



# OPEN Biochar can promote the growth of peanuts in saline alkali soil by enhancing peanut resistance and improving soil properties

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Soil salinization seriously threatens the health of existing farmland and crops, and peanut cultivation is also threatened by soil salinization. Biochar has been widely studied as a soil amendment to improve the growth of various crops such as wheat and corn in saline alkali land, yet its effects on peanut growth in saline alkali soils remain underexplored. Therefore, we aim to conduct greenhouse pot experiments to test the promoting effect of biochar on the growth of peanuts in saline alkali soil, and to study the impact mechanism of biochar microbial composition. The results indicate that the application of biochar can directly improve the physicochemical properties of peanut rhizosphere soil. Compared with the control group, peanut sprout height and fresh weight significantly increased. The exploration of its causes has found that biochar can directly or indirectly improve the properties of rhizosphere soil, including reducing soil salinity and alkalinity, and increasing water content. On the other hand, biochar treatment significantly increased the availability of essential nutrients like ammonium nitrogen, available phosphorus, and organic matter which is crucial for maintaining peanut growth. At the same time, the content of stress resistant substances, including peroxidase activity, in peanuts significantly increased, while the content of malondialdehyde also decreased, further indicating that the application of biochar promotes the resistance of peanuts to salt alkali stress. In summary, the application of biochar can directly reduce the pH and moisture content of peanut rhizosphere soil, increase rhizosphere nutrient content, and enhance peanut antioxidant enzyme activity, ultimately promoting its growth in saline alkali soil.

**Keywords** Saline alkali soil, Biochar, Peanut, Enzymes, Resistance

The Soil salinization is one of the main ways of soil degradation in the world today. Especially in arid and semi-arid regions, insufficient precipitation further exacerbates the occurrence of soil salinization. It is estimated that approximately 1.1 billion hectares of land (about 7% of the global land area) are currently affected to varying degrees by soil salinity<sup>1</sup>. And it grows at a rate of about 1–2% per year. Salinity has adverse effects on crop growth, causing billions of dollars in economic losses to global agricultural production annually<sup>2</sup>. Soil salinization can lead to an increase in soil solution osmotic pressure, making it difficult for plants to absorb water and causing physiological dehydration. On the other hand, it can also cause a large number of adverse effects such as ion toxicity and oxidative damage, seriously affecting crop yield. On the other hand, degraded soil can lead to the leaching of artificial fertilizers, further causing environmental risks such as groundwater pollution. Therefore, accelerating the restoration of saline alkali soil and ecological construction has important value and significance for local environmental health<sup>3</sup>.

Biochar is prepared by slow pyrolysis biomass under oxygen-limited conditions, during pyrolysis, one-third to half of biomass is converted into biochar<sup>4,5</sup>. Pyrolysis also brings huge specific surface area and void structure, showing excellent adsorption capacity, has been a widely using in environment refresh including water, soil and air<sup>6</sup>. Among them, there are more and more researches in soil remediation and improve plant growth, for example, enhance plant growth by supplying nutrients, and retain nutrients. In this regard, an obvious positive attribute of biochar is its nutrient value, supplied either directly by providing nutrients or indirectly by

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improving soil environment, with consequent improvement of fertilizer use efficiency<sup>7–9</sup>. Bera et al., (2017)<sup>10</sup> helps to reduce nutrient leaching and increases crop production. Peng et al., (2011)<sup>11</sup> also provides other services such as improving soil physical and biological properties.

Biochar amendments were reported to improve soil bulk density, porosity, water retention, and hydraulic conductivity<sup>12,13</sup>. It also has the capability to improve water retention properties of soil and enhance the soil's ability to retain nutrients<sup>14</sup>. It could alter various soil properties through changes in pore size distribution, residence time of soil solution and flow paths of nutrients<sup>15</sup>. Overall, biochar can potentially add a holistic dimension for enhancing the soil quality and health which sooner or later is believed to impact crop productivity positively.

