1 in red soil). Random forest analysis showed significant differences existed in the most important bacterial genera (Fig. 3E and F). *Amycolatopsis* and *Nitrolancea* were the most important bacterial genera in response to MPs in red soil and fluvo-aquic soil, respectively. Moreover, *Rubrobacter* and *Pontibacter* were the common species in both soils, while the other bacterial genera in red soil were completely different from those in fluvo-aquic soil. The results showed that MPs could colonize specific bacterial communities in both soils.

3.4. Soil microbial assembly

The βNTI values of the CK group in both soils were mainly distributed between −2 and 2, indicating that stochastic process dominated the bacterial assembly process (Fig. 4A). Under MPs exposure, some βNTI values of PE and PLA1 treatments in red soil were lower than −2. Correspondingly, the proportion of deterministic processes in these treatment groups increased from 0 to 22.22 % (Fig. 4B). In contrast, only some βNTI values under the low-dose PE treatment in fluvo-aquic soil were lower than −2. Interestingly, the proportion of deterministic processes of PE0.1 treatment in the fluvo-aquic soil also increased to 22.22 %. Furthermore, drift (DR) in the stochastic process dominated the process of bacterial community assembly in the PE0.1 and PLA1 treatments in fluvo-aquic soil, whereas homogeneous dispersal (HD) dominated bacterial community assembly in all other treatments. These findings indicated that soil bacterial assembly processes differed in the two soils and was correlated with MPs type and dose.

PE in the red soil increased the complexity of the bacterial community, which was reflected in the fact that it had more links, average weighted degree, density, and average clustering coefficient of the bacterial network (Table S3, Fig. 4C). However, PLA decreased the bacterial complexity, which was reflected in the reduction of the network topology parameters described above. Furthermore, modularity was observed to increase with PLA treatments but decrease with PE treatments. Low modularity usually means that the co-occurrence pattern of the network was unstable. Network topological parameters showed that MPs reduced the complexity of bacterial networks, and high-dose PLA had the lowest modularity in fluvo-aquic soil. Besides, the proportion of positive correlation between bacterial genera in the two soils decreased with the increasing doses of MPs.

