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# Combined Effect of Leaching Process and Biochar Application on the Restoration of a Coastal Mild Saline-alkali Soil and the Growth of Pak Choi (Brassica chinensis L.)

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**Abstract** Soil salinization has emerged as the major factor negatively impacting soil quality in the coastal mild saline-alkali soil of the Yangtze River estuary. Soil quality is vital to agricultural development and the restoration of saline-alkali soils has become an urgent task. Biochar is often used for saline-alkali soil improvement, but few studies have explored the combined effect of biochar and leaching on it. Herein, two biochar (rice straw biochar (RBC) and humic acid magnetically modified biochar (HMBC)) were applied to the coastal mild saline-alkali soil with different application amounts (1, 3, and 5% (w/w)) plus leaching process. The results showed that HMBC had better effects than RBC in improving soil properties (e.g., dissolved organic matter, cation exchange capacity, available phosphorus, and available potassium). The leaching process led to soil pH value dropping from 8.43 to 7.57 and electrical conductivity (EC) from 622 to 200 μs/cm. Furthermore, after the pot experiment, the concentration of soil soluble salts increased with soil depth. The salt content of the soil without leaching was significantly higher than that of the soil with leaching; after applying HMBC or RBC, the salt content of all soil layers decreased. Combined 5% HMBC and leaching also improved the seed germination rate, fresh weight, dry weight, and plant height, and the height reached 9.13 cm. Although leaching resulted in a slight decrease in chlorophyll content, the chlorophyll content increased with the increased concentration of biochar. Overall, the integrated use of a suitable biochar application amount (5% HMBC) and leaching for coastal mild

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saline-alkali soil could be an effective strategy to reduce soil salinity, enhance the improvement of soil quality and promote plant productivity.

**Keywords** Mild saline-alkali soil · Biochar · Humic acid · Soil fertility · Plant growth

## 1 Introduction

Approximately 20% of the world's agricultural land is saline (Hopmans et al., 2021) and the proportion of saline-alkali land is still increasing (Yang et al., 2021a). Chongming Island, located in the Yangtze River estuary, is the largest alluvial estuary island in China (Sun et al., 2010). The soil in the area is slightly alkaline and saline, and the salt in the sediments needs to be leached with fresh water to meet agricultural needs (Zheng et al., 2016). Soil salinization causes soil particles to flocculate into clumps (Wong et al., 2010) and poor air permeability, which might affect microbial community structure (Wan et al., 2021) and enzyme activity (Song et al., 2022). Furthermore, the saline-alkali soil limited nutrient uptake by plant roots (Zörb et al., 2019), resulting in lower plant growth and yield. Plants growing in saline-alkali soil are subjected to salt and oxidative stresses. All these conditions could strongly decrease the soil productivity (Mahmoud et al., 2019). Besides, agriculture is the leading industry in Chongming Island. Therefore, how to improve the quality of the coastal mild saline-alkali soil in Chongming Island has become an urgent task for agricultural development.

To alleviate the adverse effects of soil salinization, agricultural wastes have been widely used, such as the direct application of crop straw (Xie et al., 2017), composting (Meena et al., 2022), preparation of biochar to be applied to the soil (Tomczyk et al., 2020; Zhao et al., 2020). In these saline alkali soil remediation materials, biochar has shown promising potentials for application in soil remediation. As reported, biochar has a larger specific surface area, more micro-pores, rich functional groups, and high negative charge, which are conducive to the adsorption of contaminants through complexion, precipitation, and ion exchange (Chen et al., 2021; Qiu et al., 2020; Xu et al., 2023). Concretely, biochar addition can increase soil available nutrient content (Dejene & Tilahun, 2019; Li et al., 2023), and cation exchange capacity (CEC), reduce the nutrients (such as N, P) losses by leaching, and thus improve soil physical properties. Furthermore, Zhao et al. (2022) found that ball-milled biochar could promote the growth of mung beans due to nutrients contained in the biochar itself (Zhao et al., 2022). Other studies have shown that maize plants grown in soils with high salinity and nutrient deficiencies did not grow properly. However, Helaoui et al. (2023) found that 50 g $kg^{-1}$ biochar effectively promoted maize growth in salt-affected soil (Helaoui et al., 2023). Specific influencing factors of biochar in saline-alkali soil and its underlying mechanism were unknown and needed to be further studied.

Current research on biochar has mainly focused on modifications, such as chemical modification and magnetic modification. It is widely noted that magnetic biochar enhances the magnetism of biochar by attaching metal ions to the surface, thereby easy to recycle (Lohan et al., 2023; Shang et al., 2016). The high soil pH value would lead to a strong negative charge on the surface of magnetic biochar, therefore enhancing the adsorption of metal cations. The capacity of magnetic biochar is still limited, so it is urgent to be modified to increase the adsorption capacity. Studies have found that humic acid (HA) has a good affinity for magnetic nanoparticles, through ion exchange and surface complexation to inhibit the aggregation or self-oxidation of $Fe_3O_4$, and further improve the adsorption performance (Rashid et al., 2017; Zhao et al., 2019). HA could provide more adsorption sites, which is based on its unique structural characteristics and physicochemical properties, such as the abundance of oxygen-containing functional groups (phenolic hydroxyl, carbonyl, and carboxyl groups). Therefore, it is important that the introduction of HA into magnetic biochar preparation could increase the oxygen-containing functional groups and improve the adsorption capacity (Yang et al., 2019).

Although biochar improved the soil to promote plant growth, the application of biochar had limited effects on salt removal from saline-alkali soil. Therefore, soil leaching is a physical desalination technology that is fast and easy to implement. It is a technique that removes pollutants from adsorbed soil particles by dissolving them with the aid of a liquid that promotes the dissolution of pollutants in the soil environment (Li et al., 2011). However, the low permeability of saline-alkali soils made direct leaching inefficient (Dikinya et al., 2008; Ebrahim Yahya et al., 2022). The correlation between soil salinity leaching and the soil infiltration capacity and permeability was significant. In particular, to accelerate the efficiency of salt leaching from the soil and improve the soil structure, biochar promotes water infiltration and speed up desalinization in the soil (Yue et al., 2016). Leaching also improves cation composition and crop yield, and all leaching result in a significant decrease in $K^+$ and $Na^+$ content in the saline-alkali soil at 0–20 cm depth (Liu et al., 2023). However, few studies have explored the combined effect of biochar and leaching on the restoration of the mild saline-alkali soil.

