Effects of different microplastics on the activation of soil potassium by exomycorrhizal fungi

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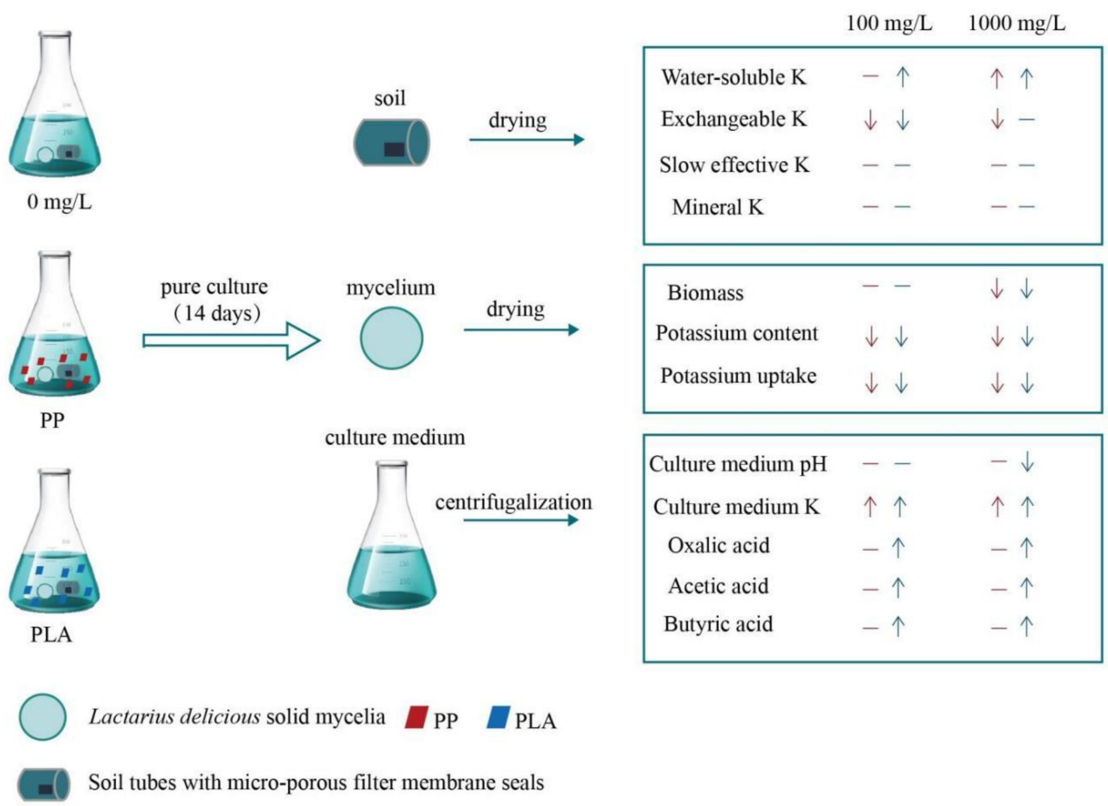
GRAPHICAL ABSTRACT



The (↑), (↓) and (—) represent up-regulation, down-regulation and no significant change in each parameter compared with the 0 mg/L MPs treatment group, respectively. Different colors represent the effects brought by different types of MPs treatment, red represents PP and blue represents PLA.

ABSTRACT

In this study, the ectomycorrhizal fungus *Lactarius deliciosus* (Ld) was used as the experimental strain, and polypropylene (PP) and polylactic acid (PLA) were used as experimental microplastics (MPs) to investigate the influence of MPs on the ability of ectomycorrhizal fungi to activate soil insoluble potassium (K). The results showed that both two types of MPs caused negatively affect to the growth of Ld, and PLA has a stronger inhibitory effect. Moreover, with increasing MPs concentration, the content of soil available K exhibited an initial decrease followed by a subsequent increase. Compared with blank group, the content of soil available K in 100 mg/L PP and PLA group decreased by 27.57% and 27.33%, respectively. However, high concentrations of MPs had a relatively minor impact on the content of soil available K, which may be attributed to the fact that the high concentrations of MPs stimulated Ld to secrete large amounts of organic acids and protons to relieve environmental stress, thus promoting the activation of soil insoluble K to a certain extent. In addition, the content of K in the soil mineral structure decreased, and the content of soil slow-released K increased, but the variation trend weakened with the addition of MPs. These results not only reveal the effect of MPs pollution on soil insoluble K activation by ectomycorrhizal fungi but also provide an important theoretical basis for the development of ecological control strategies.