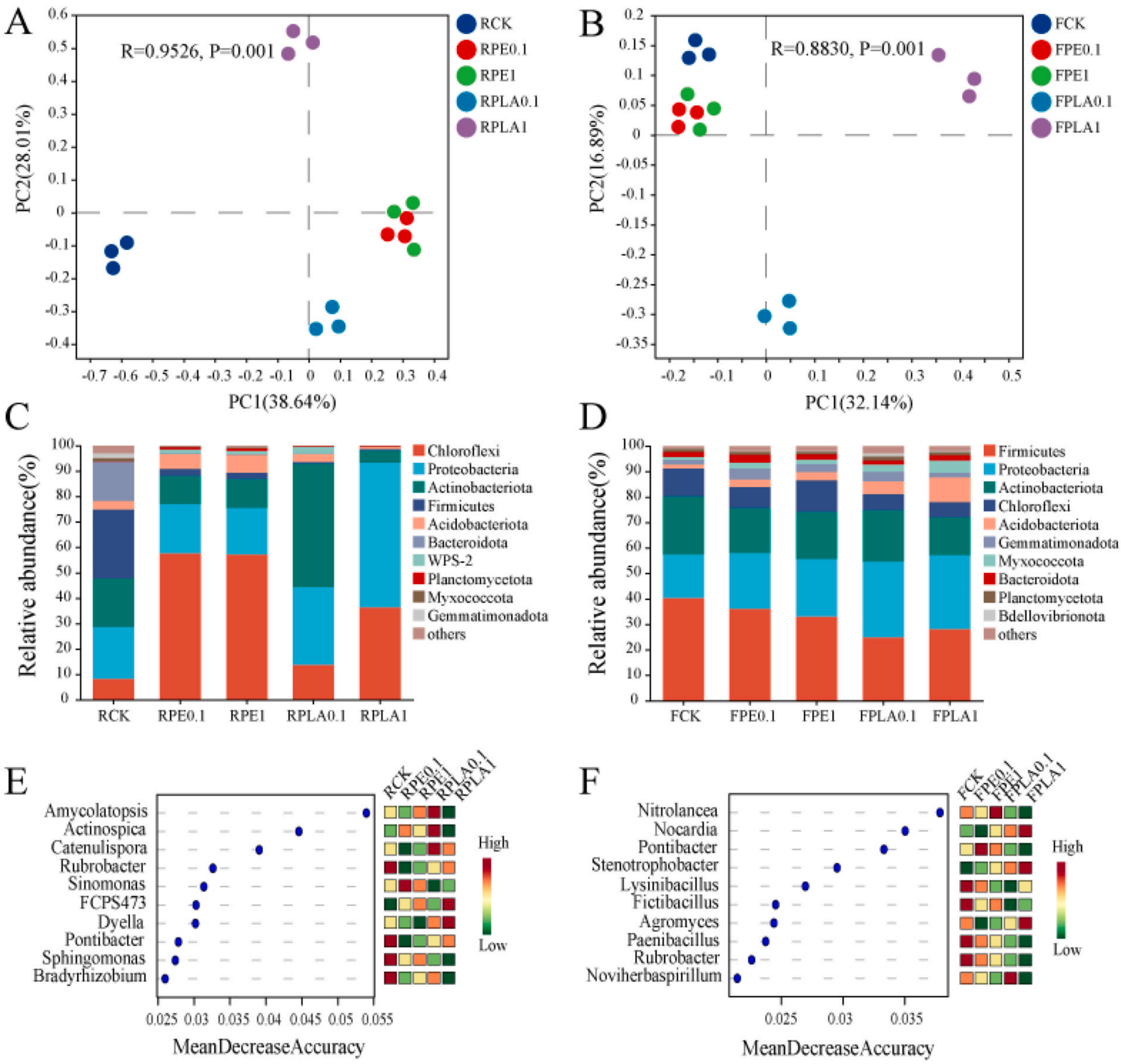

Fig. 3. PCoA plots reflecting the differences of bacterial community structure (A–B), dominant phyla composition of soil bacterial community (C–D), and the 10 most important bacterial genera predicted by random forest models (E–F) (A, C, E: red soil; B, D, F: fluvo-aquic soil). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.5. Connections between environmental variables and soil microbial communities

According to the db-RDA analysis, DOC, NH_4^+-N and NO_3^--N were the main factors affecting bacterial community in red soil, while bacteria in fluvo-aquic soil were predominantly shaped by pH, DOC and urease activity (Fig. 5A and B, Table S5). Notably, the foremost indicators in both soil types were pH (fluvo-aquic) and DOC (red soil), respectively. The interactive effects of soil properties and enzyme activities explained 62.04 % and 54.77 % of the variation in bacterial community in the red soil and fluvo-aquic soil, respectively (Fig. 5C and D). Furthermore, soil properties explained more about bacterial communities than enzyme activities with the explain rate of 27.99 % and 14.94 % of the variation in red soil and fluvo-aquic soil respectively. Residual represented the amount of microbial community change that cannot be explained by two variables. The bacterial community changes in red soil were more strongly linked to soil environmental factors, as seen by the smaller residual in red soil compared to another soil. The subsequent correlation analysis also proved this result (Fig. 6). Person correlation analysis revealed the substantial relationships between bacterial communities and changes in soil environmental parameters. In red soil, the change of soil properties under PE treatments was more strongly correlated with the bacterial community, while the effect of PLA treatments on the bacterial community was more significant in fluvo-aquic soil. These results indicated that both PE and PLA changed soil bacterial communities through changing soil properties, with the specific different action mechanisms.

3.6. Soil microbial functional prediction

FAPROTAX was used to predict microbial metabolic and ecologically relevant functional characteristics in both soils. Fig. 7 showed the top 20 functional categories in relative abundance out of the 50 functions that were identified in all samples. Chemoheterotrophy (38 %–46 %) and aerobic_chemoheterotrophy (36 %–49 %) were highly enriched under MPs treatments. The abundance of chemoheterotrophy and aerobic_chemoheterotrophy was highest in PLA0.1 (red soil) and PLA1 (fluvo-aquic soil) treatments, and decreased in other treatments compared to CK. Additionally, MPs induced some changes in function related to the C and N cycle in soil. For example, MPs increased the