Therefore, to address the above issues, the mild saline-alkali soil was used to evaluate the effect of leaching process and two biochar (rice straw biochar (RBC) and HA magnetically modified biochar (HMBC)) with different application amount (1%, 3%, and 5% w/w) on soil properties and Pak Choi (Brassica chinensis L.) growth. The following aspects were mainly considered: (1) to explore the combined effect of two biochar (RBC and HMBC) and leaching on soil physical and chemical properties in mild saline-alkali land, (2) to figure out the effect of 5% RBC and 5% HMBC with leaching on the transport of soluble salts in different soil layers, and (3) to analyze the combined effect of two biochar (RBC and HMBC) and leaching on Pak Choi growth and quality.

## 2 Materials and methods

### 2.1 Soil sampling and analysis

The soil was collected from the agricultural field of Chongming Island in Shanghai (121°31′35" E, 31°43′49" N). First, the soil surface was removed of plants, stones and other debris. The surface soil (0–20 cm) was then randomly collected by soil augers. The soil was placed in polyethylene bags and returned to the laboratory for further processing. The collected soil was air-dried under the shade, passed through a 2 mm sieve, and mixed well for subsequent experiments.

Soil pH and electrical conductivity (EC) were measured in 1:5 soil/water suspensions by a pH meter and EC meter, respectively. The total organic carbon (TOC) was determined by a TOC analyzer (multiN/C 3100, Germany). Total nitrogen (TN) was determined by the semi-micro Kjeldahl method. Dissolved organic matter (DOM) was determined by the potassium dichromate external heating method. Cation exchange capacity (CEC) in soil was detected with the cobalt trichloride extraction-spectrophotometry method (Osman et al., 2013). Available phosphorus (AP) was determined by sodium bicarbonate-molybdenum antimony anti-colorimetric method and available potassium (AK) was determined using 1 mol/L ammonium acetate extraction and quantified by a flame photometer (Zhao et al., 2018).

### 2.2 Biochar production and characterization

The rice straw was purchased from Lianyungang City, Jiangsu Province. The rice straw was washed off surface dust and dried at 105 ℃ for 24 h in a drying oven. It was then crushed into rice straw powder with a grinder. After that, the powder was grounded fully and sieved through 60 mesh and pyrolyzed at 500 ℃ for 2 h, labeled as RBC. To further improve the effective amendment and stability of RBC, the RBC was magnetically modified with $FeSO_4 \cdot 7H_2O$ and $FeCl_3 \cdot 6H_2O$ (w/w, 1.7:1,), and the pH was adjusted to 10–11 with NaOH (Nham et al., 2019). It was stirred vigorously for 1 h, then filtered and freeze-dried to obtain the solid, labeled as MBC. Then, MBC was selected for further activation by HA (Liu et al., 2008). HA was dissolved in 0.1 mol/L NaOH, stirred until dissolved, and adjusted the pH to 7.0. MBC was added to the solution and stirred for 48 h and left for 24 h, after which the product was washed with deionized water. Subsequently, it was freeze-dried in a vacuum freeze-dryer for 24 h and then ground through a 60-mesh sieve to obtain the porous HA magnetically modified biochar materials, labeled as HMBC.

The pH of the biochar was measured using a pH meter (water ratio of 1:20 w/w). The specific surface area and porosity of the biochar were determined using a fully automated rapid specific surface and porosity analyzer (Autosorb-iQ, Quadrasorb, USA). The surface morphology of RBC and HMBC was analyzed by scanning electron microscopy (SEM). Fourier transformation infrared (FTIR) spectroscopy was performed to determine the frequency of the vibrational functional groups present in various amendments using the KBr pellet method and then scanning wavenumber in the range of 400–4000 $cm^{-1}$.

## 2.3 Column leaching experiment

The soil column for the leaching experiment was made with an organic glass column with a height of 30 cm and an inner diameter of 8 cm (Fig. 1) (Zhang et al., 2021). Firstly, a 100 mesh stainless steel screen slightly larger than the pore size was placed at the bottom of the column, and 1 cm of 35 mesh quartz sand was filled, then a mixture of saline-alkali soil, biochar, and quartz sand (> 10 mesh) was slowly added (20% sand mixing ratio) with wet-packed methods at room temperatures (25℃). After filling, each soil column was naturally settled for 24 h, and then the leaching experiment was carried out. In the leaching experiment, control check (CK, without biochar) and two kinds of biochar (RBC and HMBC) were used in the soil column at three different levels (1%, 3%, and 5% w/w), and each treatment included 3 repetitions (Table 1). Each soil column was leached with 810 mL of distilled water until the leaching solution outflowed from the bottom of the soil column. After leaching, the soil was air-dried and screened by a 10-mesh sieve for subsequent pot experiments and soil properties determination. The soil water content was determined using the drying method (105 ± 2°C) (Zhang et al., 2011).

