Effects of Different Fly Ashes on Properties of Aeolian Sandy Soil and Growth of Pakchoi

Jingjing Zou[1], Junxiang Ren[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 rationally utilize different fly ashes for aeolian sandy soil improvement, this study conducted pot experiments with pulverized coal fly ash (PC) and circulating fluidized bed fly ash (CFB) at various application rates. Soil physicochemical properties (before and after the experiment) and pakchoi growth were measured to explore the improvement effects. Results showed that both fly ashes improved aeolian sandy soil physical properties; CFB outperformed PC in regulating all physical properties except bulk density and enhanced soil fertility more effectively. CFB had a higher pH than PC, and pakchoi growth was optimal at 5% CFB addition. Rational utilization of these fly ashes realizes waste recycling, ecological restoration, and supports national ecological civilization construction.

1 Introduction

Soil is the material foundation for national food security and a precious agricultural resource. Aeolian sandy soil, from aeolian sediments, is widely distributed in global arid and semi-arid regions. China faces severe desertification, with desertified land accounting for 18.03% of its total land area[1]. Therefore, improving aeolian sandy soil is crucial for promoting soil sustainable utilization, ensuring regional ecological security, and combating desertification.

Currently, aeolian sandy soil improvement mainly adopts conservation tillage, green manure planting, and soil conditioner application[2]. Among these, conditioner application has advantages of high targeting and rapid effectiveness, but conventional materials have high cost and single functionality, demanding low-cost, multi-functional alternatives. As a thermal power generation by-product, fly ash output hit 899 million tons in 2023[3], and its ineffective utilization causes environmental pollution and resource waste. Thus, developing comprehensive fly ash utilization technologies is crucial for China's ecological protection and sustainable economic development[4,5].

This study used pulverized coal fly ash and circulating fluidized bed fly ash as soil conditioners to improve aeolian sandy soil. By measuring aeolian sandy soil physicochemical properties before and after treatment, it explored the impacts of structural and compositional differences of fly ash from different processes on its improvement. Additionally, it identified the effects of different fly ashes on aeolian sandy soil nutrient availability and fertility by examining pakchoi growth indicators. This research aims to provide a scientific basis for rational fly ash application to enhance aeolian sandy soil fertility and comprehensive productivity.

2 Materials and Methods

2.1 Experimental Materials

Test soil was collected from farmland in Zhanggutai Town, Zhangwu County, Fuxin City, Liaoning Province (122°55′E, 42°72′N), southeast of the Horqin Sandy Land and dominated by aeolian sandy soil. Sampled in March 2024, the 0–20 cm surface layer was used for the experiment. After natural air drying, plant residues and litter were removed, and the soil was sieved through a 2 mm mesh to eliminate impurities. The homogenized soil was sealed in double-layer nylon bags for pot experiments.

The phase composition, particle size distribution and micromorphology of the fly ash are shown in Figure 1. As can be seen from Figure 1(a), PC exhibited diffraction peaks of quartz (PDF card: 97-003-9830) at $2\theta = 20.84°$ and 26.72°, together with a broad diffraction peak at 20°–25°, indicating that PC was mainly composed of quartz and amorphous aluminosilicates. For CFB (Figure 1(a)), no distinct sharp diffraction peaks were observed; only a broad "halo peak" appeared at 20°–25°, suggesting that CFB was dominated by amorphous aluminosilicates with high reactivity. PC consisted mainly of smooth spherical particles, whereas CFB had low sphericity and mostly occurred as irregular angular, flocculent or porous aggregates. The D50 and D90 of PC were 29.907 μm and 133.103 μm, respectively, and CFB had a finer particle size than PC.