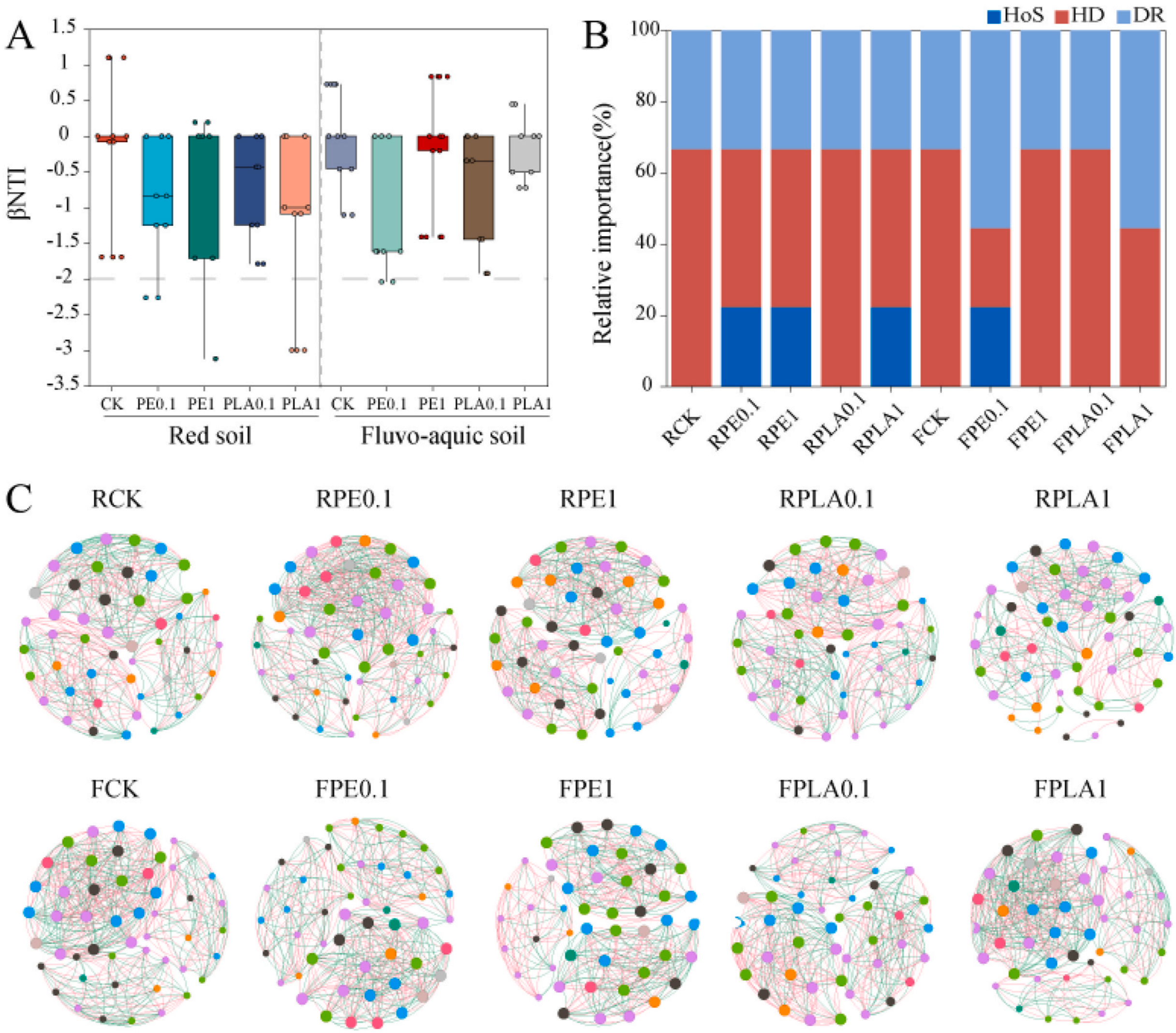

Fig. 4. βNTI values of soil bacterial communities (A), changes in stochastic and deterministic processes (B), co-occurrence networks of the top 50 bacterial genera in abundance (C).

abundance of nitrogen_fixation, while decreased nitrogen_reduction and nitrification (except for FPE1). Compared with PE, PLA has a greater increase in cellulolysis, but a lower abundance of ureolysis. Notably, MPs also had an impact on microbial function associated with human pathogens. MPs, especially low-dose PLA in fluvo-aquic soil significantly stimulated the relative abundance of human_pathogens_all compared with CK. On the contrary, all MPs decreased human_pathogens_all abundance in red soil.

