Effects of fly ash with different mesh sizes on the physicochemical properties of aeolian sandy soil and the growth of Pakchoi

Junxiang Ren[1,*], Jingjing Zou[1], Chunbin Gun[2]

[1]College of Environmental Science and Engineering, Liaoning Technical University, Fuxin 123000, China
[2]Department of Materials Science and Engineering, Liaoning Technical University, Fuxin 123000, Liaoning, China

Abstract: To rationalize the application of fly ash for aeolian sandy soil improvement, this study used 0–180 mesh, 180–325 mesh, and >325 mesh fly ash as amendments in a pot experiment, determining soil physicochemical properties and pakchoi growth indices to evaluate improvement effects. All fly ash treatments reduced soil bulk density. 180–325 mesh fly ash increased soil permeability coefficient, while >325 mesh fly ash performed best in enhancing water absorption and holding capacity but significantly elevated soil pH, making it unsuitable for large-scale application. 180–325 mesh fly ash mainly improved available nitrogen and total phosphorus, while >325 mesh fly ash enhanced available phosphorus and total potassium. All treatments promoted pakchoi growth, with the most significant effect observed at 10% 180–325 mesh fly ash application ($p < 0.01$).

1 Introduction

Soil is the material basis for national food security and a precious agricultural resource [1]. Aeolian sandy soil, developed from aeolian deposits, is widely distributed in arid and semi-arid regions globally [2]. In China, desertification is severe, with desertified land accounting for 18.03% of the total land area [3], making aeolian sandy soil amelioration crucial for improving soil sustainable utilization, safeguarding regional ecological security, and controlling desertification [4]–[6].

Current aeolian sandy soil amelioration methods mainly include conservation tillage, green manure planting, and soil conditioner application [7], among which conditioners have the advantages of strong targeting and rapid effectiveness. However, conventional amendments are costly and single-functional, creating an urgent need for low-cost, multi-functional alternatives. Fly ash, an industrial by-product from thermal power generation, had an annual output of 899 million tons in 2023; ineffective utilization leads to environmental pollution and resource waste, so its comprehensive utilization is significant for China's ecological protection and economic sustainability.

This study used three fly ash types with different mesh sizes (0–180 mesh, 180–325 mesh, and >325 mesh) as amendments for aeolian sandy soil. By determining soil physicochemical properties before and after treatment, and analyzing pakchoi growth indicators, we clarified the effects of different mesh fly ash on soil amelioration, nutrient availability, and fertility. This study aims to provide a scientific basis for the rational application of fly ash to improve aeolian sandy soil fertility and comprehensive productivity.

2 Materials and Methods

2.1 Experimental Materials

Test The tested soil was collected from farmland in Zhanggutai Town, Zhangwu County, Fuxin City, Liaoning Province (122°55′E, 42°72′N), which is located in the southeastern part of the Horqin Sandy Land. The soil type is mainly aeolian sandy soil. The soil samples were collected in March 2024, with the 0–20 cm surface layer used for the experiment.

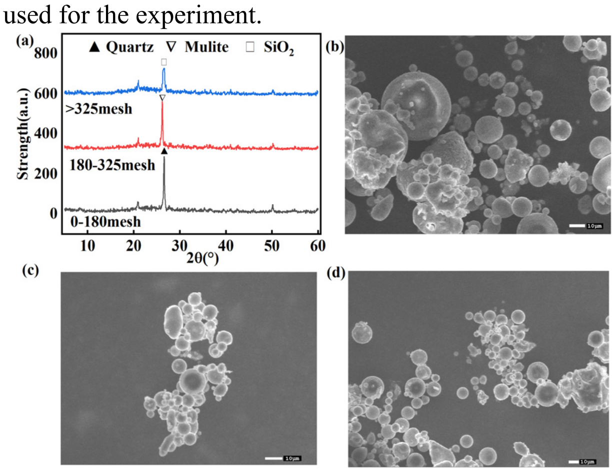

Figure. 1 X-ray diffraction pattern of fly ash (a), scanning electron micrographs of fly ash at 0–180 mesh (b), 180–325 mesh (c), and >320 mesh (d)