The impact of biochar on crop productivity is largely influenced by the crop type, soil and biochar properties, which in turn depend on feedstock source and pyrolysis temperature. As one of the main soils to be developed in China, the full development of saline alkali soil is of great significance. However, limited by the alkalinity of biochar, there is little research on biochar applied in saline alkali soil at present, Huang et al (2019) reported biochar improved plant growth in saline soil, and think soil improvement is the main reason for plant growth<sup>16</sup>. Meanwhile, Zhou et al (2021) also discovered that the remarkable adsorption properties of biochar play a significant role in reducing the uptake of Na<sup>+</sup> by plants<sup>17</sup>. This is achieved through the rapid adsorption of Na<sup>+</sup> ions by biochar, which limits their availability to plants. On the other hand, the properties of biochar are severely affected by the production process, including preparation temperature, etc. Therefore, different biochar have different properties, which also leads to different impacts in different environments. Currently, most commonly used biochar contains abundant organic functional groups, which may have good adsorption value for excessive alkaline functional groups in saline alkali soil. Therefore, research has been conducted on the growth of various crops such as wheat and corn in saline alkali soil, But the research on peanuts is not deep and specific enough. Therefore, we set a pot experiment to study the mechanism of peanut shell biochar on the growth of peanut in saline alkali soil and the influence of soil quality, aims to establish a healthy and environment friendly biochar utilization method.

## Materials and methods

### Experiment design

The experimental materials were selected from the salt-tolerant variety Huayu 25 (HY 25). Soil samples were collected from Dongying City, Shandong Province. After collecting 20 cm of surface soil, they were brought back to the greenhouse for future use. The soil indicators are as follows: Organic Matters:6.5 g kg<sup>-1</sup>,hydrolyzable Nitrogen 35.5 mg kg<sup>-1</sup>,Available Phosphorus 23.2 mg kg<sup>-1</sup>, Available Potassium 89.9 mg kg<sup>-1</sup>, Soil Salt Content 3.0 g kg<sup>-1</sup>, pH8.8.

### Experimental design

This experiment was conducted in a greenhouse, and soil samples were collected from in Dongying City (118° 39' N, 36 °57' E), Shandong Province. 20 cm of surface soil was collected and brought back to the greenhouse for future use. The soil indicators are as follows: Organic Matters: 6.5 g kg<sup>-1</sup>, hydrolysable Nitrogen 35.5 mg kg<sup>-1</sup>, available Phosphorus 23.2 mg kg<sup>-1</sup>, available Potassium 89.9 mg kg<sup>-1</sup>, soil Salt Content 3.0 g kg<sup>-1</sup>, pH8.8.

Biochar was prepared by mixing biomass (peanut shells and wood fiber,1/2,w/w). Firstly, dry the biomass at 90 °C and slowly pyrolyze it with oxygen at 480 °C for 2 h. With hydrochloric acid for 30 min, air dry and grind it into powder for later use. The basic properties of biochar are pH 6.8 and conductivity of the EC was 0.51 mS cm<sup>-1</sup>, the content of C was 79%, O was 18%, K was 1%.

Design treatment groups by adding biochar with different concentrations. Including control (CK) adding 2% biochar treatment (PB2), adding 3% biochar treatment (PB3). Mix the biochar evenly with the soil and fill it into the pot. Three repetitions per treatment.Plant three peanut seeds in each pot (25 cm diameter and 30 cm height) and maintain a field water holding capacity of 60%. The greenhouse maintains a temperature of 25 °C, with 12,000 lx of light and 55% humidity. Then, following normal irrigation treatment, samples were collected after 90 days of uniform growth for subsequent property determination.