4. Discussion

4.1. Changes of soil properties in different soils

Soil nitrogen (N) and phosphorus (P) are foundation elements for plant growth and microbiological survival (Dong et al., 2021). Studies have demonstrated that MPs can alter available N and P levels in soil (Meng et al., 2022; Wu et al., 2024). We found that PLA caused a decline in the N levels to varying extents. Correlation analysis showed that soil N levels were significantly correlated with microorganisms, and the inhibitory effect of PLA on N cycling-related microorganisms (*Sinomonas*、*Sphingomonas*、*Nitrolancea*、*Paenibacillus*) may be one of the reasons why PLA decreased N levels. Furthermore, PLA as a carbon-rich substance may promote the fixation of N by microorganisms (Yin et al., 2023). At this time, inorganic N was absorbed by microorganisms for the synthesis of organic nitrogen, resulting in the decline of soil N levels (Wang et al., 2022b). In fluvo-aquic soil, PE raised NO_3^--N while decreasing NH_4^+-N concentrations. One possible explanation is that MPs increased soil porosity, which may promote the soil nitrification process (de Souza Machado et al., 2018). In contrast, low-dose PE decreased NO_3^--N in red soil. Fluvo-aquic soil, characterized by its neutral pH and high carbon content, fostered the growth of nitrifying bacteria, thereby enhancing the nitrification process (Li et al., 2024). However, the activity of nitrifying bacteria was likely suppressed in red soil due to its acidic conditions. There was no significant change in AP in red soil, which may be related to the strong fixation of phosphorus by high ferric aluminum oxides, indicating the buffering ability of soil background properties to effect of MPs (Dong et al., 2024). Additionally, we found that PE had no discernible impact on AP, but high-dose PLA decreased AP contents in fluvo-aquic soil. Generally, the increase in phosphatase activity would promote the decomposition and conversion of organophosphates, resulting in an increase in soil AP (Wang et al., 2023). Interestingly, our findings were the opposite, with phosphatase activity under PLA1 treatment increasing rather than decreasing in fluvo-aquic soil. Another study showed that MPs reduced AP content and had no significant correlation with phosphatase activity (Feng et al., 2022), which further confirms our results (Fig. S4).

Soil DOC concentrations increased under PLA may be partially explained by the release of low molecular weight organic acids and other

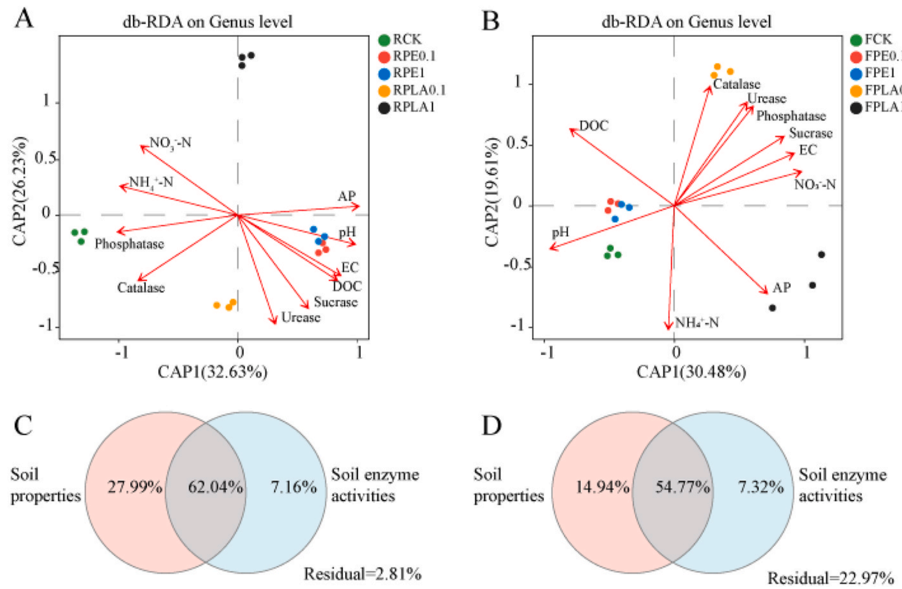

Fig. 5. Important environmental driving factors affecting soil bacterial communities (A: red soil, B: fluvo-aquic soil), the interpretation of environmental factors on differences in bacterial communities (C: red soil, D: fluvo-aquic soil). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