*Corresponding Author's Email Address: 17308329807@163.com

The X-ray diffraction patterns and scanning electron micrographs of fly ash with different mesh sizes are shown in Figure 1. As can be seen from Figure 1(a), fly ash of 0–180 mesh exhibits a diffraction peak of quartz (PDF card: 97-003-9830) at 2θ = 26.64°, indicating that 0–180 mesh fly ash is mainly composed of quartz. This fraction has a relatively large particle size, and its morphology is characterized by the coexistence of rough-surfaced quartz particles and porous carbonaceous particles. Fly ash of 180–325 mesh shows a characteristic peak of mullite (PDF card: 15-0776) at 2θ = 26.30°, suggesting that it is mainly composed of mullite. This fraction is dominated by smooth glass microspheres, with mullite encapsulated inside. Fly ash larger than 325 mesh presents a broad and diffuse diffraction peak at 2θ = 20°–30°, indicating that it is mainly composed of amorphous SiO_2. The ultrafine fly ash exists as amorphous glassy microspheres, with morphologies including fine glass microspheres, glass fragments, and agglomerates.

2.2 Experimental Design

The experiment was conducted at Liaoning Technical University (121°66′E, 42°02′N).The region has a typical temperate continental monsoon climate, with an annual average temperature of approximately 6°C and an annual average precipitation of 300–500 mm. A pot experiment was carried out from April to June 2024.The test plant was Brassica chinensis L. (four-season pakchoi), and seeds were purchased from Qingxing Xingyun Seed Industry Co., Ltd. A pot culture method was used to investigate the effects of fly ash with different mesh sizes and application rates on aeolian sandy soil.Five application gradients were set: 0 (CK), 5%, 10%, 20%, and 40%, Plastic pots with an upper diameter of 20 cm, a bottom diameter of 10 cm, and a height of 17 cm were used as cultivation containers. Filter paper was placed at the bottom of each pot to prevent soil loss. The soil and fly ash were mixed uniformly. Each pot was filled with 2 kg of dry aeolian sandy soil. The mixture was thoroughly moistened with water at one time according to the saturated water content of the formula, and then water was supplemented every three days using the weighing method, with the amount of water calculated based on the weight difference, with a total of 13 treatments, and each treatment was performed in triplicate.The experimental period was 60 days. Twenty-five pakchoi seeds were sown uniformly in each pot (10 holes, 2 seeds per hole).Seedlings were thinned to 5 plants per pot on the 7th day after sowing. Data sorting and calculation were performed using Microsoft Excel 2018.Analysis of variance (ANOVA) and correlation analysis were conducted using SPSS Statistics 27, and Duncan’s multiple range test was used for significance testing.All figures were plotted using Origin 2021 software.

2.3 Experimental Methods

Soil total nitrogen content was determined by the Kjeldahl method. Alkali-hydrolyzable nitrogen content was measured using the alkaline hydrolysis diffusion method. Total phosphorus content was determined by alkali fusion-molybdenum antimony anti-spectrophotometry. Available phosphorus content was measured by sodium bicarbonate extraction-molybdenum antimony anti-spectrophotometry. Total potassium content was determined by NaOH-flame photometry. Available potassium content was measured using CH_3COONH_4 extraction-flame photometry. Soil pH was determined with a glass electrode at a water-to-soil ratio of 5:1. Soil bulk density and permeability coefficient were determined using the cutting ring method. All measurements were performed in replicates, and the mean values were reported.