### Measurements of soil and plant properties

The soil suspension (water: soil, 1:5, w/v) was shaken for 1 h. pH and EC values were determined using a pH meter and conductivity meter, respectively<sup>13</sup>. The total N was measured using the Kjeldahl technique. The total P and K were measured using the NaOH melting and UV-vis spectrophotometer method and atomic absorption spectrophotometry method, respectively. Soil organic matter (SOM) content was determined via potassium dichromate oxidation. Soil contents of sodium (Na) and potassium (K) were determined using inductively coupled plasma mass spectrometry (ICP-MS). Nitrate nitrogen (NO<sub>3</sub><sup>-</sup>-N) in soil was determined with the phenol-disulfuric acid colorimetric method. Ammoniacal nitrogen (NH<sub>4</sub><sup>+</sup>-N) in soil was extracted with 2.0 M KCl and determined using the colorimetric method. The determination of soil enzyme activity is carried out using commercial reagent kits, and the specific methods are described in the instructions. The amount of available potassium was determined by leaching with 1.0 M NH<sub>4</sub>OAc and flame photometry<sup>15–17</sup>.

The measurement of plants adopts traditional measurement methods, including the use of rulers and scales. The determination of plant enzyme activity and MDA content is carried out using commercial reagent kits, and the specific methods are described in the instructions.

### Soil total DNA extraction and high-throughput sequencing

Soil samples, after collection, were quickly frozen and stored at –80 C. Bacterial DNA was isolated from soil samples using the DNeasy PowerSoil kit (Qiagen, Hilden, Germany) following the manufacturer's instructions. The DNA concentration and integrity were measured using a NanoDrop 2000 spectrophotometer (Thermo Fisher

Scientific, Waltham, MA, USA) and agarose gel electrophoresis, respectively, with agarose gel electrophoresis used for the measurement. PCR amplification of the V3–V4 highly variable region of the bacterial 16 S rRNA gene was performed using a universal primer pair (343 F: 5' 0'-TACGGRAGGCAGCAG-3' 0; 798R: 5' -AGGG TATCTAATCCT-30) in a 25  $\mu$  L reaction. The reverse primer contained a sample barcode, and both primers were ligated with Illumina sequencing adapters. Amplicon quality was visualized via gel electrophoresis. PCR products were purified using Agincourt AMPure XP beads (Beckman Coulter, Brea, CA, USA) and quantified using the Qubit dsDNA detection kit. Concentrations were then adjusted for sequencing. Sequencing was performed on an Illumina Miseq with two paired read cycles of 300 bases each (Illumina Inc., San Diego, CA, USA; OE Biotech Company, Shanghai, China). Paired reads were preprocessed using Trimmomatic software to detect and cut off ambiguous bases (N). It also cut off low-quality sequences with an average quality score of less than 20 using a sliding window pruning method. After trimming, pairs of reads were assembled using FLASH software (10.1). The parameters for the assembly were as follows: minimum overlap of 10 bp, maximum overlap of 200 bp and maximum mismatch rate of 20%. Sequences were further denoised as follows: reads with ambiguous, homologous sequences or below 200 bp were discarded. Seventy-five per cent of the reads with bases above Q20 were retained using QIIME software (version 1.8.0). Reads with chimeras were then detected and removed using VSEARCH software (2.8.1). Primer sequences were removed and clustered based on clean reads using VSEARCH software to produce actionable taxonomic units (OTUs) with 97% similarity. Representative reads for each OUT were selected using the QIIME software package. All representative reads were annotated and tested against the Silva database (version 123) using the RDP classifier threshold of 70%

### Statistical analysis

We analyzed the data in SPSS 17.0 software. Treatments were compared with one way analysis of variance and Duncan's multiple range test. Unless otherwise stated, the significance threshold was a p-value less than 0.05.

## Results

### The use of biochar promotes the growth of peanuts

The growth indicators of plants can directly reflect the quality of their living environment. Compared with the control, biochar treatment improved the growth indicators of peanuts in saline alkali soil. On the one hand, plant height significantly increased in biochar treatment, with an increase of 44.91% to 49.90% compared to CK. Similarly, the fresh weight of aboveground stems increased by 20.47% to 31.87% in biochar treatment and it has reached a significant level. This indicates that the use of biochar significantly improves the growth status of peanuts. On the other hand, the growth indicators of peanut roots have also been improved, including a significant increase in root length and fresh weight. Especially, the maximum value was obtained in PB3 processing.