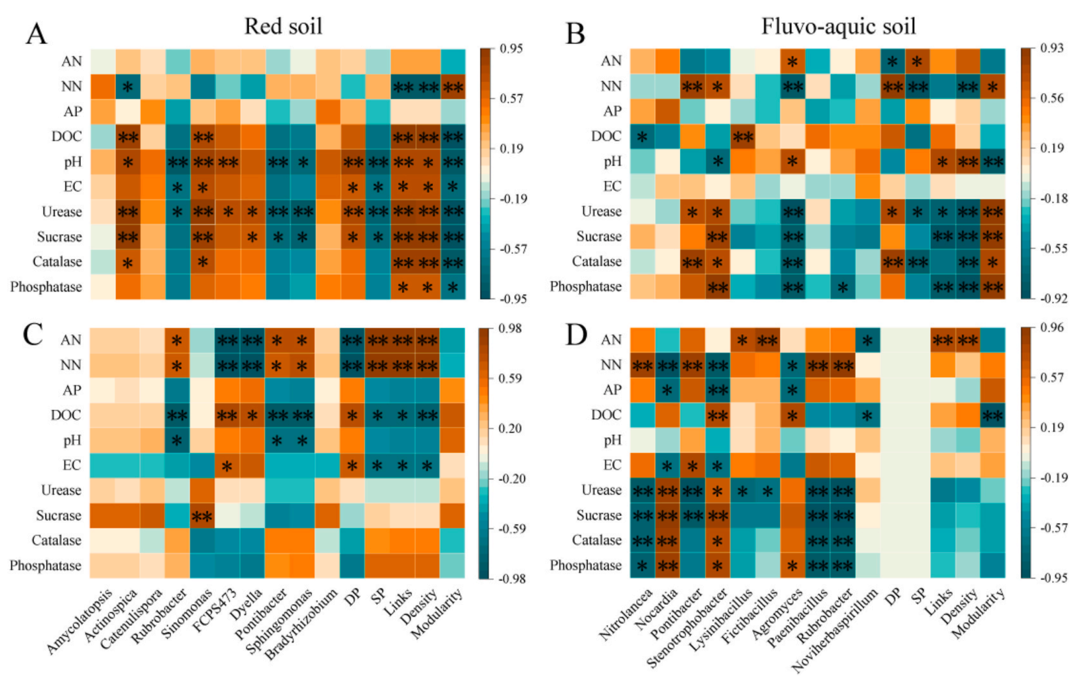

Fig. 6. Relationship between environmental factors and bacterial communities in soil treated with PE (A–B) and PLA (C–D).

soluble organic matter during the degradation of PLA, which can directly increase the DOC content in soil (Feng et al., 2022). Additionally, the degradation products of PLA can serve as carbon sources for microorganisms, enhancing microbial activity and further promoting DOC dynamics (Rillig et al., 2021). PE is a non-biodegradable plastic, which may change the physical structure of red soil and lead to the increase of DOC. However, high-dose PE reduced the DOC in fluvo-aquic soil, which may be due to the absorption of rich organic matter in the surface of PE (Souza et al., 2022). Ren et al. (2020) observed that PE didn't change soil DOC, which may be due to different exposure conditions. We found that MPs increased the pH in red soil, while PE decreased the pH in fluvo-aquic soil. The primary cause of the different changes in pH between the two soils may be the variations in aggregate and bulk density (Shao et al., 2023). PE was found that could lower pH via altering the soil nitrification process, which released H^+ (Rong et al., 2021). Moreover, MPs can change the adsorption characteristics in different soils, thus affecting the pH values. Soil EC can represent the soil salinity status and conductivity (Meunier et al., 2018). In our study, MPs didn't change EC except for a slight increase in EC caused by PE0.1 in the red soil. This showed that MPs had minimal impact on the soil salinity. MPs can selectively adsorb positively or negatively charged substances, thereby altering ion exchange in solution (Yuan et al., 2023). The adsorption effects of MPs on salt ions may be the cause of the rise in soil EC under low-dose PE treatment (Xu et al., 2024).