* Corresponding author: guochunbin@lntu.edu.cn

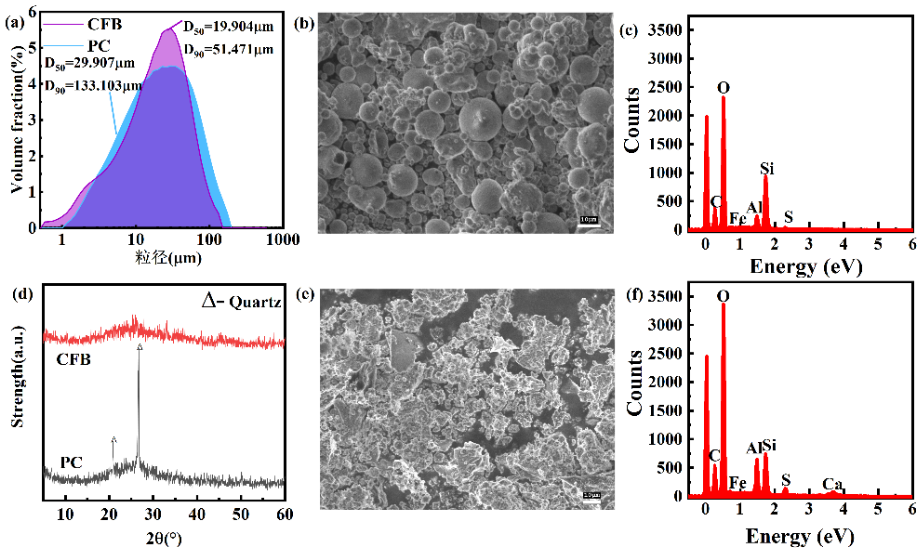

Figure. 1 Particle size analysis of fly ash (a), PC scanning electron microscopy (b), PC energy spectrum (c), X-ray diffraction spectrum (d), CFB scanning electron microscopy (e), CFB energy spectrum (f)

2.2 Experimental Design

In this study, a pot experiment was conducted to investigate the effects of fly ash type and application rate on aeolian sandy soil.Five application gradients were set: 0 (CK), 5%, 10%, 20%, and 40%, resulting in a total of 9 treatments with 3 replications per treatment. The experimental duration was 60 days.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, lined with filter paper at the bottom to prevent soil loss.Each pot was filled with 2 kg of dry aeolian sandy soil, and water was added once to achieve uniform moistening according to the saturated moisture content of the corresponding formulation.Twenty pakchoi seeds were sown uniformly in each pot (10 holes with 2 seeds per hole), and seedlings were thinned to 5 plants per pot on the 7th day after sowing.During the growth period, water was replenished every 2 days, with the irrigation volume calculated based on the weight difference.All pots were arranged in a completely randomized design and systematically repositioned every 2 days. Data sorting and calculation were performed using Microsoft Excel 2018. Error analysis was conducted with SPSS Statistics 27, and Duncan's multiple range test was adopted for significance testing. Figures were plotted using Origin 2021 software.

3 Results and Discussion

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

Figure 2 shows the effect of fly ash addition on the physical properties of aeolian sandy soil. As shown in Figure 2(a), both types of fly ash reduced the bulk density of aeolian sandy soil, and the reduction magnitude was positively correlated with the application rate. The M_4 and L_4 treatments exhibited the most significant reduction in bulk density, with decreases of 0.33 and 0.28 $g \cdot cm^{-3}$ compared with the CK group, respectively, and the differences were significant ($p < 0.05$). Pulverized coal-fired fly ash (PC) showed a better effect on reducing the bulk density of aeolian sandy soil than circulating fluidized bed fly ash (CFB).

This was attributed to the difference in operating temperatures: pulverized coal furnaces generally operate at 1200–1400 °C, while circulating fluidized beds operate at 800–900 °C [6]. The high temperature in pulverized coal furnaces completely melts the coal ash. During combustion, the rapid release of volatile matter forms internal cavities, and the molten droplets shrink into spheres under surface tension, followed by rapid cooling and solidification by flue gas, eventually forming hollow microspheres[7,8]. In contrast, the temperature in circulating fluidized beds is lower than the eutectic temperature of most ash components, failing to form a continuous molten phase or spherical particles via surface tension, resulting in irregular particle morphologies after cooling. Therefore, PC fly ash is more effective in reducing the bulk density of aeolian sandy soil.