Keywords: Microplastics (MPs), ectomycorrhizal fungi, organic acids, soil potassium

1. Introduction

With the advancement of global industrialization and urbanization, plastic products have already become an indispensable part of people's lives. The problem of microplastic pollution caused by this has also become increasingly serious. Microplastics (MPs) are plastic particles with a diameter of less than 5 mm that are widely distributed and difficult to degrade (Wright *et al*., 2017). Owing to these characteristics, MPs easily accumulate in organisms and are transmitted through the food chain, posing a substantial risk to the environment and ecological security, and have been identified by the United Nations Environment Program as among the top ten emerging pollutants (Auta *et al*., 2017).

In recent years, research on microplastics (MPs) has mainly focused on their sources, distribution, migration, and their ecological toxicological effects in aquatic ecosystems, while few researchers have paid attention to their environmental behaviors in terrestrial ecosystems (Shuli *et al*., 2023; Ahsan *et al*., 2023). It is worth noting that Zhang *et al*. (2024) conducted a survey of different agricultural systems in the North China Plain of China and found that the MPs in the soil could reach up to 3.7×10^4 items/kg, which is 4 to 23 times the number of MPs in the marine environment. This highlights the severity of the land-based MPs pollution problem. The entry of MPs into the soil ecosystem can alter soil physicochemical properties, including permeability, ion concentration, moisture content, and pH. (Wang *et al*., 2022; Alhadede *et al*., 2025). Han *et al*. (2024) found that MPs such as polyethylene (PE) and polylactic acid (PLA) increased the proportion of microaggregates while reducing the size of larger aggregates, thereby compromising soil structural stability and weakening its water-holding capacity. Furthermore, Yüze *et al*. (2023) found in their study that traditional MPs such as polypropylene (PP) accelerated the loss of organic carbon in the soil, thereby reducing microbial biomass and the stability of the coexisting network. Meanwhile, Wang *et al*. (2024) conducted research and found that MPs can reduce the expression of the *amoA* gene in ammonia-oxidizing microorganisms, inhibit the nitrification process, and thereby interfere with the soil nitrogen cycle. These changes all indicate that MPs pollution would affect the key elements of cycling such as carbon (C), nitrogen (N) and potassium (K) in the soil, reduce the diversity of microbial communities, impact the cycling and utilization of substances in the soil, and ultimately inhibit plant growth. Therefore, evaluating the environmental risks of MPs on the biogeochemical cycle of the soil is of great significance.

K is an essential mineral element for plant growth, playing an important role in various physiological processes such as photosynthesis and plant oxidative stress (Tiwari *et al*., 2025). The forest soils in southern China are distributed mainly in mountainous areas, with thin and highly weathered soil layers, suffering from severe K deficiency without additional K sources. Therefore, the activation and utilization of insoluble K in the soil is particularly important for forest plants. The research conducted by Muhsin *et al*. (2025) revealed that the availability of K in the soil is significantly positively correlated with the biomass of plant roots, which is a key factor driving the soil element cycle. Mycorrhiza is a symbiotic structure formed by ectomycorrhizal fungi and plant roots, and it is an important component of forest ecosystems. The epitaxial hyphae, mantles and Hartig's mesh produced by mature ectomycorrhizae are entangled and wrapped around the surface of the vegetative root and the intercellular spaces of the cortex, not only changing the morphology and structure of the root system to increase the absorption surface area but they can also enter soil cavities smaller than root hairs and absorb K ions at extremely low concentrations in the environment, thereby improving the acquisition of limiting mineral nutrients by plants (Genre *et al*., 2020). Shahid *et al*. (2023) discovered in the calcareous soil of the northern forest that ectomycorrhizal fungi drive the mycelium to move in the deep mineral layer through the process of photosynthetic carbon allocation, significantly enhancing the activation of mineral elements such as magnesium (Mg) and K and the absorption efficiency of plants. Owing to the strong adhesion and high surface area of the MPs particles, they easily bind to the polysaccharide mucus and organic acids produced by the mycorrhizal symbionts and affect the normal metabolic activities of the symbionts (Leifheit *et al*., 2021), which ultimately affects the uptake, activation and utilization of insoluble K in the soil by ectomycorrhizal fungi (Eduardo *et al*., 2021; Sutariati *et al*., 2025). Xia *et al*. (2024) reported that when ectomycorrhizal fungi were exposed to high concentrations of nonbiodegradable PP and polystyrene (PS), their growth was significantly inhibited when they secreted organic acids and hydrogen ions also significantly decreased, which in turn significantly weakened the activation of inorganic phosphorus (P) in soil.

Studies have shown that 2% PLA can significantly reduce the content of available K in soil and severely inhibit the uptake and use of K by plants (Huang *et al*., 2023). Furthermore, studies have shown that increasing concentrations of PP progressively inhibit the uptake and utilization of essential nutrients—such as N, P, and K—by corn seedling roots, leading to a significant reduction in root and shoot biomass. (Martine *et al*., 2023). However, the mechanism underlying the effects of different types of MPs on the activation of insoluble K by soil fungi is unclear and rarely reported. Therefore, in this study, *Lactarius deliciosus* (Ld) was used as the test strain, with soil as the sole K source, to study the effects of two different types of MPs on the biomass of ectomycorrhizal fungi, organic acid secretion, and available K in the soil. The purpose of this study was to provide a theoretical basis for evaluating the toxic effects of MPs on ectomycorrhizal fungi and their capacity of K activation.