### The use of biochar improves soil properties

The poor physicochemical properties of saline alkali soil are one of the main reasons limiting plant growth. As shown in the results, the application of biochar significantly reduced soil acidity and alkalinity, and increased with the increase of usage concentration, indicating that the use of biochar can directly reduce soil acidity and alkalinity, and both reached a significant level. At the same time, the soil moisture content increased in the biochar treatment group, with the PB3.0 treatment group having the highest content, an increase of nearly 50% compared to the control group. On the contrary, soil bulk density decreased under biochar treatment.

### The application of biochar improved the nutrient levels of rhizosphere soil

The growth status of peanuts is closely related to the root soil environment. Therefore, we further collected rhizosphere soil to determine soil nutrient indicators. The results showed that the content of ammonium nitrogen significantly increased in the biochar treatment group, with an increase of about 25% compared to the control. Furthermore, the content of available phosphorus increased by nearly 50% in the biochar treatment group, with the highest increase observed in PB3 treatment. Similarly, the content of available potassium was also affected, and the content of available potassium increased in the biochar treatment group. Correspondingly, both nitrate nitrogen and organic matter content showed an increase in the biochar treatment group, with an increase of approximately 11% to 31% compared to the control group. This indicates that the use of biochar directly or indirectly improves the nutrient levels of peanut root soil.

### Application of biochar improved root soil enzyme activity

Soil enzyme activity represents the ability of nutrient cycling and is also one of the indicators of soil health. The results of this experiment showed that the application of biochar promoted an increase in soil enzyme activity. The activity of catalase significantly increased compared to the control group, increasing by 12.52%~14.39%, while the activity of phosphatase increased by 21.13%~31.84%, both reaching significant levels. The activities of urease and sucrase also increased in biochar treatment, but compared to phosphatase, the increase in activity did not reach a significant level, increasing by about 10% each.

### The application of biochar affects the ability of peanuts to resist salt alkali stress

Peanuts growing in saline alkali soil are inevitably subjected to salt alkali stress and oxidative stress, so the improvement of peanut growth status is closely related to its stress resistance ability. Therefore, we also measured the physiological indicators of peanut stress resistance. The results showed that the activity of three representative antioxidant enzymes (SOD, POD, CAT) significantly increased compared to the control, with SOD showing a smaller increase of about 20% each, while POD showed the largest increase of over 50% each. On the other hand, as the main osmotic regulator, the content of free proline is also significantly affected by biochar treatment. Compared

with the control, the proline content significantly increased by nearly twice in biochar treatment, significantly improving the stress resistance of peanuts. On the contrary, the content of malondialdehyde, which characterizes the degree of membrane damage, significantly decreased in the biochar treatment group, indicating that the application of biochar reduced the salt alkali stress on peanuts.

### The application of biochar affects the microbial composition of peanut roots

Root microbiota plays an important role in plant growth, and the results of this experiment showed that the application of biochar affects the composition and diversity of peanut root microbiota community structure (Fig. 1). Compared with the control group, the bacterial diversity in the biochar treatment group increased, with chao increasing by 29% to 38%, significantly improving root diversity. On the other hand, the Shannon index also increased significantly in the biochar treatment group.

In terms of composition, the application of biochar significantly increased the relative abundance of Proteobacteria and Bacteroidetes. The abundance of *Acidobacteria* decreased, while the relative abundance of Actinobacteria increased, and the abundance of *Gemmatimonas* significantly decreased. On the other hand, the relative abundance of *Saccharibacter* increases. This indicates that the application of biochar significantly affects the community composition of root microorganisms.