Both fly ash types exerted significant effects on the sand and silt fractions of aeolian sandy soil. As shown in Figure 2(b), sand accounted for over 90% of the original soil. PC increased silt content and decreased sand content in a dosage-dependent manner, while CFB altered particle composition more markedly: at 5% addition, CFB increased silt by 64.79% and reduced sand by 67.12% ($p<0.01$), compared with 3.37% and 3.50% for PC, owing to its smaller D90 particle size.

As illustrated in Figure 2(c) and Figure 3, at 5% addition, the saturated hydraulic conductivity decreased by 0.0093 $cm \cdot s^{-1}$ for PC and 0.083 $cm \cdot s^{-1}$ for CFB, with a declining trend as dosage increased. The greater reduction by CFB was attributed to its finer particles, higher CaO and reactive aluminosilicate contents, which formed C-S-H gel via pozzolanic reactions and better filled soil pores.

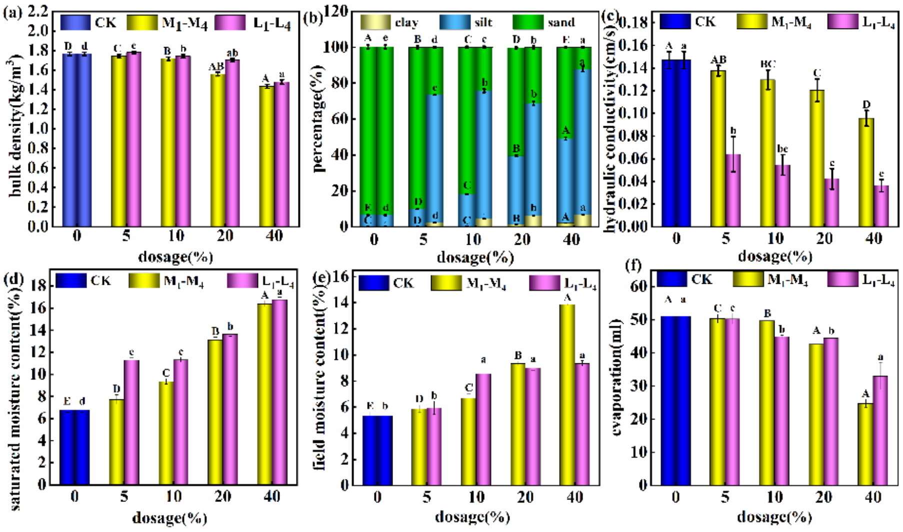

Figure 2 Effects of Fly Ash Addition on the Physical PrPCerties of Aeolian Sandy Soil

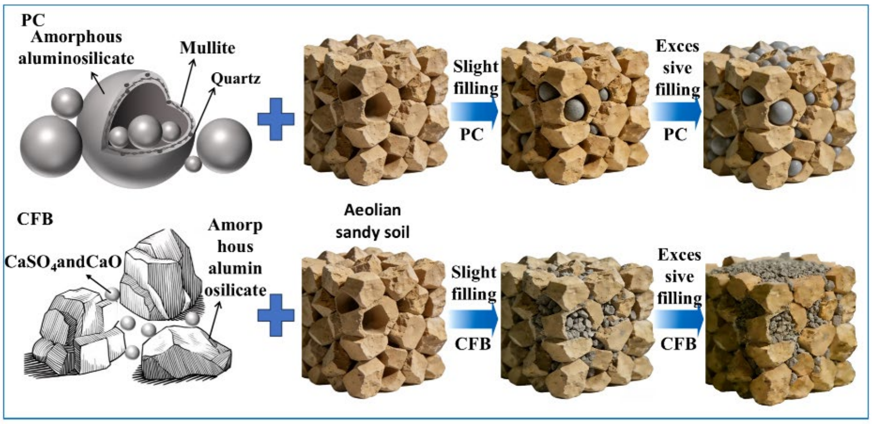

Figure 3 MicroscPCic Mechanism Diagrams of Pulverized Coal Furnace Fly Ash and Circulating Fluidized Bed (CFB) Fly Ash

Figure 2(d) shows that CFB improved saturated water content more effectively: at 5% addition, it increased by 4.5% ($p<0.05$) for CFB and 0.92% for PC, with a positive dosage response, due to higher CaO and $CaSO_4$ in CFB that formed hydrated gypsum.