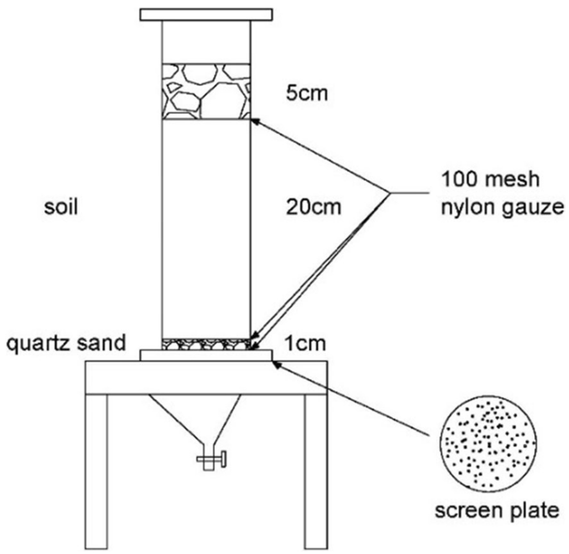


**Fig. 1** Schematic diagram of soil column

## 2.4 Pot experiment on planting Pak Choi

First, the collected saline-alkali soil from Chongming was mixed evenly with biochar (RBC and HMBC) as one of the soil (no-leaching treatment) for pot experiment. Meanwhile, the soil from the laboratory column leaching experiment was used as the other soil (leaching treatment) for pot experiments. Then 500 g of these two types of soil were respectively placed into plastic pots (15 cm height and 10 cm inner diameter) which were used to cultivate Pak Choi. 10 Pak choi seeds with similar shapes were selected to be sowed equidistantly, and the soil was covered. The experiment was conducted with a total of 14 treatments (Table 1), and each treatment had three replicates. The soil was irrigated with 20 ml of deionized water every day. The pot experiment was conducted

**Table 1** Experimental design for potted plants

| | Treatment | Application amounts | Name | | Treatment | Application amounts | Name |
|---|---|---|---|---|---|---|---|
| No Leaching | CK | 0% | CK | With Leaching | CK | 0% | L-CK |
| | RBC | 1% | RBC1 | | RBC | 1% | L-RBC1 |
| | | 3% | RBC3 | | | 3% | L-RBC3 |
| | | 5% | RBC5 | | | 5% | L-RBC5 |
| | HMBC | 1% | HMBC1 | | HMBC | 1% | L-HMBC1 |
| | | 3% | HMBC3 | | | 3% | L-HMBC3 |
| | | 5% | HMBC5 | | | 5% | L-HMBC5 |

CK (original soil with no biochar), RBC1 (3,5) (original soil with 1%, 3%, and 5% RBC), HMBC1 (3,5) (original soil with 1%, 3%, and 5% HMBC), L-CK (soil with leaching and with no biochar), and L-RBC1 (3,5) (soil with leaching and with 1%, 3%, and 5% RBC), L-HMBC1 (3,5) (soil with leaching and with 1%, 3%, and 5% HMBC) in a constant temperature foster box with 25℃ for 30 days, and full-spectrum plant fill lights were used to simulate sunlight. On Day 30, the soil and Pak choi samples were collected for further analysis. The plant growth indicators (germination rate, fresh weight, dry weight, and plant height) and plant quality indicators (leaf chlorophyll, soluble protein, soluble sugar) were measured. Plant height was measured by a ruler. Leaf chlorophyll content was measured using an acetone extraction-spectrophotometer method (Mackinney, 1941). Soluble protein content was determined by the Coomassie brilliant blue method (Bradford, 1976). Soluble sugar content was determined by anthrone colorimetry (Leng et al., 2016).

Moreover, to further explore the migration character of soluble salt in soil after pot experiment, the soil treated with CK, RBC5, and HMBC5 was selected. The potting soil was divided into 5 layers and naturally air-dried. Then the salt content of each layer was measured. The water-soluble $K^+$, $Na^+$, $Ca^{2+}$, and $Mg^{2+}$ contents of the soil samples after pot experiment were determined by a flame photometry.

### 2.5 Statistical analysis

The statistical significances of the differences in soil physicochemical properties and plant indicators between treatments were figured up with one-way analysis of variance (ANOVA). The least significant difference (LSD) was used to separate the means. Statistical analysis was conducted and corresponding significance values ($P < 0.05$) using Microsoft Excel 2013 and SPSS (27.0, IBM, USA). Figure preparation was performed by Origin 2018 (OriginLab, USA).

## 3 Results and discussion

### 3.1 Characterization of biochar

Firstly, it can be seen from Table 2 that RBC and HMBC were alkaline, which might be due to the formation of peroxides on the surface of carbon and the increase of hydroxyl groups at higher pyrolysis temperatures (Yuan et al., 2011). These carbon–oxygen complexes can act as a Lewis base (Antal & Grønli, 2003) to produce alkaline biochar. The pH value of RBC pyrolyzed at high temperatures was high, which was related to the reduction of -O and -H functional groups (Igalavithana et al., 2017). The pH of HMBC was lower than RBC because the adhesion of HA reduced the alkalinity of HMBC. HA was rich in oxygen-containing functional groups (e.g., -COOH). The specific surface area and pore volume of RBC were 52.79 $m^2/g$ and 0.064 $cm^3/g$, while the specific surface area and pore volume of HMBC significantly increased by 2.78 times and 3.81 times compared with RBC (Du et al., 2020a). Therefore, the

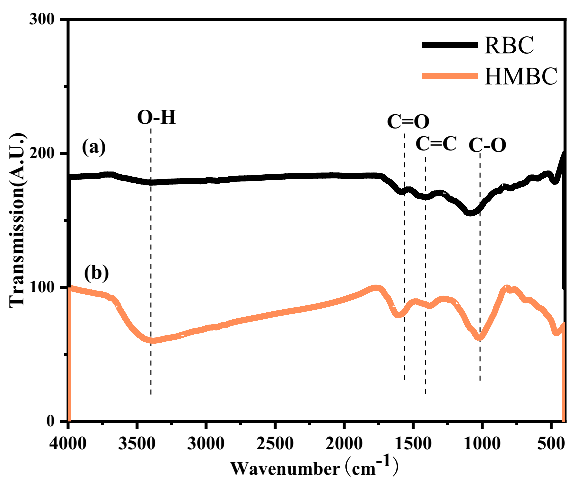


**Fig. 2** Characterization of (**a**) RBC, (**b**) HMBC by FTIR

**Table 2** Physicochemical properties of biochar

| Biochar | Yield % | C % | H % | O % | N % | pH | Specific surface area ($m^2$/g) | Pore volume ($cm^3$/g) |
|---|---|---|---|---|---|---|---|---|
| RBC | 41.23 | 46.39 | 1.78 | 18.11 | 1.26 | 10.18 | 52.79 | 0.064 |
| HMBC | 36.21 | 30.25 | 1.89 | 26.96 | 0.74 | 7.42 | 146.69 | 0.244 |

introduction of magnetic and HA increased the specific surface area of RBC.