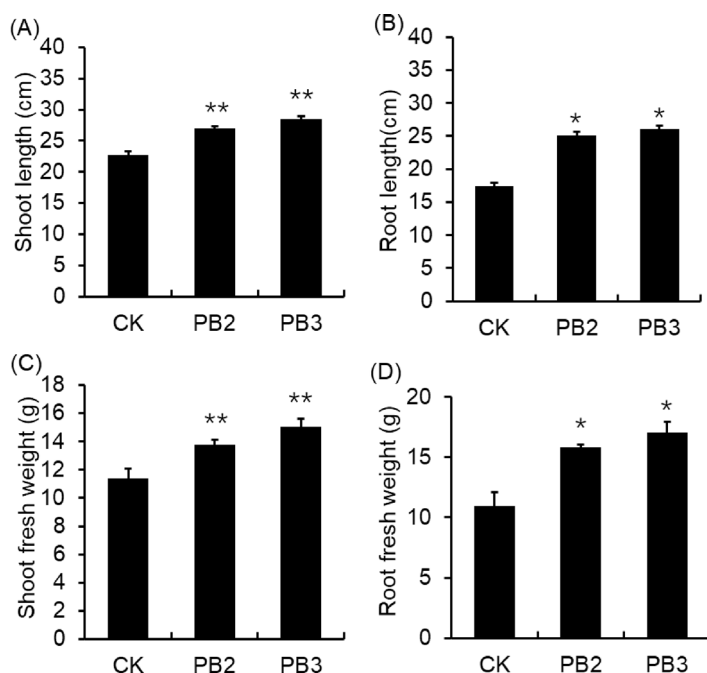
## Discussion

### The effect of biochar on peanut growth

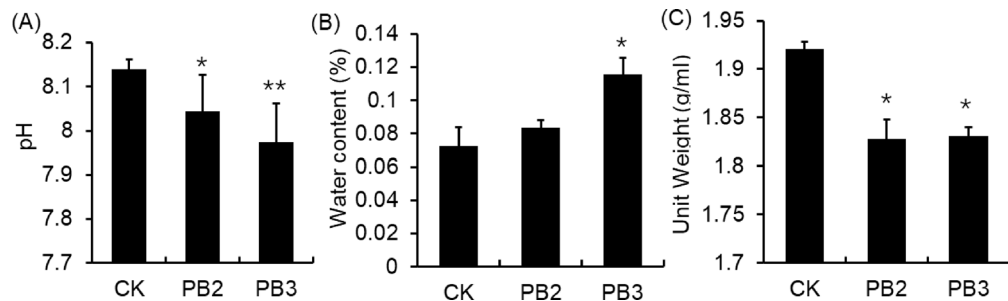
As a popular green soil additive, biochar has been widely used in various soil remediation applications. Including acidic, heavy metal contaminated soil, saline alkali soil, etc.<sup>18, 19</sup>, however, due to the preparation method of biochar, different biochar has different effects. For example, Guo et, al(2015) reported that using straw biochar promoted the growth of corn and significantly increased crop yield compared to the control. Similarly<sup>20</sup>, Mao et, al (2023) reported that the application of biochar improved soil properties, enhanced cotton stress resistance, and promoted growth<sup>21</sup>. In this experiment, the application of biochar significantly improved the plant height, fresh weight, and root growth of peanuts(Fig. 2). This indicates that the application of biochar has a positive effect on peanut growth, which may be explained as follows: biochar itself can promote peanut growth, including stimulating root growth<sup>22</sup>, and secondly, biochar can promote peanut growth by improving the peanut growth environment, including improving soil properties, etc<sup>23, 24</sup>.