As shown in Figure 2(e,f), at 20% fly ash addition, the field water capacity increased by 74.77% for PC and 68.6% for CFB compared with the CK group, while the one-month soil water loss decreased by 12.75% and 8.35%, respectively, with significant differences between groups ($p<0.01$). At an application rate $\leqslant 10\%$, CFB-treated soil exhibited higher field water capacity and lower one-month water loss than PC. In contrast, at a rate $\geqslant 20\%$, PC showed superior water retention performance.

This could be explained by the finer particle size of CFB, which effectively filled the macropores in aeolian sandy soil and formed capillary pores, thus enhancing water-holding capacity. However, when the application rate exceeded 20%, CFB tended to excessively block the large aerated pores and even clog capillary pores, transforming the soil pore structure from "macropore-dominated" to an extremely "micropore-concentrated" state. The sharp decline in pore connectivity impaired gas exchange and impeded water infiltration, resulting in a contradictory condition of "surface water stagnation and deep water deficit", thereby leading to lower water retention capacity than PC[9].

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

As shown in Figure 4, different fly ash treatments affected the pH of aeolian sandy soil. The pH values of all fly ash-amended treatments were higher than that of the original sandy soil, and pH increased with increasing fly ash application rate. Compared with the CK treatment, the pH increase was most pronounced at 40% CFB application, with an increment of 0.48, and the difference was highly significant ($p < 0.01$).

The pH of fly ash is related to combustion conditions, desulfurization measures, and mineral components. The relatively low combustion temperature in circulating fluidized beds restricts the reaction between CaO and Al_2O_3/SiO_2, leaving more CaO in a free state, which readily increases pH upon hydration. In addition, circulating fluidized bed boilers adopt in-furnace desulfurization with large amounts of limestone. The decomposition of limestone produces CaO, and the substantial unreacted CaO hydrates to form calcium hydroxide, further enhancing alkalinity.

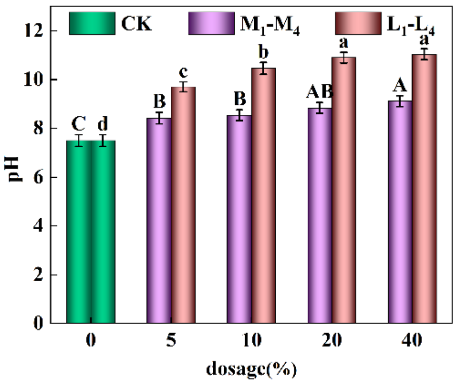

Figure 4 Effects of Fly Ash Addition on the pH Value of Aeolian Sandy Soil

3.3 Effects of Fly Ash Addition on the Nutrient Content of Aeolian Sandy Soil

Figure 5 illustrates the changes in soil nutrients under different treatments before and after Chinese cabbage planting. As shown in Figure 5(a) and 5(b), the contents of total nitrogen and available nitrogen in the aeolian sandy soil decreased by 3.6 and 10.5 mg·kg^{-1} after planting, respectively. At a 5% fly ash application rate, the PC treatment decreased by 3.22 and 10.4 mg·kg^{-1}, which were 0.28% and 0.36% higher than the CK group; the CFB treatment decreased by 2.8 and 4.75 mg·kg^{-1}, which were 0.59% and 20.54% higher than CK, with significant differences ($p < 0.05$). The variation was positively correlated with the fly ash application rate. Comparative analysis showed that the changes in total nitrogen and available nitrogen were the greatest at 5% application for both PC and CFB, and the increase in available nitrogen under CFB was higher than that under PC. However, the changes in CFB treatments were significantly smaller than those in PC at higher dosages, which was attributed to the higher combustion temperature of PC that enhanced nitrogen volatilization.