As shown in Fig. 2, the broad peak near 3400 $cm^{-1}$ is the stretching vibration of the hydroxyl group. It can be seen that the peak height of (a) RBC and (b) HMBC hydroxyl vibration increases in turn. The enhancement of HMBC was due to the introduction of hydroxyl groups by NaOH to adjust pH during the preparation of magnetic biochar, and HA was grafted based on magnetic biochar. HA contained a large number of hydroxyl groups, so HMBC contained more hydroxyl groups than RBC. The stretching vibration of aromatic ring C=C and C=O is between 1411 $cm^{-1}$ and 1564 $cm^{-1}$, and the bending vibration peak of O–H is between 1450 $cm^{-1}$ and 1400 $cm^{-1}$, which can be used to determine whether there are carboxylic acids. On the other hand, the peaks at about 1000 $cm^{-1}$ may be owing to stretching of carbohydrate (C–O) (Zhu et al., 2015). Compared with RBC, the vibration peaks of C=O and C-O of HMBC are significantly enhanced. Interestingly, the oxygen-containing functional groups of HA easily bind to $Fe_3O_4$ and coat the surface of the magnetic biochar (Du et al., 2020b). It may be because HA contains rich oxygen-containing functional groups, and HA was successfully grafted on magnetic biochar, so HMBC contained a large number of oxygen-containing functional groups (Yang et al., 2021b).

It can be seen from Fig. 3a and b that RBC and HMBC, respectively had different surface structures. RBC had an obvious carbon skeleton and particle agglomeration, and its carbon skeleton mainly came from the cellulose of raw materials. HMBC had a rough surface and many granular substances. It has been stated that the activation of HA and magnetism was beneficial for the carbon material to produce a rich porous structure (Du et al., 2020b). The complexation of oxygen-containing functional groups on the HA surface (i.e., phenol-OH, -COOH, etc.) with Fe ions was conducive to the uniform dispersion of magnetic particles on the biochar skeleton. Furthermore, compared to Fig. 3c, the characteristic peak of Fe can be clearly seen in Fig. 3d that HA and

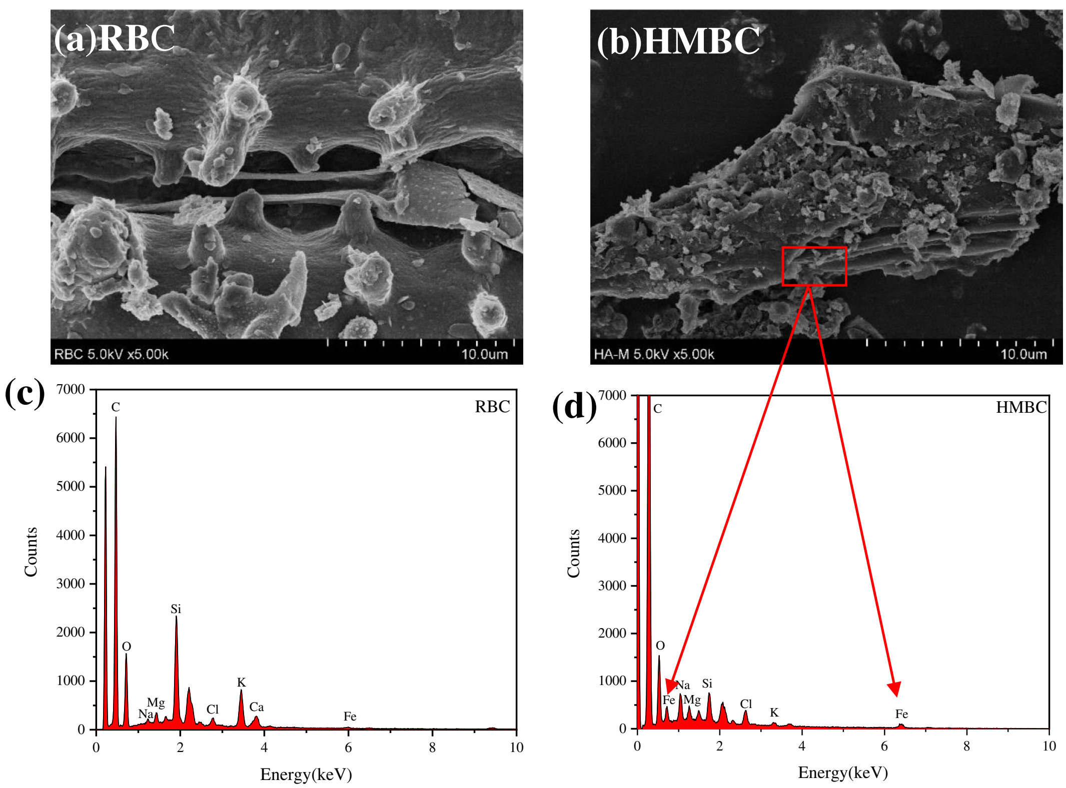


Fig. 3 SEM images of (a) RBC, (b) HMBC, (c) EDS image of RBC and (d) EDS image of HMBC

magnetic particles ($Fe_3O_4$) have successfully adhered in HMBC.

### 3.2 Effect of biochar and leaching on soil properties

Leaching had a significant effect on the reduction of pH of saline-alkali soil, which made the soil pH reduced from 8.43 to 7.57 (Fig. 4a) ($p<0.05$). The increase of soil alkalinity after RBC addition was attributable to the higher pH for RBC (pH = 10.18) (Table 2), and the release of base cations from biochar itself (Wu et al., 2022). It is worth mentioning that biochar contains rich ash and mineral elements such as $K^+$, $Na^+$,$Ca^{2+}$ and $Mg^{2+}$, and when it was applied to the soil, thus increasing the soil pH (Wu et al., 2021b). However, the application of alkaline biochar in alkaline soils did not have a significant effect on pH. This might be a consequence of the buffering capacity of alkaline soils and the oxidation and decomposition of biochar to produce acid (Islam et al., 2021). The decrease in soil alkalinity after HMBC addition was attributable to the lower pH for HMBC (pH = 7.42). Soil pH decreased when the content of carboxyl functional groups on the surface of biochar was high, which may be caused by the conversion of urea to ammonia nitrogen in the soil induced by carboxyl functional groups (Nan et al., 2021). In addition, as the amount of biochar applied increased, the pH in the soil increased accordingly.