2. Materials and methods

2.1. Test materials

The ectomycorrhizal fungus *Lactarius deliciosus* used in this study was preserved in the Microbiology Laboratory of the School of Chemistry and Bioengineering, Taizhou College, Nanjing

Normal University, and was originally collected from a *Pinus massoniana* forest in Jinyun Mountain. Potassium-free Pachlewski solid medium was used and activated at a constant temperature of 25 °C for 14 d. The composition of the medium was as follows: 0.5 g/L $C_4H_{12}N_2O_6$, 1 g/L NaH_2PO_4, 0.5 g/L $MgSO_4$, 20 g/L glucose, 0.1 g/L vitamin B_1, 1.0 mL/L trace element mixture solution (containing 8.45 mg H_3BO_3, 5 mg $MnSO_4$, 6 mg $FeSO_4$, 0.625 mg $CuSO_4$, 2.77 mg $ZnCl_2$ and 0.27 mg $(NH_4)_2MoO_4$ per liter), agar 15 g to 20 g; Shake and heat the container until the solute is completely dissolved, adjust the pH to 5.5, make up the volume to 1 L with deionized water, and steam sterilize at 121 °C for 30 min.

The soil used in the test was red soil developed on acid magmatic rocks and sedimentary rocks and was collected from the bottom soil of the Masson pine forest in the Renhuang Mountain Scenic Area in Wuxing District, Huzhou city, Zhejiang Province. The soil pH was 4.73, the organic matter concentration was 17.90 g/kg, the total nitrogen concentration was 0.31 g/kg, the total K concentration was 18.20 g/kg, and the available K concentration was 104.38 mg/kg. The air-dried soil samples were ground and passed through a 100-mesh sieve. Afterward, 1.00 g of soil was placed in the middle of a 1 cm diameter plastic tube with both ends open. Then, glass fibers were inserted into both ends to hold the soil in the middle. Finally, both ends were sealed with 0.22 μm pore size microporous filters. They were placed in an autoclave and subjected to high-pressure steam sterilization at 121 °C for 120 min. During the cultivation of ectomycorrhizal fungi, a plastic tube contained with soil was placed into the liquid medium. Water molecules, MPs, inorganic ions, and organic acids can freely enter and exit, but the soil does not enter through the filter membrane.

Polypropylene (PP) and polylactic acid (PLA) powders were purchased from Dongguan Huachuang Plastic Raw Material Firm. As observed using a scanning electron microscope (Gemini Sigma 300, ZEISS company, Germany), the two MPs both had irregular shapes (Figure 1A-B), the surface functional groups of the microplastic particles were analyzed by Fourier transform infrared spectrometry (Alpha II, BRUKER company, USA) in the range of 4000-500 cm^{-1} with a resolution of 4 cm^{-1}, confirming that the two types of MPs were PP (Figure 1C) and PLA (Figure 1D). The particle size distributions of the two MPs were measured using a laser particle size measuring instrument (Zetasizer Nano ZS90, Malvern Panalytical Company, UK). The particle sizes of the 500 mesh PP and PLA were 1.67 ± 0.035 μm and 1.62 ± 0.034 μm (Figure 1A-B). On an ultraclean bench, the two MPs powders were reconstituted with sterile water to prepare a mother solution at 10 g/L.

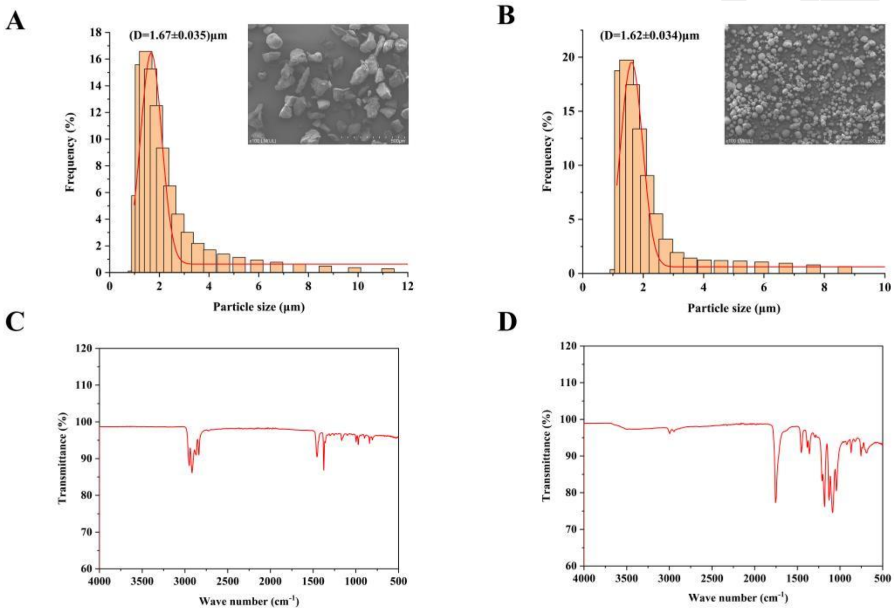


Figure 1. SEM image and particle size map of PP (A); SEM image and particle size map of PLA (B); PP IR spectrum (C); PLA IR spectrum (D)