### Improvement effect of biochar on soil physicochemical properties

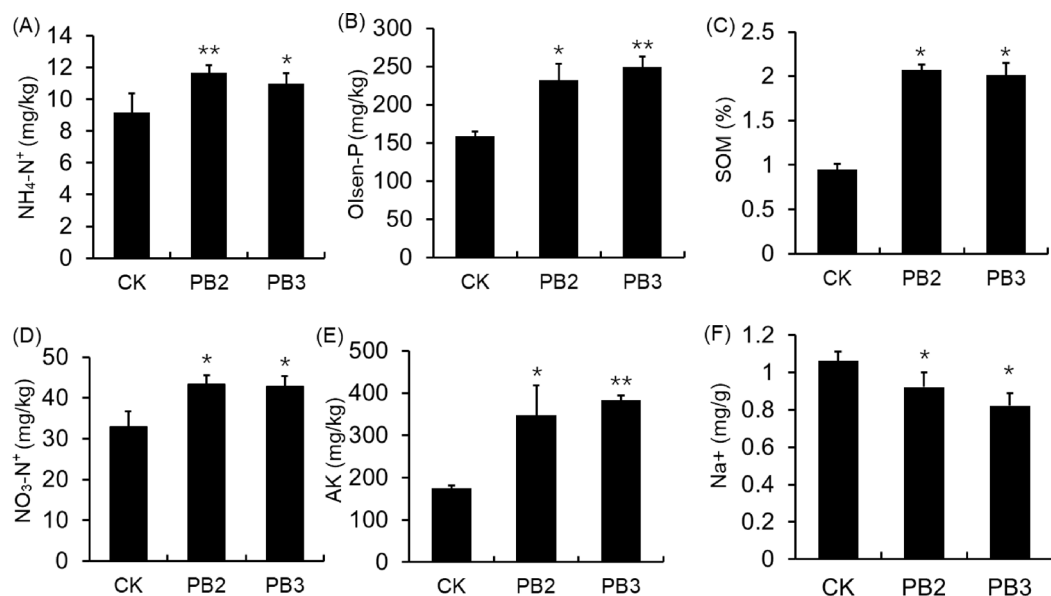
The improvement of peanut growth is inevitably accompanied by an improvement in the growth environment. Saline alkali soil poses significant barriers to peanut growth, leading to reduced yields. The application of biochar has been extensively reported to improve soil properties, including reducing soil pH, increasing soil moisture and organic matter content, etc<sup>25-27</sup>. In this experiment, the same results were also obtained, such as a decrease in pH and an increase in moisture content (Fig. 3). At the same time, the significant increase in effective nutrients such as nitrogen, phosphorus, and potassium (Fig. 4) indicates that the application of biochar significantly improves the fertility level of saline alkali soil, thereby ensuring the nutrient supply for peanut



**Fig. 1.** Biochar affects peanut growth indicators (A–D). PB2 represents 2% addition of biochar, PB3 represents 3% addition of biochar. Data were expressed as mean  $\pm$  SD ( $n = 3$ ).



**Fig. 2.** Biochar affects roots growth indicators (A-C). PB2 represents 2% addition of biochar, PB3 represents 3% addition of biochar. Data were expressed as mean  $\pm$  SD (n = 3)..



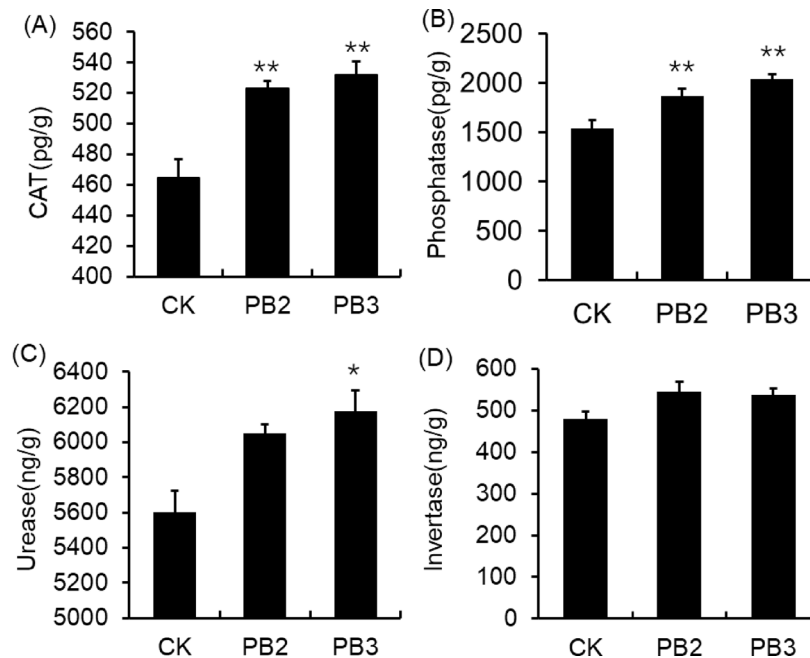
**Fig. 3.** Biochar affects soil fertilizer characters (A-F). PB2 represents 2% addition of biochar, PB3 represents 3% addition of biochar. Data were expressed as mean  $\pm$  SD (n = 3).