Leaching also had a significant effect on the reduction of EC of saline-alkali soil, which reduced soil EC from 622 to 200 µs/cm (Fig. 4b) ($p<0.05$). The biochar type and application rate showed a significant effect on soil EC under no-leaching treatment, compared to CK. After the addition of biochar, soil EC decreased, but EC increased with the increase of biochar application. Previous studies concluded that the EC significantly decreased after biochar treatment (Alshaal et al., 2024; Wang et al., 2024). This was

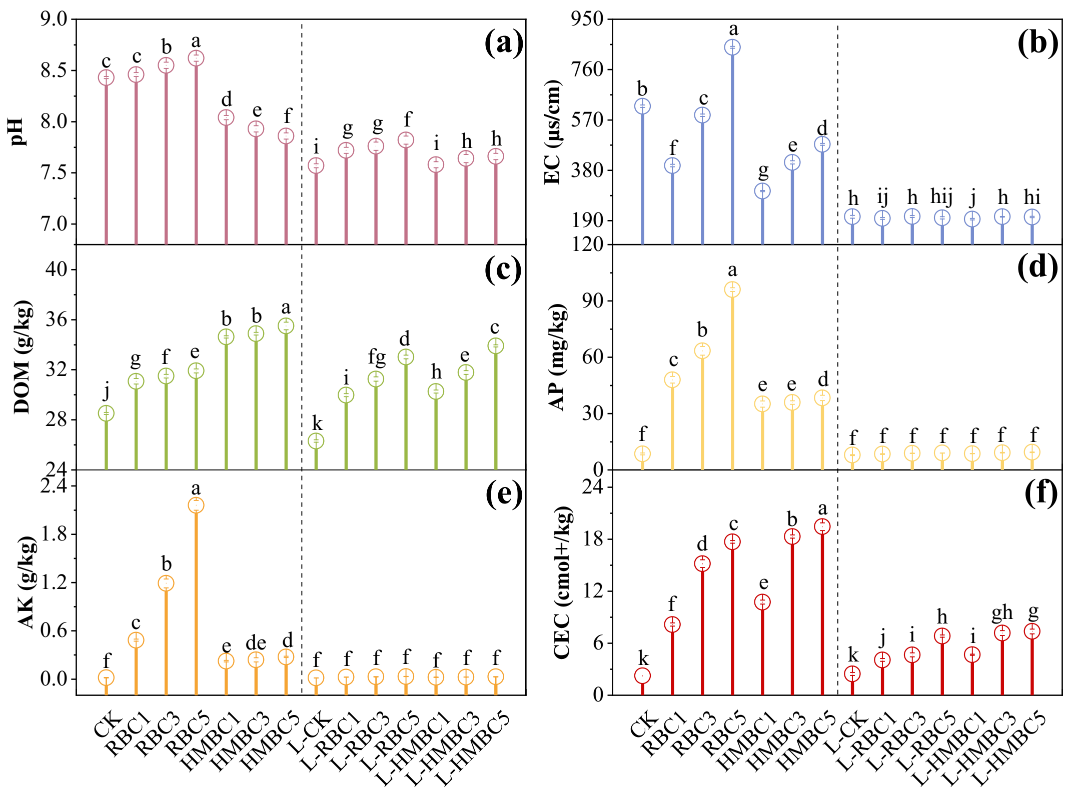


**Fig. 4** Properties of soil under different treatments: (**a**) pH, (**b**) EC, (**c**) DOM, (**d**) AP, (**e**) AK, and (**f**) CEC. Notes: Averages ± standard deviations were used to analyze the dispersion of data from triplicate samples ($n=3$). The difference between the letters represents a significant difference, which is based on a probability level of 0.05

most likely due to the biochar adsorbing salt from the soil and fixing $Na^+$ from the soil solution, further reducing soil salinity (Huang et al., 2019). However, the addition of biochar did not affect the soil EC after leaching treatment ($p > 0.05$). It may be because the leaching effect eluted most of the salt, resulting in a weakening of biochar adsorption.

Leaching decreased the content of DOM, AP, and AK in soil under CK treatment (Fig. 4c-e). The leaching with application of biochar increased DOM, AP and AK content in the soil, but the increase in AP and AK content was not significant. That's because biochar itself contains nutrients and releases the nutrients into the soil. Also, biochar has an adsorption effect on nutrients in the soil and avoids being lost by leaching (Zhang et al., 2021). Nutrient retention was caused by adsorption to an exchange complex created by the biochar addition (Lehmann et al., 2003). DOM, AK, and AP increased significantly with RBC and HMBC treatments. Compared to CK, DOM increased 9.01%-11.92% with RBC treatment and 21.43%-24.52% with HMBC treatment. Compared to L-CK, DOM increased 13.95%-25.50% with L-RBC treatment and 15.01%-28.89% with L-HMBC treatment. RBC5 and HMBC5 treatments increased soil AP by 10.27% and 3.50%, while increasing soil AK by 126, 88% and 15.34%, respectively, compared to CK. L-RBC5 and L-HMBC5 treatments increased soil AP by 13.95% and 19.42%, while increasing soil AK by 104.29% and 83.58%, respectively, compared to L-CK. This result showed that biochar could increase the AP and AK in the soil. With the increase of biochar application, AP and AK also increased. Biochar had a high surface area, which can adsorb more substances and increase the soil nutrient content (Yan et al., 2022).