3 Results and Discussion

3.1 Effects of Fly Ash Addition on the Physical Properties of Aeolian Sandy Soil

As shown in Figure 2(a), all three types of fly ash with different mesh sizes reduced the bulk density of aeolian sandy soil, and the reduction magnitude was positively correlated with the application rate.The application of 40% fly ash of 180–325 mesh and >325 mesh produced the most significant reduction in bulk density, decreasing by 0.21 $g\cdot cm^{-3}$ and 0.26 $g\cdot cm^{-3}$ compared with the control group (CK), respectively, with significant differences ($p < 0.05$).Fly ash >325 mesh exhibited the best effect in reducing soil bulk density, followed by 180–325 mesh fly ash. This was mainly attributed to the differences in particle size and mineral phase composition among the three size grades, leading to different reconstruction mechanisms of aeolian sandy soil.Fly ash of 0–180 mesh mainly consisted of quartz and residual carbon, with high compactness and low porosity.Due to its large particle size, it mainly functioned to reconstruct the soil skeleton when mixed with aeolian sandy soil, resulting in a relatively weak effect on bulk density reduction. Fly ash of 180–325 mesh was dominated by smooth glass microspheres embedded with mullite crystallites, with moderate particle gradation and medium porosity.It effectively diluted the original solid phase of aeolian sandy soil and thus significantly reduced the bulk density. Fly ash >325 mesh was mainly composed of amorphous glassy phases and fine mullite crystals, characterized by large specific surface area, electrostatic agglomeration between particles, and high porosity.However, its extremely fine particle size led to the blockage of macropores at high application rates, so its effect on reducing bulk density was only slightly higher than that of 180–325 mesh fly ash.

All three types of fly ash exerted significant effects on the permeability coefficient of aeolian sandy soil. As shown in Figure 2(b), 0–180 mesh fly ash had the weakest effect on the permeability coefficient, whereas 180–325 mesh fly ash caused the greatest change and significantly improved soil permeability. At a 40% addition rate, the permeability coefficient increased by 0.05 $cm\cdot s^{-1}$ compared with the control ($p < 0.01$). As illustrated in Figure 3, this improvement can be explained by the more favorable particle-size distribution and phase composition of 180–325 mesh fly ash, which effectively reshapes the structure of aeolian sandy soil.

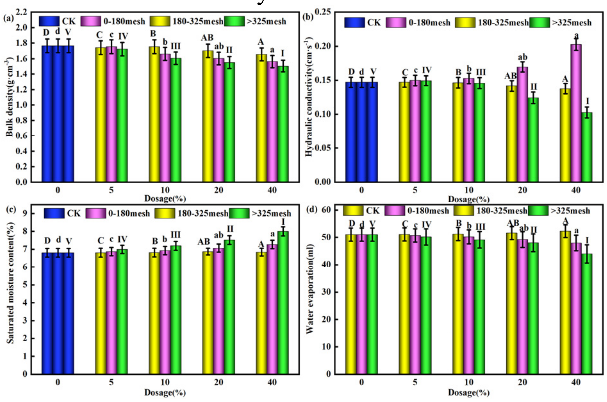

Figure 2 Effects of Fly Ash Addition on the Physical Properties of Aeolian Sandy Soil

Figures 2(c) and 2(d) indicate that fly ash larger than 325 mesh exhibited the most pronounced enhancement in saturated moisture content and the greatest reduction in soil water evaporation, followed by 180–325 mesh fly ash. The underlying mechanism is that finer particles (>325 mesh) can efficiently fill macropores in sandy soil and promote the formation of capillary pores. Moreover, this fraction contains more amorphous glassy phases with a larger specific surface area, thereby greatly improving the water-holding capacity