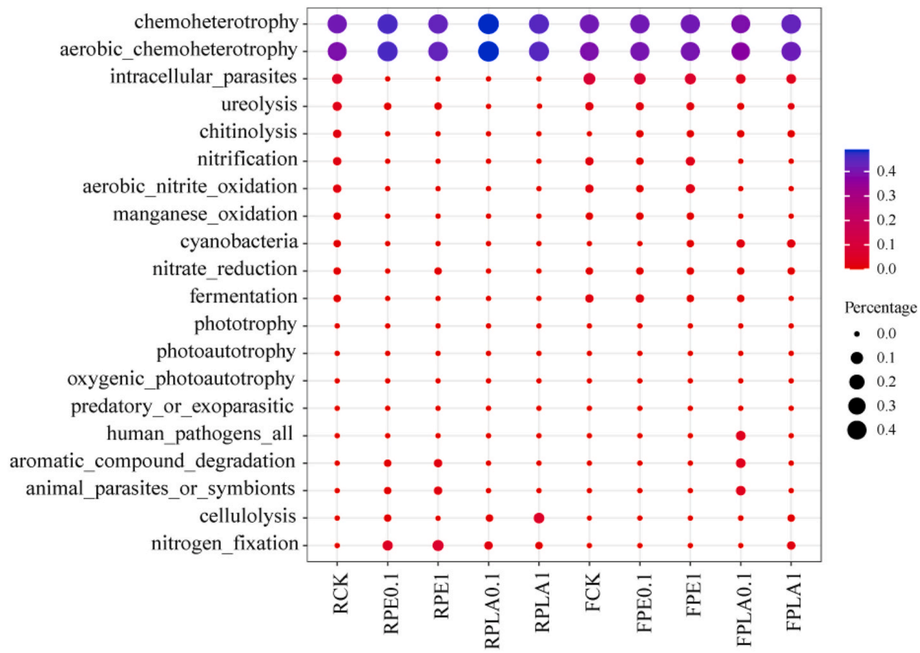

Fig. 7. The top 20 functional categories of soil bacterial communities predicted by FAPROTAX.

4.2. Changes of enzyme activities in different soils

Soil enzymes are substrates that catalyze nutrient cycling processes and are commonly used to evaluate soil fertility and microbial metabolic activity (Galhardi et al., 2020). Soil chemical elements and microbial structure were changed under the presence of MPs, which may translate into corresponding changes in soil enzyme activities (Wang et al., 2024b). We observed that MPs raised soil enzyme activities in most cases, but varied in different soils. An essential component of the N cycle, urease is a hydrolase that can accelerate the conversion of organic materials in soil that contains nitrogen (Ingram et al., 2005). We found that urease activity was significantly increased under PE treatments in red soil, but there was no correlation with the NH_4^+-N content. PE may indirectly promote urea hydrolysis, in which the release of ammonia increased soil pH. In response, soil microorganisms may stimulate urease production, resulting in increases in urease activity (Huang et al., 2024). Soil phosphatase and sucrase can regulate the biotransformation capacity of soil carbon and phosphorus, reflecting the supply of soil carbon and phosphorus (Li et al., 2022b; Yu et al., 2023). The activity of soil catalase represents the ability of microorganisms to control harmful oxidative stress (Han et al., 2024). In red soil, although other MPs had no discernible impact on enzyme activities, low-dose PE dramatically raised the activities of catalase and sucrase. This conclusion went against the results of Feng et al. (2022), who found that high-dose PLA increased soil enzyme activities whereas PE had no discernible impacts on soil sucrase and catalase activities. The variance may be explained by soil characteristics and MPs dose and size (Gao et al., 2024).

We observed that all MPs promoted enzyme activities in fluvo-aquic soil, indicating that the soil has a higher immune-like responses to MPs pollution. This could be explained by the higher fertility in fluvo-aquic soil (Mir et al., 2023). Besides, MPs as a pollutant may stimulate the metabolic activity of related microorganisms in soil. To a certain extent, soil microorganisms would change their original composition and interactions in order to alleviate the damage to soil structure brought by pollutants, thus minimizing soil damage (Xiao et al., 2022; Qi et al., 2024). The differential alterations in physicochemical properties of red soil and fluvo-aquic soil induced by MPs may explain the observed variations in soil enzyme activities. This was corroborated by correlation analysis (Fig. S4).

4.3. Change in diversity and composition of microbes in different soils

Previous studies have shown that MPs can promote, inhibit or have no effect on soil microbial diversity (HUANG et al., 2019; FEI et al., 2020; REN et al., 2020). We found that MPs, especially PLA, reduced the bacterial diversity in red soil. MPs significantly increased the pH of red soil, which may inhibit the activity of some acid-sensitive bacteria, resulting in a decrease in bacterial diversity (Li et al., 2024). However, MPs didn't change the bacterial diversity in fluvo-aquic soil. This may be because soil system has a certain buffering and self-purification capacity to mitigate the interference of pollutants (Tang et al., 2023). Additionally, the high content of carbon and phosphorus in fluvo-aquic soil can provide sufficient metabolic substrate for microorganisms to maintain the stability of bacterial diversity through metabolic redundanc (Meng et al., 2023).