Compared with RBC and HMBC treatments, leaching decreased soil CEC under L-RBC and L-HMBC treatments (Fig. 4f). Compared to CK, CEC increased 3.66–7.94 times with RBC treatment and 4.82–8.72 times with HMBC treatment. Compared to L-CK, CEC increased 1.65–2.77 times with L-RBC treatment and 1.90–2.99 times with L-HMBC treatment. As reported, the increase in soil CEC may be attributed to an increase in the oxygen-containing functional group in biochar (Zhao et al., 2020). HMBC had more oxygen-containing functional groups than RBC, so the CEC content in HMBC treated soil was higher. With the increase in biochar concentration, CEC also increased, indicating that biochar can effectively improve the cation exchange capacity of the soil (Wu et al., 2012). Biochar application to the soil generated positive and negative charges, reducing nutrient losses and thus increasing the soil CEC (Cao & Harris, 2010). In general, biochar application, especially HMBC5, with leaching contributed to the significant increase in soil fertility and improvement in soil quality.

### 3.3 Migration character of soluble salt in planting soil

To further explore the migration character of salt in the soil, the potting soil treated with RBC5 and HMBC5 with the best improvement effect was selected to determine the salt. The results showed (Fig. 5a) that the soil EC increased with the increase of soil depth. Compared to CK, both RBC5 and HMBC5 treatments decreased the soil EC. However, leaching significantly decreased soil EC in each layer. Combined with leaching and biochar application, soil EC decreased significantly. The addition of biochar increased the leaching of salts, helping to wash out the salt from the soil (Yue et al., 2016). What's more, HMBC5 was more effective than RBC5 in reducing soil EC. The content of $Na^+$ (Fig. 5b) in the soil profile of biochar treatment was similar to EC. The large specific surface area of HMBC provided more adsorption sites, which expanded the maximum adsorption capacity of biochar salt-based ions (Zhu et al., 2018). In addition, HA modification introduced oxygen-containing functional groups (-COOH, -OH, etc.), increased the surface complexation of $Na^+$ with carboxyl and hydroxyl functional groups, thus enabling salt ions to be immobilized in the biochar (Yang et al., 2021b). Therefore, HMBC5 showed the best adsorption effect.

The content of water-soluble $Ca^{2+}$ in soil decreased first and then increased (Fig. 5c), while the content of $K^+$ and $Mg^{2+}$ increased first and then decreased (Fig. 5d, e). The content of $Ca^{2+}$ decreased gradually in the 0–7.5 cm soil layer and increased gradually in the 7.5–12.5 cm soil layer. $K^+$ and $Mg^{2+}$ gradually increased in the 0–7.5 cm soil layer and gradually decreased in the 7.5–12.5 cm soil layer. The $K^+$ content of RBC treatment was much higher than that of other treatments, indicating that RBC

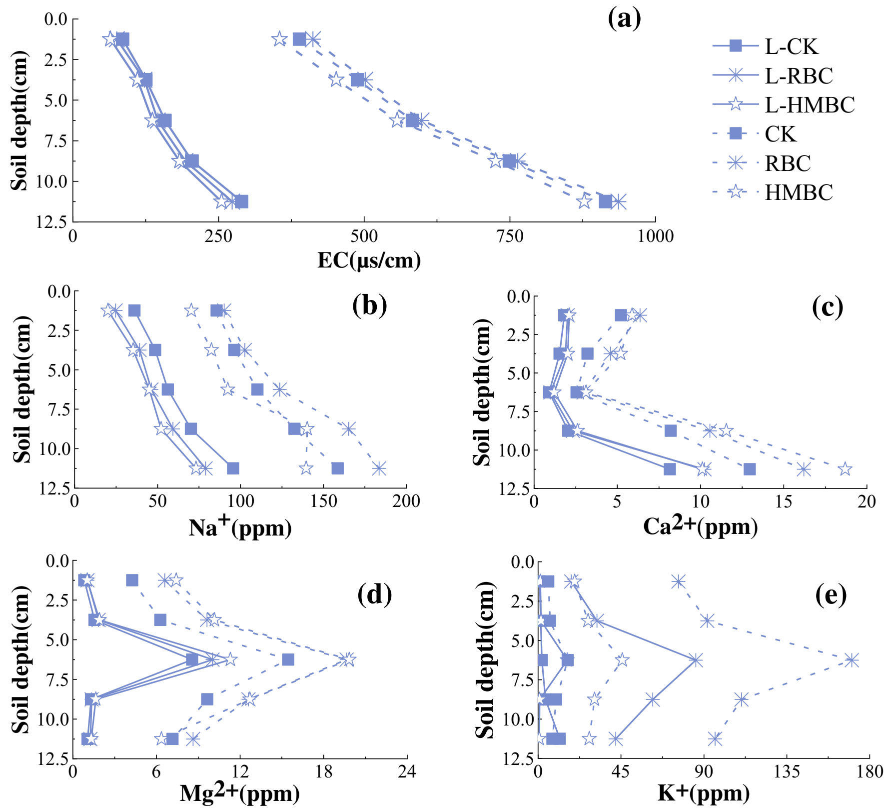


**Fig. 5** Distribution of (**a**) EC, (**b**)$Na^+$, (**c**)$Ca^{2+}$, (**d**) $Mg^{2+}$ and (**e**)$K^+$ at the end of the pot experiment with 5% biochar treatment

itself was rich in soluble potassium ions. Compared to under no-leaching treatment, $Na^+$, $Ca^{2+}$, $K^+$, and $Mg^{2+}$ under leaching treatment were reduced by 80% to 137% because of ion leaching. Leaching can greatly reduce salt concentration, which can alleviate the adverse effects of high concentrations of salt ions on plant growth. After applying biochar, current results clearly showed that the content of $Na^+$ in the soil decreased, and the content of $Ca^{2+}$, $K^+$, and $Mg^{2+}$ increased, indicating that biochar can enhance the $Na^+$ adsorption capacity of the soil (Akhtar et al., 2015; Xu et al., 2023) and release more $K^+$, $Ca^{2+}$, and $Mg^{2+}$ to the soil, which reduced the absorption of sodium by plants to alleviate the negative effects of salt stress, thereby improving plant growth. However, HA had more oxygen-containing functional groups that increased surface complexation with $Na^+$, so the most significant reduction of $Na^+$ was observed in HMBC-treated soils.