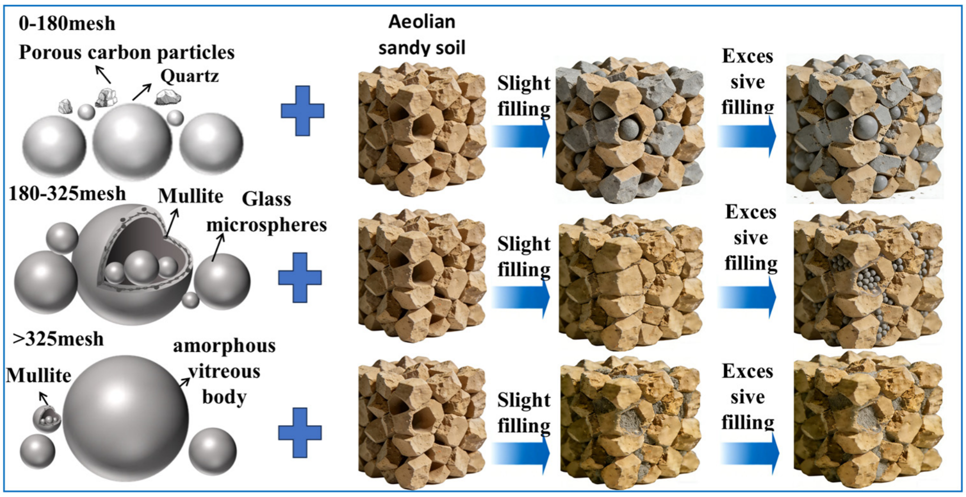

Figure 3 Micromechanism diagram of fly ash with different particle sizes

3.2 Effects of Fly Ash Addition on the pH of Aeolian Sandy Soil

As shown in Figure 4, fly ash treatments with different mesh sizes all affected the pH of aeolian sandy soil. Fly ash larger than 325 mesh exhibited the most significant increase in soil pH. Compared with the CK treatment, the pH value of aeolian sandy soil increased most significantly (by 0.84) when 40% of >325 mesh fly ash was added, with an extremely significant difference ($p < 0.01$).

The alkaline substances in fly ash mainly originate from the hydrolysis of inherent metal ions and alkaline components added during desulfurization. The proportion of alkaline substances varies among different particle-size fractions. Ultrafine fly ash has a higher content of alkaline substances, the highest proportion of amorphous glassy phases, and the largest specific surface area, which facilitate the fastest dissolution and reaction of alkaline components. Therefore, it shows the most significant effect on increasing the alkalinity of aeolian sandy soil.

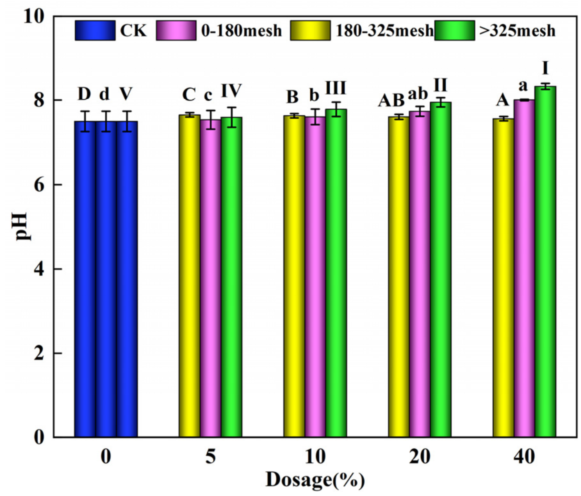

Figure 4 Effects of Fly Ash Addition on pH of Aeolian Sandy Soil

3.3 Effects of Fly Ash Addition on Nutrient Contents in Aeolian Sandy Soil

Figure 5 shows the soil nutrient status of aeolian sandy soil after treatment with three types of fly ash with different mesh sizes.As shown in Figure 5(a), all three types of fly ash had no significant effect on total nitrogen in aeolian sandy soil ($p > 0.05$).As shown in Figure 5(b), 0–180 mesh fly ash decreased available nitrogen in the soil, whereas 180–325 mesh and >325 mesh fly ash increased available nitrogen, with 180–325 mesh fly ash showing a more significant effect, and the magnitude of change was positively correlated with the application rate.At a 40% addition rate of 180–325 mesh fly ash, available nitrogen increased by 1.73 $mg \cdot kg^{-1}$ compared with the CK group ($p < 0.01$).This was because >325 mesh fly ash had a finer particle size, which was more conducive to the release of available nitrogen, thus better improving the available nitrogen content of aeolian sandy soil.

Figure 5(c) shows the changes in total phosphorus in aeolian sandy soil after adding three types of fly ash.The addition of 0–180 mesh fly ash reduced total phosphorus, and the reduction was positively correlated with the application rate.The addition of 180–325 mesh fly ash significantly increased total phosphorus; at 40% addition, total phosphorus increased by 0.32 $g \cdot kg^{-1}$ compared with the control (CK) ($p<0.01$).The improvement effect of >325 mesh fly ash on total phosphorus was moderate.Total phosphorus in fly ash mainly exists as P_2O_5, which is mainly concentrated in the 200–325 mesh fraction, while coarse particles are dominated by silicoaluminates. Therefore, 180–325 mesh fly ash showed the most significant improvement in total phosphorus. Figure 5(d) shows the effect of different mesh sizes of fly ash on available phosphorus. A smaller particle size corresponded to a higher phosphorus dissolution efficiency; thus, >325 mesh fly ash exhibited the most significant improvement in available phosphorus.