2.2. Experimental design

Under ultraclean bench conditions, a specific volume of the two MPs mother solutions (10 g/L) was added to sterilized K-deficient Pachlewski liquid medium (the NaH_2PO_4 was replaced with KH_2PO_4), were subjected to ultrasonic dispersion treatment before and after dilution to prepare K-free Pachlewski liquid media with MPs concentrations of 0, 100, and 1000 mg/L (pH 4.2). Afterward, 30 mL of the abovementioned media was added to 150 mL Erlenmeyer flasks, and the same sterile plastic tube filled with soil was added to each Erlenmeyer flask. Finally, one block of agar bacteria with a diameter of 6 mm was placed in each bottle. The liquid medium without inoculation, without MPs but with only one soil plastic tube was set as the control group. The rest of the treatments were the same as the inoculation treatment, and each treatment was repeated five times. After the inoculation, the inoculated media were placed in static culture at 25 °C for 14 days, after which the relevant indicators were measured.

2.3. Measurement items and methods

At the end of the cultivation, the hyphae were filtered, and the filtrate was collected. The pH value of the culture solution was measured with a digital pH meter and determined the content of K in the culture solution using a 6400A type flame photometer (Shanghai Precision Scientific Instruments Co., Ltd.). The biomass was determined after the hyphae were dried (105 °C). In addition, the content of K of dried mycelia was determined by flame photometry after wet digestion with concentrated sulfuric acid-hydrogen peroxide (Gatica-Saavedra *et al*., 2022). The soil in the plastic tube was removed and air-dried naturally. The water-soluble K, exchangeable K and slow-release K in the soil were extracted with distilled water, ammonium acetate (1 mol/L) and boiling nitric acid (1 mol/L), respectively. After the extraction of the above solutions, solid sodium hydroxide was added to the soil, and the mixture was fused in a muffle furnace at 450 ℃ to obtain mineral-structured K. Finally, the content of K was determined by flame photometry (Bai *et al*., 2020).

The content of organic acids in the cultures was determined using a high-performance liquid chromatographer (HITACHI, Japan). The chromatographic conditions were as follows: Diode Array L-7455 UV detector, Ion-300 column for organic acid analysis (Phenomenex, Torrance, CA, USA), mobile phase: 2.5 mmol/L sulfuric acid, flow rate: 0.5 mL/min, injection volume: 20 μL of sample solution, UV detection wavelength: 210 nm, column temperature: 35 °C, and pressure: 450 psi. The organic acids measured included oxalic acid, formic acid, acetic acid, succinic acid, and citric acid.

2.4. Data processing

Microsoft Excel 2013 software was used for data collation and basic calculations. Univariate (ANOVA) analysis was performed using IBM SPSS 19 software. The significance of the difference among the treatments was analyzed using Duncan's multiple comparison test (P < 0.05). The histogram, violin plot, and correlation heatmap were constructed by Origin (2021b).

3. Results and analysis

3.1. Effects of MPs on the biomass, content of K and K uptake of exomycorrhizal fungi

After standing in liquid culture for 14 days, the effects of the two types of MPs on the biomass of Ld are shown in Figure 2A. Compared with the 0 mg/L MPs treatment group, the 100 mg/L MPs treatment group had no significant inhibitory effect on Ld biomass. However, under the 1,000 mg/L MPs treatment, the Ld biomass decreased significantly, and the inhibition was most obvious under the PLA treatment, with a decrease of 40.11%.

The effects of the two types of MPs on the content and uptake of K in Ld hyphae are shown in Figure 2B-C. With respect to Ld exposed to the two kinds of MPs, the content of K and amount of K absorbed by hyphae showed similar trends as a function of MPs mass concentration. However, two types of MPs caused the significantly variation trends of the content and absorbed amount of K. Compared with those in the 0 mg/L MPs treatment group, the content and uptake capacity of K in Ld hyphae gradually decreased in the PP treatment group with increasing mass concentration, with the most significant decrease occurring in the 1000 mg/L treatment group, whose values decreased by 83.31% and 88.64%. In the PLA treatment group, as the mass concentration increased, the content and uptake capacity of K in Ld hyphae first decreased but then increased, with the most significant decrease occurring in the 100 mg/L treatment, with decreases of 80.01% and 80.92%, respectively.