### 3.4 Effect of biochar on Pak Choi growth

The results of plant pot experiments were shown in Fig. 6. As shown in Fig. 6a, compared with CK, the germination rate of Pak Choi treated with biochar significantly increased by 58.32%-108.32%. Similarly, biochar helped improve the maize germination rates (Głodowska et al., 2016; Xu et al., 2023). The germination rate of Pak Choi planted in mild saline-alkali soil under leaching treatment was significantly higher than the no-leaching treatment. Therefore, leaching the soil to reduce salinity could improve the germination rate. The plant heights of L-RBC and L-HMBC treatments were nearly twice as high as that of L-CK (Fig. 6b), while L-HMBC5 had the most obvious effect on the plant height, which reached 9.13 cm. Compared to CK, plant height under L-CK was increased by 9.7%. The increase in plant height was attributed to soil improvements in pH and the preservation of nutrients by biochar application (He et al., 2021). Plant roots tend to grow from deeper in biochar containing soils and thus take up more nutrients (Feng

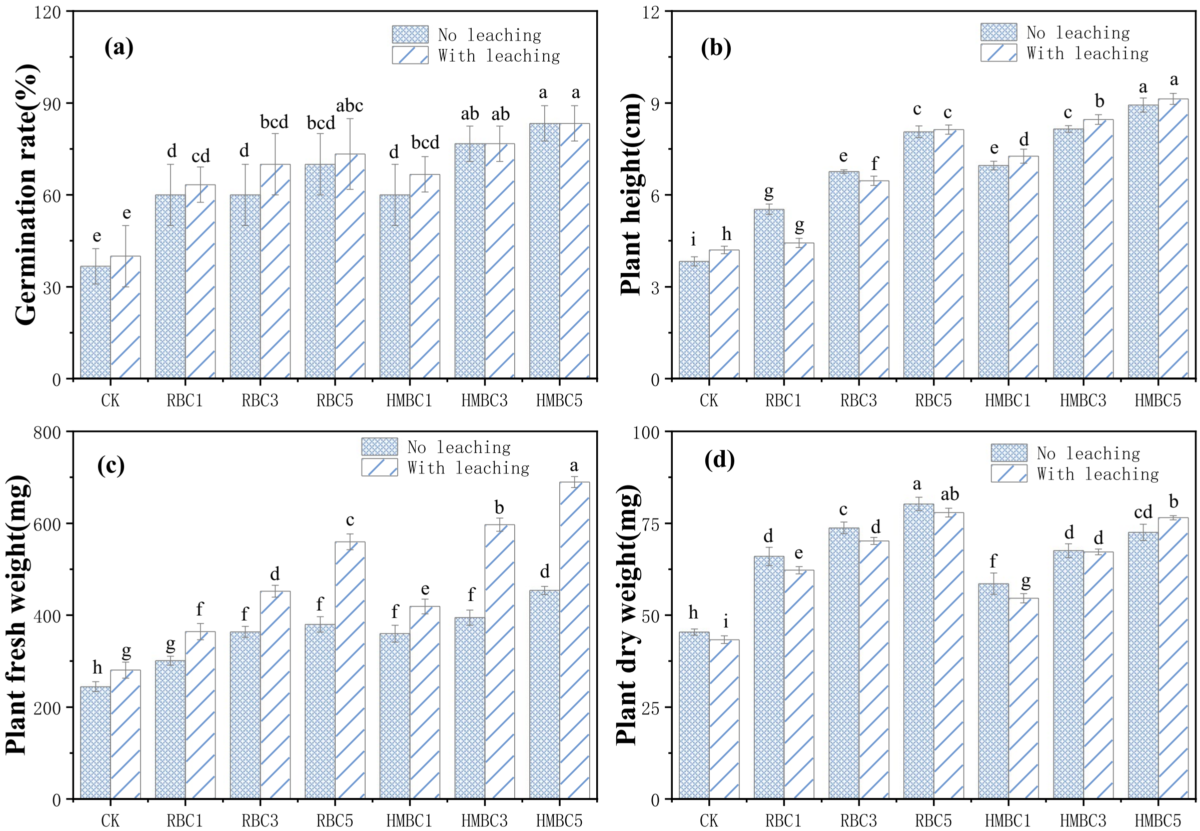


**Fig. 6** Effects of Leaching and Biochar on Growth Parameters of Pak Choi: (**a**) germination rate; (**b**) plant height; (**c**) plant fresh weight; (**d**) plant dry weight

et al., 2021; Sun et al., 2023). Due to the special structure of biochar, the application of biochar can also improve soil porosity and increase soil water-holding capacity (Hou et al., 2023), thus reducing soil water leaching (Abideen et al., 2020; Verheijen et al., 2019), which was conducive to the growth of plant roots in the soil. The porosity of HMBC was higher than that of RBC, so HMBC had a better effect on soil nutrient retention. HMBC can also increase the water supply of plants and improve agricultural productivity, which can alleviate environmental problems such as water shortage (Adhikari et al., 2022).

The fresh weight of Pak Choi treated with L-RBC5 and L-HMBC5 was significantly increased by 99.6% and 146.1% (Fig. 6c), respectively, compared to L-CK. Under L-CK treatment, fresh weight was increased by 14.8%, compared to CK. The dry weight of Pak Choi treated with L-RBC5 and L-HMBC5 also increased by 79.9% and 76.6% (Fig. 6d), respectively, compared to L-CK. Compared to CK, the dry weight of Pak Choi under L-CK treatment decreased by 2.08 mg. It can be seen that the dry weight of L-RBC5 treated plants was the heaviest, up to 77.91 mg. The effect of HMBC on plant dry weight was significantly different from that on fresh weight. These results confirmed that the germination rate, fresh weight, dry weight, and height of Pak Choi were more obvious with the increase in biochar application amount ($p > 0.05$). At the same time, the changing trend of HMBC with and without leaching was almost consistent with that of RBC. The leaching treatment and the application of biochar had a more pronounced effect compared to the direct application of biochar without leaching, indicating that the salt content of the soil inhibits the effect of biochar on the soil. In this study, similar to a previous report (Yan et al., 2022), the application of biochar can alter the nutrient availability and physical structure in the soil and further influence plant growth. Once biochar was applied, plants would grow better (Cui et al., 2022) and with the increase of biochar application, there was a promotion effect on plant growth. For example, studies have shown that rice straw biochar application on rice growth and yield showed a positive impact, especially the high amount of biochar (Wu et al., 2021a). Besides, HMBC was more effective than RBC in promoting the growth of Pak Choi. The plant height under L-RBC was shorter than L-HMBC. It may be due to HMBC having a stronger adsorption effect on nutrients, which was more conducive to maintaining soil nutrient loss. These results confirmed that RBC application could cause nutrient loss, whereas HMBC application facilitated to mitigate this negative effect. Therefore, the growth height of Pak Choi was highest under L-HMBC treatment.