As shown in Figure 5(e), the addition of 0–180 mesh fly ash reduced total potassium in aeolian sandy soil,whereas 180–325 mesh and >325 mesh fly ash increased total potassium, with >325 mesh fly ash showing the most significant effect.At a 40% addition rate, total potassium increased by 1.53 $g \cdot kg^{-1}$ compared with CK ($p < 0.01$).Total potassium in fly ash mainly exists in the form of insoluble silicoaluminates (K-feldspar, illite), which are mainly distributed in fractions larger than 200 mesh.

As shown in Figure 5(f), the three types of fly ash had no significant effect on available potassium in aeolian sandy soil.This was because the available potassium content in the original sandy soil was higher than that in fly ash,and most potassium in fly ash existed in an insoluble form, making it difficult to increase available potassium.However, the native available potassium in aeolian sandy soil was within the normal range for agricultural soil, so no additional potassium fertilizer was required.

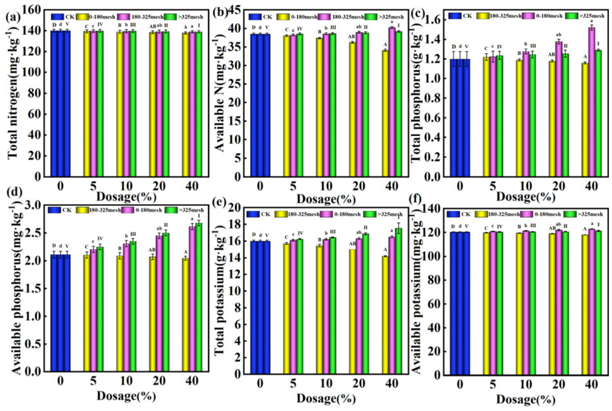

Figure 5 Effects of Fly Ash Addition on Nutrient Contents in Aeolian Sandy Soil

3.4 Effects of Fly Ash Amendment on the Growth of Pakchoi

As shown in Figure 6(a), the addition of 0–180 mesh and 180–325 mesh fly ash increased the germination rate of pakchoi, while the addition of >325 mesh fly ash slightly decreased it. This was related to the soil physical structure and pH of the aeolian sandy soil. The higher alkalinity of >325 mesh fly ash inhibited the germination of pakchoi. As shown in Figure 6(b), all three types of fly ash increased the plant height of pakchoi. The application of 180–325 mesh fly ash showed the best effect on plant height, followed by >325 mesh fly ash. The optimal enhancement was observed at a 10% addition rate of 180–325 mesh fly ash, with an increase of 126.77 cm ($p < 0.01$). The leaf growth of pakchoi was strongly correlated with nitrogen content.

As shown in Figure 6(c), all three types of fly ash promoted root growth of pakchoi. Among them, 180–325 mesh fly ash had the strongest promoting effect, whereas >325 mesh fly ash showed the weakest effect. When the addition rate of 180–325 mesh fly ash exceeded 10%, the promoting effect on root growth tended to be stable, with a maximum increase of 77.7 cm ($p < 0.01$). Root growth of pakchoi was related to phosphorus content and soil structure. The application of >325 mesh fly ash resulted in excessively compact soil particles, which restricted root growth.

As shown in Figure 6(d), all three types of fly ash increased the total biomass of pakchoi. The application of 40% 180–325 mesh fly ash achieved the most significant increase in total biomass, with an increment of 13.4 g. This was because the increase in soil pH reduced the availability of trace nutrients such as phosphorus, iron, and zinc, further leading to nutrient deficiency, inhibited photosynthesis, and insufficient carbohydrate synthesis.