In our study, MPs altered the abundance of soil dominant bacterial phyla and specific bacterial genera. The most dominant bacteria phylum Chloroflexi in red soil increased under MPs treatment, and the abundance in PE treatments was higher than that in PLA treatment. Compared to PE treatments, Proteobacteria were more abundant in PLA-treated soils, especially at high doses. It has been reported that Proteobacteria plays a key role in soil biochemical geoprocesses, and its increased abundance implied that some bacterial genera belonging to this phylum may have the ability to degrade PLA (Sharma et al., 2022; Wang et al., 2022b). For example, *Pseudarthrobacter* is a known bacterium that can degrade MPs, which belongs to Proteobacteria (Chung et al., 2022). By contrast, MPs decreased Firmicutes and Actinobacteria, possibly due to their poor tolerance to MPs (Zhang et al., 2024). At the genus level, PE enriched *Actinospica*, *Sinomonas* and *FCPS473*, and PLA enriched *Catenulispora* and *Dyella* in red soil (Fig. 3E and F). Differently, PE enriched *Pontibacter* and *Stenotrophobacter*, and PLA enriched *Nocardia* and *Stenotrophobacter* in fluvo-aquic soil. These specific bacterial genera were crucial to the response to MPs, and they may mitigate the detrimental impacts of MPs on soil systems by shaping microbial structure (Qi et al., 2024; Xiao et al., 2022). The clay mineral content in different soil types may alter the adsorption and migration of MPs, leading to the enrichment of specific microorganisms. For example, red soil usually contains more iron and aluminum oxides and kaolinite, which may affect the distribution and degradation of MPs through surface adsorption or electrostatic action (Zhao et al., 2023). Fluvo-aquic soil may contain more montmorillonite or illite, and the expansibility and cation exchange capacity of these minerals may affect the migration and bioavailability of MPs (Zhang et al., 2023a). In addition, the biofilm formed on the surface of MPs can also induce colonization of specific microorganisms (Zheng et al., 2023).

4.4. Changes of microbial assembly and co-occurrence

Previous studies have confirmed that environmental pollutants interfere with the microbial assembly process (Fang et al., 2024; Yan et al., 2023). Stochastic process usually means higher nutrient levels and more available resources in soil (Zhou et al., 2014). Stochastic processes in the control group may be related to the higher N and P contents, which provide rich resources available to the microbes (Hou et al., 2021). MPs caused selective pressure on the microbial community, which prompted the microorganisms to alter their original assembly processes, leading to an increase of deterministic processes (Sun et al., 2021). PE was more tended to alter the stochastic/deterministic balance compared to PLA, increasing the microbial deterministic processes, which might be related to the degradability of PLA (Rosli et al., 2021). MPs as exogenous additives was a deterministic ecological force, and microorganisms could counteract some of the MPs stress through interrelationships with soil environmental factors and co-occurrence patterns (Fang et al., 2024). As shown in Fig. 6, the rise in urease activity may also increase the deterministic process, possibly because urease stimulated certain microbes such as *Sinomonas* and *FCPS473*. The assembly of soil microorganisms was more affected by homogeneous dispersal, and the increase of drift process in fluvo-aquic soil may be a potential factor for the differences in soil microbial communities.

Microbial interactions impact soil systems' stability and complexity in addition to the different relationships among community members (Cui et al., 2024). Because bacterial species under environmental stress have less functional redundancy and succession, PLA in our study lowered bacterial complexity (Gao et al., 2021). The depolymers and degradation products of PLA can also blunt the executive cooperation of the associated microorganisms, resulting in reduced network complexity (Wang et al., 2024c). However, PE had opposite effects on network complexity in the two soils. The results may be partially explained by the considerable pH difference between the two soils, which had a significant impact on microbial building and interactions (Gai et al., 2024). Furthermore, the two soils' composition and organic matter concentration differed, which had a further impact on MP behavior. Through surface interaction with MPs, organic matter can influence the stability of microbial communities (Liu et al., 2024). As MP dose increased, the percentage of bacterial networks with positive correlations declined, indicating that low-dose MPs induced more cooperative bacterial relationships. Cooperation among bacteria can improve soil buffering effectiveness and assist the bacterial community withstand MPs stress (Fang et al., 2024). In this case, the coexistence of bacterial taxa may be disrupted by high-dose MPs, which may have a bigger impact on soil.

4.5. Environmental drivers affecting bacterial community structure

The db-RDA results showed that DOC was a common factor influencing bacterial communities in different soils. This observation seems plausible since MPs can increase the soil carbon content, thus facilitating the carbon cycling process and inducing the distribution and composition of microorganisms (Rillig et al., 2021). Soil pH was considered to be an important determinant of soil bacterial community structure (Gai et al., 2024). This aligns with our results, which identified pH as the key factor influencing bacterial communities in fluvo-aquic soil. Differences in soil configuration are the main reason for the inconsistency of the driving forces in the two soils (Xu et al., 2022). In our study, soil properties had a higher interpretation of bacterial community than enzyme activities, indicating a strong correlation between soil properties and bacterial community. It has been reported that MPs can regulate the response of soil systems to environmental stress (Zettler et al., 2013). Soil enzyme activities were significantly correlated with the complexity and stability of the bacterial community under PE treatments, while there was no significant correlation between the two under PLA treatments, which further indicated that PLA interfered more with the bacterial community. PLA may be degraded, and the secondary effects of degradation intermediates may cause significant changes in microbial communities (Ainali et al., 2022). Other soil properties were also positively or negatively correlated with bacterial communities, which indicated that MPs-induced habitat modification indirectly affected changes in bacterial communities (Feng et al., 2022). Overall, the driving effect of environmental factors on bacterial communities may help to alleviate the disturbance of MPs to soil ecosystems.