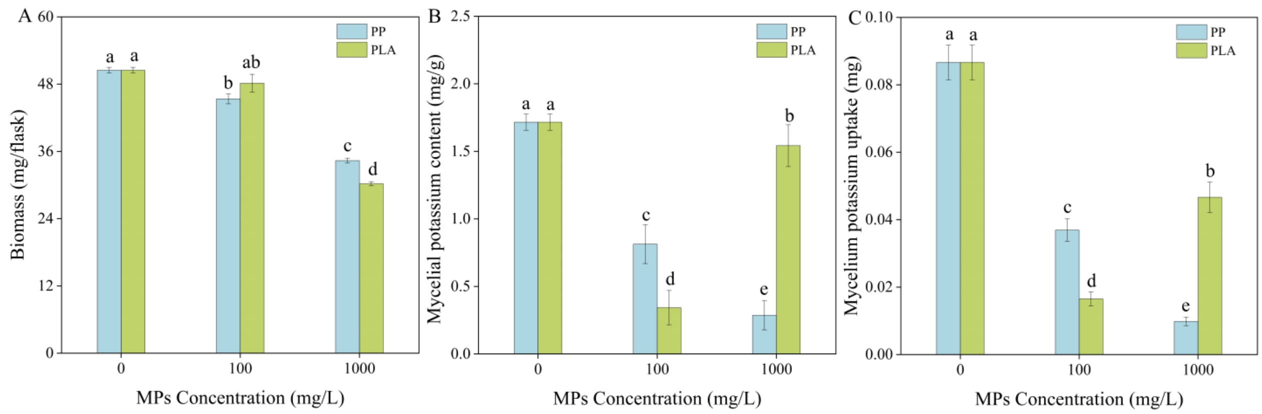


Figure 2. Effects of two MPs on Ld biomass (A), potassium content (B), and potassium uptake (C)

Note: Duncan's post hoc test showed that different lowercase letters indicate significant differences ($P < 0.05$).

3.2. Effects of MPs on the secretion of organic acids and the pH of the culture solutions

3.2.1. Effect of MPs on the release of organic acids from exomycorrhizal fungi

According to Table 1, after static culture for 14 days, five organic acids including oxalic acid, formic acid, acetic acid, succinic acid and citric acid were detected in the liquid medium. Among them, the secretion amount of oxalic acid was the highest, while that of citric acid was the lowest. A small amount of oxalic acid was also detected in the cultures not inoculated with Ld (control group), but the content was so low that it could be ignored. Under PP contamination, with increasing mass concentration, the contents of various acids in the culture medium tended to gradually increase. Among them, when exposed to the highest concentration (1000 mg/L) of PP treatment, the content of oxalic acid and total organic acid is the highest. Under PLA contamination, as the mass concentration of PLA increases, the contents of oxalic acid, acetic acid and total acid first decrease and then increase in the culture medium. Therefore, it can be speculated that the type of MPs may affect the release of organic acids by ectomycorrhizal fungi.

3.2.2. Changes in the pH of the liquid medium

After standing for 14 days of Ld culture, the pH of the culture solution tended to first increase but then decrease with increasing mass concentration of the MPs, and the pH values of all the treatment groups were slightly lower than that of the control group (Figure 3). In comparison, the pH of the culture solution decreased most significantly when the cells were exposed to high concentrations (1000 mg/L) of two MPs (PP and PLA), with decreases of 3.98% and 4.48%, respectively.

Table 1. Effects of different types of MPs on the secretion of Ld organic acids (mg/L)

Treatment	Concentration (mg/L)	Oxalic acid	Formic acid	Acetic acid	Citric acid	Butyric acid	Total organic acid
Control	0	0.83e	ND	ND	ND	ND	0.83e
	0	70.96c	3.29ab	8.99b	2.40ab	5.56b	91.21c
PP	100	71.50c	3.43ab	9.48ab	2.77a	5.81b	92.98c
	1000	83.08a	3.80a	10.03a	2.80a	6.28a	105.99a
	0	70.96c	3.29ab	8.99b	2.40ab	5.56b	91.21c
PLA	100	65.72d	3.91a	8.20c	2.58ab	5.67b	86.08d
	1000	76.60b	3.73a	10.09a	2.86a	6.11ab	99.38b

Note: Duncan's post hoc test revealed that different lowercase letters in the same column indicated significant differences ($P < 0.05$); ND indicated that no relevant organic acid was detected in the solution.