Similarly, the current research found that rice straw biochar can not only promote the growth of Pak Choi but also improve its quality. Figure 7a, compared with CK, the chlorophyll content of RBC5 and HMBC5 increased by 38.5% and 76.9%, respectively. Compared with L-CK, the chlorophyll content of L-RBC5 and L-HMBC5 increased by 57.5% and 138.6%, respectively. A similar pattern of results was obtained in a previous study (Feng et al., 2022). However, the chlorophyll content of Pak Choi planted in mild saline-alkali soil with leaching treatment was lower than that without leaching, except for HMBC5. It can be seen that leaching had a side effect on the content of chlorophyll, indicating that the elements of chlorophyll synthesis in soil were leached. The reduction in chlorophyll content may also have been due to the production of reactive oxygen species (ROS) resulting in impaired chlorophyll a, which inhibited photosynthesis in plants (Aldinary et al., 2021). Therefore, it was detrimental to plant growth.

The content of soluble protein in Pak Choi was opposite to that of leaf chlorophyll, and the content with leaching treatment was higher than that without leaching. The content of soluble protein had significant differences among different treatments ($P<0.05$). Compared with CK treatment, the content of soluble protein in L-CK treatment increased by 0.84 mg·g$^{-1}$. With the increase of biochar dosage, the content of protein increased, and the content of soluble protein in HMBC5 treatment was the highest (26.88 mg·g$^{-1}$). The results were shown in Fig. 7b, compared with CK, the soluble protein content of RBC5 and HMBC5 treatments with leaching increased by 26.7% and 32.2%. The content of soluble sugar had significant differences among different treatments ($P<0.05$). As shown in Fig. 7c, the content of soluble sugar with leaching treatment was slightly higher than that without leaching. The content of soluble sugar in L-CK increased by 0.55 mg·g$^{-1}$, compared to CK. Compared with L-CK, the soluble sugar content of the L-RBC5 treatment decreased by 2.06 mg, and the soluble sugar content of the L-HMBC5 treatment increased by 5.31 mg. It indicated that the application of RBC had a side effect on the soluble sugar content of plants, while HMBC had a positive effect. Saline-alkali soil environment had a certain inhibitory effect on the Pak Choi growth, leading to the increase of soluble sugar content as a stress regulator (Rosa et al., 2009).

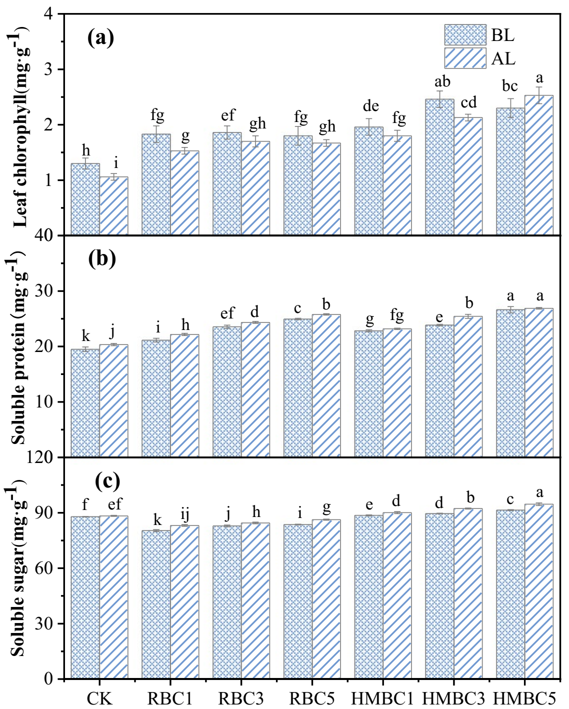


**Fig. 7** Effects of leaching and biochar on the quality of Pak Choi: (**a**) leaf chlorophyll; (**b**) soluble protein; (**c**) soluble sugar

## 4 Conclusions

Compared with RBC, HMBC significantly increased the number of oxygen-containing functional groups, specific surface area, and porosity. HMBC treatment could improve DOM, AK, AP, water content, and CEC in soil. Moreover, the combination of leaching and HMBC had a better remediation effect on saline-alkali soil than the no-leaching treatment, indicating that the salt content of the soil inhibited the effect of biochar on the soil remediation. Leaching had a significant effect on the salinity reduction of saline-alkali soil, lowering the pH from 8.43 to 7.5 and EC from 622 μs/cm to 200 μs/cm. HMBC released more $Ca^{2+}$, $K^{+}$, and $Mg^{2+}$ into soil and enhanced the $Na^{+}$ sorption capacity of soil in each layer. Due to the greatly reduced salt concentration, the adverse effects of high salt ion concentrations on Pak Choi growth were alleviated. In addition, the application of RBC and HMBC with leaching could enhance the germination rate, fresh weight, dry weight, and plant height of Pak Choi. Among these treatments, HMBC5 with leaching was most effective in repairing mild saline-alkali soil. The application of HMBC to saline-alkali soil may solve the problem of poor soil quality to a certain extent, thus realizing the improvement of Pak Choi. Therefore, the combination of HMBC with leaching may be a promising way to improve soil properties and promote plant growth in the coastal mild saline-alkali soil, which can provide certain theoretical support for the remediation and improvement of mild saline-alkali soil in the future.

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**Data Availability** Data will be made available on reasonable request.

**Declarations**

**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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