As shown in Figure 5(c) and 5(d), the contents of total phosphorus and available phosphorus in the control soil decreased by 0.05 g·kg^{-1} and 0.12 mg·kg^{-1} after planting. At 5% fly ash addition, the PC and CFB treatments decreased by 0.05 g·kg^{-1}, 0.27 mg·kg^{-1} and 0.15 g·kg^{-1}, 0.89 mg·kg^{-1}, which were 13.04%, 157.58% and 56.52%, 253.54% higher than CK, respectively, with significant differences ($p < 0.05$). Significant differences were labeled with different letters, and the changes were positively correlated with the fly ash dosage. The L4 treatment showed the largest decrease in total phosphorus but a slight change in available phosphorus, whereas the M4 treatment exhibited the largest decrease in available phosphorus but a slight change in total phosphorus. These differences were related to the inherent phosphorus contents and the effects on phosphorus immobilization and desorption of the two fly ash types. The lower combustion temperature and in-furnace desulfurization of CFB resulted in a higher phosphorus content, but the stronger alkalinity of CFB hindered the transformation of total phosphorus and reduced available phosphorus.

As shown in Figure 5(e) and 5(f), the contents of total potassium and available potassium in the control soil decreased by 0.9 g·kg^{-1} and 86.29 mg·kg^{-1} after planting, with significant differences ($p < 0.05$). At 5% fly ash addition, compared with CK, the PC treatment decreased total potassium by 16.49% and increased available potassium by 92.75%, while the CFB treatment increased total potassium by 6.75% and available potassium by 30.92%. Comparative analysis indicated that the total potassium content of CFB was higher than that of PC, because the low combustion temperature suppressed potassium volatilization. The release of available potassium in PC was lower than that in CFB, because the high formation temperature of PC immobilized potassium ions in aluminosilicates with low activity, making them less available for plant uptake.

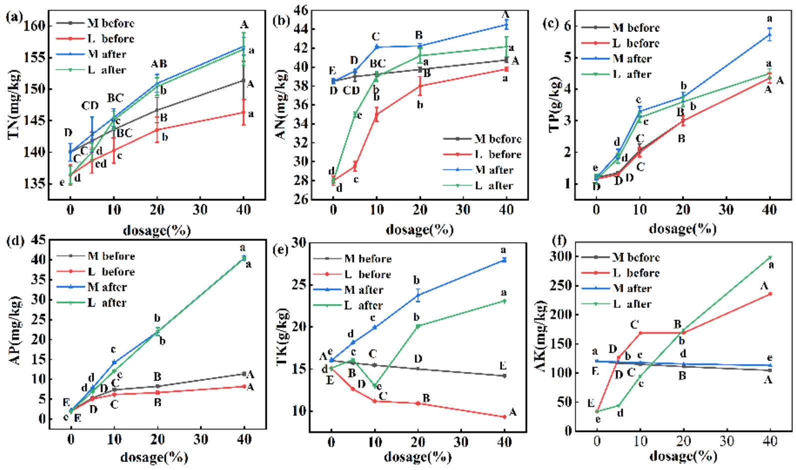

Figure 5 Effects of Fly Ash Addition on the Nutrient Content of Aeolian Sandy Soil

3.4 Effects of Fly Ash Amendment on the Growth of Pakchoi

As shown in Figure 6(a), (b) and (c), both PC and CFB promoted shoot growth and stem biomass accumulation of Chinese cabbage at a 5% application rate. Compared with CK, plant height increased by 0.6 and 22.33 cm, and stem biomass by 0.78 and 1.17 g, respectively, with a better effect observed for CFB. CFB also improved the germination rate of Chinese cabbage by 1%. However, CFB application exceeding 5% inhibited germination, which was related to its strong alkalinity.

As illustrated in Figure 6(d), (e) and (f), 5% CFB significantly promoted root elongation, root biomass and total biomass accumulation by 36.6 cm, 1.22 g and 1.99 g, respectively, with significant intra- and inter-group differences ($p<0.05$). PC application below 20% enhanced total biomass accumulation, with the optimal promotion at 10%, increasing total biomass by 0.98 g compared with CK.

Plant height, stem weight and total biomass showed similar responses to fly ash addition. PC application over 20% and CFB over 5% inhibited these parameters. The inhibitory effect was attributed to high pH, which reduced the availability of P, Fe, Zn and other micronutrients, causing nutrient deficiency, impaired photosynthesis and insufficient carbohydrate synthesis.