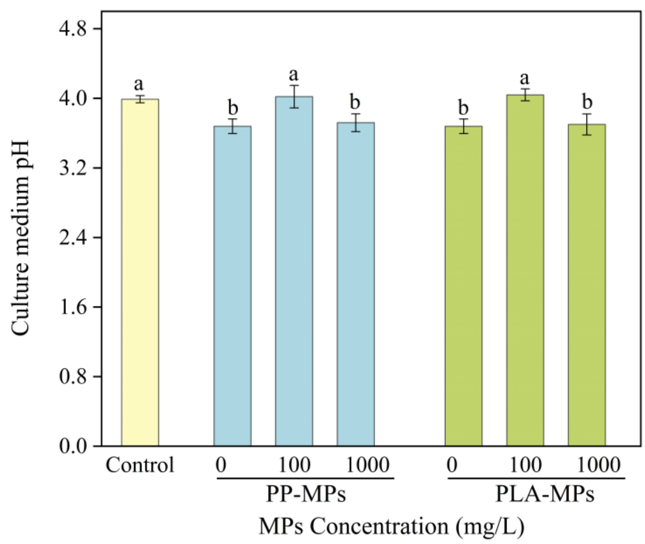


Figure 3. Effect of different types of MPs on the pH of the culture solution

Note: Duncan's post hoc test revealed that different lowercase letters indicated significant differences among the various treatment groups ($P < 0.05$).

3.3. Changes in potassium content in the cultures

In the culture medium, the content of K in the control group was the lowest at 0.47 μg/mL (Figure 4). The content of K of the culture fluid changed differently under the influence of different MPs. Under the PP treatment, the mass concentration of MPs was positively correlated with the content of K of the culture solution, whereas under the PLA treatment, as the mass concentration increased, the content of K in culture solution first increased but then decreased. The content of K in media changed the most significantly under the 1000 mg/L PP and 100 mg/L PLA treatments, whose contents increased by 210.40% and 159.46%, respectively, compared with those in the 0 mg/L treatment group.

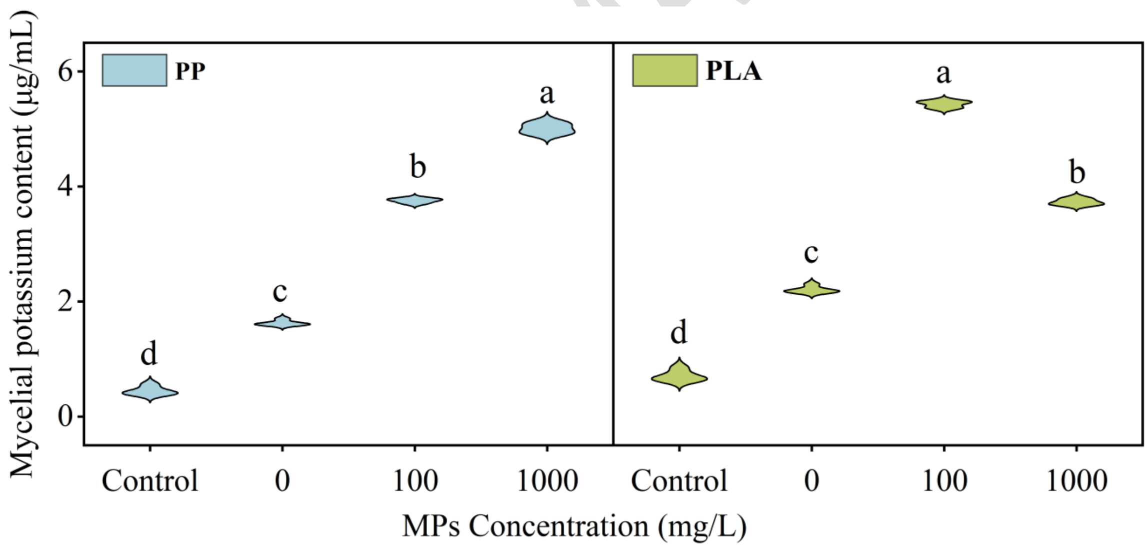


Figure 4. Effects of different types of MPs on the potassium content in the cultures

Note: Duncan's post hoc test revealed that different lowercase letters indicated significant differences among the various treatment groups ($P < 0.05$).

3.4. Effects of ectomycorrhizal fungi on the contents of different forms of K in soil under the influence of MPs

The addition of different types and different concentrations of MPs to the culture solutions had different effects on the activation of soil K by Ld see Table 2. Compared with that in the 0 mg/L MPs treatment group, the water-soluble K in the soil of1000 mg/L PP and 100 mg/L PLA treatment groups increased significantly, by 86.24% and 53.76% respectively; Secondly, under the conditions of 100 mg/L PP and 100 mg/L PLA treatments, the exchangeable content of K in the soil significantly decreased, dropping by 41.35% and 44.54% respectively; Meanwhile, under the 100 mg/L PP treatment, the content of soil slowly available K decreased by 9.40%. In addition, compared with that in the control group, the content of K in the mineral structure in each treatment group decreased, indicating that this portion of the K was converted to other forms.