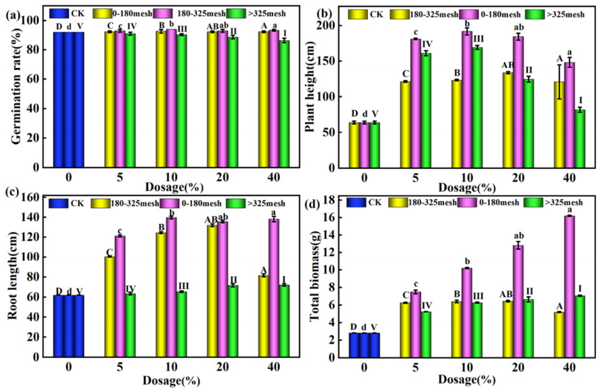

Figure 6 Effects of Fly Ash Addition on the Growth of Pakchoi

3.5 Significance analysis

Table 1 presents a summary of the significance analysis. In this study, a two-way analysis of variance (ANOVA) was conducted to investigate the effects of fly ash mesh size, fly ash addition amount, and their interaction on the physicochemical properties, water characteristics of aeolian sandy soil, and the growth indices of Chinese cabbage (Brassica rapa var. pekinensis). The significance of differences between groups is indicated by different letters in the figure. As shown in Table 1, fly ash mesh size, fly ash addition amount, and their interaction exerted significant or stronger effects on all measured indices. Fly ash mesh size and addition amount did not act independently; instead, there were significant synergistic or antagonistic effects between them, which collectively regulated the properties of aeolian sandy soil and the growth of Chinese cabbage.

Table 1 Summary of Significance Analysis

	Bulk density	Hydraulic conductivity	Saturated moisture content	Water evaporation
Fly ash particle size	*	**	*	*
Addition amount of fly ash	*	*	*	*
Mesh size * Addition amount	*	**	*	*
	pH	TN	AVN	TP
Fly ash particle size	*	*	**	**
Addition amount of fly ash	*	**	**	**
Mesh size * Addition amount	*	*	**	**
	AVP	Germination percentage	AVK	TK
Fly ash particle size	**	**	**	**
Addition amount of fly ash	**	**	**	**
Mesh size * Addition amount	**	**	**	**
Continued Summary of Significance Analysis				
	Total biomass	Root length	Plant height	
Fly ash particle size	*	**	**	
Addition amount of fly ash	**	**	**	
Mesh size * Addition amount	*	**	**	

Note: * indicates significant difference at $p < 0.05$, ** indicates significant difference at $p < 0.01$.

4 Conclusions

A pot experiment was conducted with aeolian sandy soil as the test soil and 0–180 mesh, 180–325 mesh, and >325 mesh fly ash as amendments, determining soil physicochemical properties, nutrient contents, and pakchoi growth indices. The main conclusions are as follows: All three fly ash types improved soil physical structure, pH value, and nutrient level, with significant differences among groups; 0–180 mesh fly ash had the weakest effect. 180–325 mesh fly ash was more conducive to comprehensive soil improvement, while >325 mesh fly ash mainly enhanced soil nutrients but significantly increased soil alkalinity, making its high application rate unsuitable for aeolian sandy soil amelioration. The optimal promoting effect on both soil and pakchoi growth was achieved with 10% 180–325 mesh fly ash application.

Acknowledgment

This work was supported by Ordos Science and Technology Research Project(JBGS2024010).

References

1. Fei G, S S Fan, J Y Liu, et al. Current situation and suggestions of cultivated land construction and protection laboratories in various districts and counties of Beijing[J]. Journal of Smart Agriculture, 2022, 2(14): 40-42.
2. Y S Cao, B Xiao, Z H Jiang, et al. Effects of biological soil crust development on base ion release and mineral weathering of aeolian sandy soil[J]. Journal of Soil and Water Conservation, 2022, 36(03): 77-8
3. L Zhou, Y L Ma, Z Wang, et al. Effects of coal gasification slag on physicochemical properties of desert soil and plant growth[J]. Environmental Protection of Chemical Industry, 2025, 45(06): 858-864.
4. C Tian, H Q Liu, D L Li, et al. Effects of combined application of fly ash and organic fertilizer on physicochemical properties of aeolian sandy soil and ryegrass growth[J]. Soils and Fertilizers Sciences in China, 2022, (07): 98-106.

5. Z C Zhao, Y Luo, J B Huang. Global warming and warming in China[J]. Progressus Inquisitiones de Mutatione Climatis, 2024: 1-7.
6. T N Sun. Global water resources situation highlights the intensification of climate change[N]. Guangming Daily, 2024-10-16(012).
7. T H Liu, W L Xu, S R Tang, et al. Effects of organic amendment application on extracellular enzyme activity and soil fertility of aeolian sandy soil[J]. Environmental Science, 2025: 1-13.