4.6. Microbial function in different soils

FAPRPTAX analysis showed that chemoheterotrophic functional bacteria were dominant in both soils and were strongly influenced by PLA. Chemoheterotrophic microorganisms play an important function in ecosystems, and their energy mainly comes from the oxidative decomposition of exogenous organic matter (Osman et al., 2024). There may be some degradation of PLA providing a relatively adequate carbon source for these microorganisms. Cellulolysis increased under MPs treatments and was highly enriched in high doses of PLA. Zhuang et al. (2021) reported that cellulolysis function could promote the breakdown of cellulose into monosaccharides and use it as a biomass resource available to microorganisms. It was inferred that MPs interfered with the soil carbon cycle. Furthermore, the result that high-dose PLA significantly increased DOC content was consistent with the change in cellulolysis. In our study, MPs had an inhibitory effect on ureolysis and PLA had a stronger inhibitory effect on ureolysis. This result confirmed that MPs had an effect on the nitrogen cycle because ureolysis was associated with the hydrolysis of urea to carbon dioxide and ammonia (Zhang et al., 2024). Different MPs had varying effects on the nitrogen cycle, as evidenced by the various alterations in nitrogen cycle function. PLA0.1 treatment in the fluvo-aquic soil was significantly enriched in human pathogens, probably due to the fact that low-dose PLA were more easily degraded in alkaline soil thus producing smaller particles that led to the aggregation of pathogens (Qi et al., 2024). The acidic environment of red soil was generally unsuitable for the survival and proliferation of human pathogens, which may explain why MPs reduced the functionality of human pathogens in red soil. Additionally, when MPs interacted with clay particles, the heavy, clay-rich texture of red soil, in combination with inadequate aeration, probably improved pathogens adsorption and immobilization, limiting the proliferation of human infections (Zhang et al., 2024).

5. Conclusion

We novelly found that MPs differently induced the changes in the contents of DOC, inorganic N, AP, pH and EC in two soils, but promoted the rise of soil enzyme activities. The differences in soil properties and enzyme activities mainly depended on soil type and MPs dose, respectively. The microbial diversity of MPs treatments decreased significantly in red soil, but didn't change significantly in fluvo-aquic soil. Furthermore, MPs altered microbial community composition and colonized specific bacterial taxa in different soils. In the microbial assembly process dominated by stochastic process, MPs promoted the increase of deterministic process, especially in red soil. Compared to PE, PLA MPs exhibit less microbiological complexity. Soil properties and enzyme activities were significantly correlated with microbial community composition, assembly and co-occurrence. Soil DOC and pH were key drivers of microbial structure in red and fluvo-aquic soils, respectively. Moreover, perturbation of the microbial community also altered the metabolism-related functions. Our results showed that the driving effects of different types and doses of MPs on microbial community structure and assembly varied by soil types. This study can help to asses the environmental threats of MPs to different soil ecosystems.

In conclusion, this study advanced our understanding of how MPs alter soil ecosystems by providing a comprehensive analysis of their impacts on microbial communities, soil properties, and enzyme activities across different soil types. The unique contributions of this work include the comparative analysis of red soil and fluvo-aquic soil, the exploration of dose- and type-dependent effects of MPs, and the identification of key environmental drivers (DOC and pH) that mediate microbial responses. Our findings highlighted the importance of considering soil-specific factors when assessing the ecological risks of MPs, providing critical insights for the development of targeted mitigation strategies in diverse agricultural systems.

CRediT authorship contribution statement

Qingjie Li: Writing – original draft, Formal analysis. **Xiaoxing Wang:** Software. **Jiaqi Zhang:** Formal analysis. **Xueqi Guo:** Software, Data curation. **Yanli Li:** Methodology, Conceptualization. **Okbagaber Andom:** Writing – review & editing. **Zhaojun Li:** Writing – review & editing, Funding acquisition.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121672.

Data availability

Data will be made available on request.

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