The water-soluble K and exchangeable K in soil are together called available K, which is the portion of K that can be directly absorbed and utilized by plant systems. As shown in Table 2, the content of soil available K increased in response to inoculation with ectomycorrhizal fungi but decreased to varying degrees in response to MPs contamination. Compared with the control group, the content of soil available K decreased most significantly under the influence of a low concentration (100 mg/L) of MPs, with decreases of 27.57% and 27.33%, respectively.

Table 2. Effect of different types of MPs on the activation of soil K by Ld

Treatment	Concentration (mg/L)	Water-soluble K (mg/kg)	Exchangeable K (mg/kg)	Slow effective K (mg/kg)	Mineral K (mg/kg)	AK (mg/kg)
Control	0	6.13b	47.25b	231.45cd	17885.17a	53.38b
	0	4.65c	57.07a	261.34a	17711.94ab	61.72a
PP	100	5.19bc	33.47c	236.78c	17744.56ab	38.66c
	1000	8.66a	49.7b	245.56b	17706.08ab	58.36ab
	0	4.65c	57.07a	261.34a	17711.94ab	61.72a
PLA	100	7.15ab	31.65c	243.21b	17745.99ab	38.79c
	1000	6.99ab	53.69ab	242.34b	17735.98ab	60.68a

Note: Duncan's post hoc test revealed that different lowercase letters in the same column indicated significant differences ($P < 0.05$).

3.5 Correlations of each factor

After 14 days of culture, according to the Pearson correlation, the correlation between the content of soil available K and exchangeable K ($P < 0.001$) was significant positive, which was negative with soil pH ($P < 0.05$); and the soil mineral structure K was significantly negatively correlated with the content of oxalic acid content and total acid ($P < 0.001$) (Figure 5). These results suggest that oxalic acid is the main organic acid secreted by ectomycorrhizal fungi and that the secreted organic acids reduce the pH of the environment. Environmental changes are conducive to the transformation of soil insoluble K into directly available K to plants.

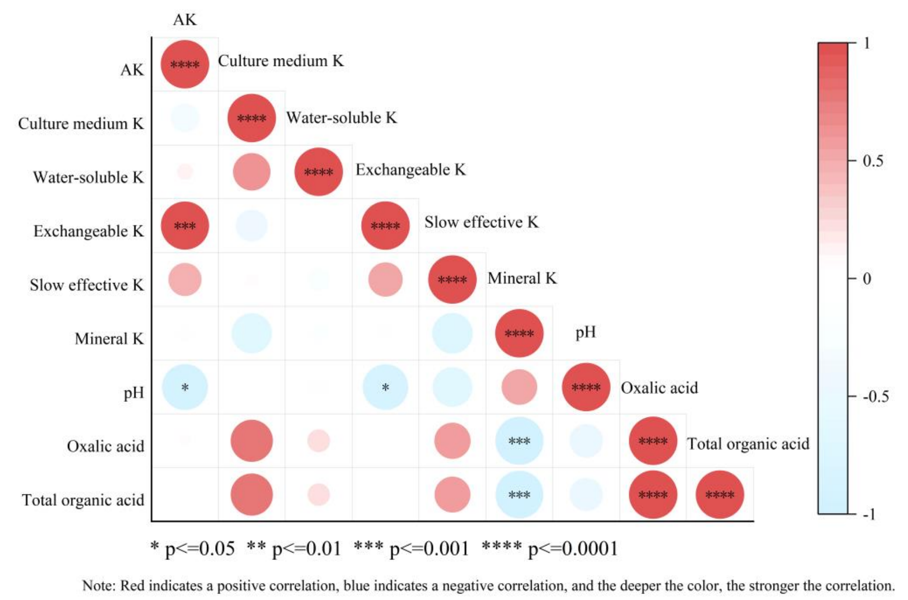


Figure 5. Correlation coefficients of soil potassium cycling factors

4. Discussion

As an important component of forest ecosystems, mycorrhizal fungi can form mycorrhizal symbiosis with over 90% of terrestrial plants, helping them absorb nutrients and enhance stress resistance (Martin *et al*., 2024). However, the latest research indicates that changes in the soil environment, such as MPs pollution, can significantly affect the growth and function of mycorrhizal fungi (Kralj *et al*., 2025). Yu *et al*. (2023) found that when soybeans and corn were treated with polybutylene terephthalate (PBAT) at a concentration of 0.2% to 1%, the root biomass of both would decrease by up to 40% and 61% respectively. Moreover, the smaller-sized MPs would also enter the roots and hinder the transfer of nutrients. Furthermore, studies have shown that high doses (>1%) of MPs weaken the plant's ability to acquire nutrients by disrupting the stability of soil aggregates (reducing it by 25%) and by disrupting the microbial symbiotic network (Al-Muhe *et al*., 2024). Liu *et al*. (2022) found that 32 years of plastic film mulching led to a 64% reduction in the biomass of cotton roots, ultimately resulting in a 38% decrease in cottonseed yield. It is worth noting that Wang *et al*. (2024) found that the nanoplastics released during the mineralization process of degradable MPs could penetrate the cell walls of root cells, trigger oxidative stress responses and increase the activity of superoxide dismutase in wheat roots by 3.2 times. In this study, Ld was cultured in K source-limited media and compared with that in 0 mg/L MPs treatment group, its biomass decreased with increasing microplastic concentration. Moreover, under the treatment with high concentrations of MPs, the reduction in PLA biomass was the most obvious. These findings indicate that the toxic effect of MPs on fungi depends on the dose of MPs and that the biotoxicity of biodegradable MPs, such as PLA, may be stronger than that of PE.