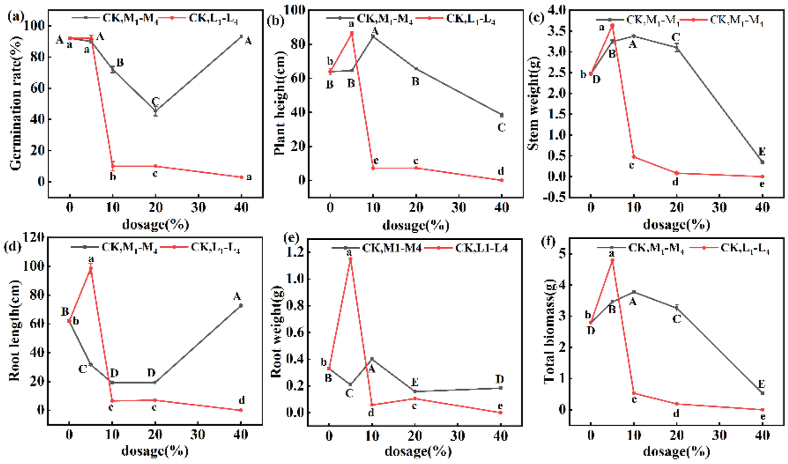

Figure 6 Effects of Fly Ash Addition on the Plant Height, Root Length, and Root Weight of Pakchoi

4 Conclusions

A pot experiment was conducted with aeolian sandy soil as substrate and pulverized coal fly ash (PC) and circulating fluidized bed fly ash (CFB) as amendments. Determination of soil physicochemical properties, nutrient contents, and pakchoi growth indices before and after treatment yielded the following conclusions: Both fly ashes significantly improved aeolian sandy soil physical properties, and CFB outperformed PC in regulating bulk density, particle size distribution, saturated moisture content, field water-holding capacity, hydraulic conductivity, and one-month soil water loss. Both treatments increased soil pH, with a more obvious increase in CFB treatments: soil pH reached ~8 with 5% CFB and ~11 with 40% CFB. CFB was superior to PC in enhancing soil pH, total nitrogen, available nitrogen, total phosphorus, available phosphorus, and total potassium, but weaker in reducing available potassium. Application of 5% CFB increased the pH value to approximately 9, close to the upper limit suitable for the growth of Chinese cabbage.

Acknowledgment

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

References

1. 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(6): 858-864.
2. T H Liu, W L Xu, S R Tang, et al. Effects of organic amendment application on extracellular enzyme activity and fertility of aeolian sandy soil[J]. *Environmental Science*, 2025: 1-13.
3. Y Zhu, Y M Jia, et al. Study on the Macroscopic Properties and Microstructure of High Fly Ash Content Alkali-Activated Fly Ash Slag Concrete Cured at Room Temperature[J]. Materials, 2025, 18(3):547-566.
4. L Yang, Y H Wu, S H Ma, S L Zheng, et al. Utilization of coal fly ash in China: a mini-review on challenges and future directions[J].Environmental Science and Pollution Research, 2021, 28:18727-18740.
5. F Y Teng; ZY Wang, et al. Analysis of composition characteristics and treatment techniques of municipal solid waste incineration fly ash in China [J].Journal of Environmental Management, 2024, 357:120783.
6. E Wang. Comparison of mineralogical properties between pulverized coal-fired fly ash and circulating fluidized bed fly ash[J]. Clean Coal Technology, 2016, 22(04):26-29.
7. Y Yue, Q Yao, Q Song, et al. Comparative study on morphology and heavy metal distribution of PM10 emitted from different coal combustion sources[J]. Proceedings of the CSEE, 2007, (35): 33-38.
8. G L Fisher. Fly ash collected from electrostatic precipitators: microcrystalline structures and the mystery of the spheres[J]. Science, 1976, 192(4239): 553-555.
9. Y Z Xu, J Y Liu, C B Xu, et al. Preliminary study on the relationship between permeability coefficient and pore size of saturated soil[J]. Safety and Environmental Engineering, 2024, 31(01): 67-74.