Lattice K is present in the lattice structure of K feldspar and mica and accounts for 90%-98% of the total content of K in soils. Lattice K needs to undergo a slow weathering process to be released, making it difficult for current-season crops to be effectively absorbed and utilized. K-solving microorganisms usually form a complex with plants and activate insoluble K in the soil through a variety of ecological mechanisms for effective use by plants (Sindhu *et al*., 2014). In this study, it was found that after inoculation with ectomycorrhizal fungi, all the experimental groups showed a reduction in the content of mineral-bound K to varying degrees, while the other forms of K increased significantly. At the same time, the intervention of MPs affected the K cycling in the cultivation system. Under the intervention of MPs, the content of K in the culture medium showed an overall upward trend, which was highest under 1000 mg/L PP and 100 mg/L PLA treatments. This indicates that MPs, as an environmental stress factor, may have affected the release process of K in the soil mineral structure. Further analysis of the different K components in the soil revealed that although the content of water-soluble K in the soil increased under the MPs treatment compared to the 0 mg/L MPs treatment group, due to its limited proportion in the total content of K, its contribution to the overall improvement of K effectiveness was relatively small. Compared to the group without introducing MPs but only inoculating Ld, the content of effective K in the 100 mg/L MPs treatment group significantly decreased, while the effect on the content of effective K in the 1000 mg/L MPs treatment group was relatively small. It is also worth noting that there is a significant negative correlation ($P < 0.05$) between the content of available K and the pH value of the soil. Thus, it can be inferred that the hydrogen ions secreted by ectomycorrhizal fungi are one of the key factors driving the release of soil insoluble K. Studies have shown that organic acids in root exudates can dissolve and transform some insoluble minerals through acidification, complexation exchange and reduction processes, achieving the effect of nutrient release and enhancing biological availability (Guo et al., 2007). Therefore, the production of organic acids by ectomycorrhizal fungi can be regarded as an important criterion for evaluating their ability to activate insoluble K.

The effect of MPs on K activation process is likely achieved by regulating the physiological functions of ectomycorrhizal fungi. The type and concentration of MPs jointly affect the stress response pattern of fungi, especially the secretion characteristics of organic acids. This phenomenon is in line with the common stress response mechanisms in the plant kingdom. For instance, Katja *et al*. (2023) confirmed through their research that the stress responses of many plants involve the secretion of organic acids at the root-soil interface. This process can enhance the ability to acquire soil minerals and increase the tolerance of toxic substances. This study found that in the culture medium treated with different concentrations of MPs, various organic acids such as oxalic acid, formic acid, acetic acid, succinic acid, and citric acid were detected, and the secretion of oxalic acid was the highest. Among them, as the quality concentration of MPs increased, the total secretion of organic acids showed different trends depending on the type of MPs, and the acid-producing ability was stronger under the stimulation of PP. Meanwhile, under the high concentration (1000 mg/L) of MPs, the content of oxalic acid and total acid secreted by the fungi was the highest. There was a highly significant negative correlation ($P < 0.001$) between the oxalic acid concentration and the content of K in the mineral structure, supporting its role in promoting K release through acid hydrolysis and complexation of metal ions such as Ca, Al, Fe (Fatima *et al*., 2025). Therefore, under the treatment of high concentrations of MPs, the Ld cells secrete a large amount of organic acids and hydrogen ions to alleviate environmental stress, and at the same time, it plays a promoting role in the activation of soil insoluble K to a certain extent.

5. Conclusion

This study emphasized the effect of soil K activation by exomycorrhizal fungi under the influence of different types of MPs. The results showed that MPs inhibited the growth of exomycorrhizal fungi and that the degree of harm depended on the dose and type. Moreover, exposure to high concentrations of MPs could induce ectomycorrhizal fungi to produce more organic acids to resist the stress of MPs. Although, in the short term, high proton concentrations can promote the conversion of insoluble soil K into available K, the ecological risk posed by MPs should not be underestimated. In summary, our research has demonstrated that under different concentrations and types of MPs pollution, the ability of ectomycorrhizal fungi to activate soil insoluble K is inhibited to varying degrees. Future research should focus on the effects of long-term MPs pollution on K availability in plant–soil microbial systems.

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