growth<sup>28</sup>. On the other hand, the increase in organic matter content also indicates the improvement of saline alkali soil, which suggests that the application of biochar directly or indirectly promotes the improvement of soil properties, thereby affecting the growth environment of peanut roots<sup>29</sup>.

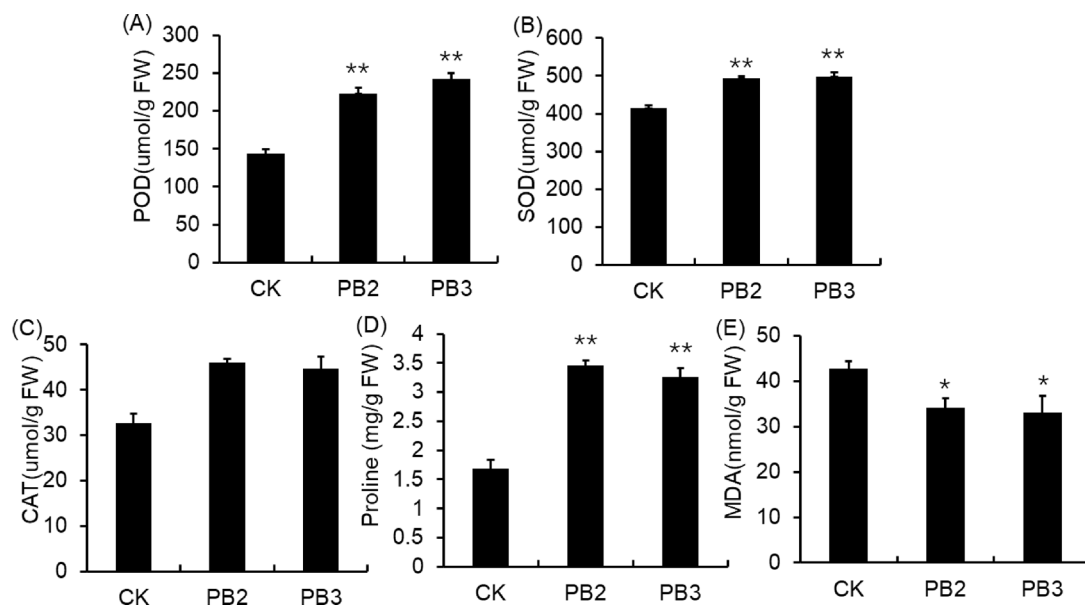
As one of the important links in nutrient cycling, the activity of soil enzymes directly reflects the rate of soil nutrient cycling. In this experiment, the application of biochar significantly increased soil enzyme activity (Fig. 5), which is consistent with the report by Saha et al (2019)<sup>30</sup>. Similarly, Tu et al (2020)<sup>31</sup> reported that the use of biochar promoted the activity of urease and phosphatase in soil, indicating that the application of biochar can directly improve soil nutrient levels. On the other hand, the structure of soil microbial communities is also significantly influenced by biochar<sup>32,33</sup>. As the main component of soil, changes in bacterial community structure directly affect soil element cycling. Montes et al (2020)<sup>34</sup> reported that the use of biochar significantly affected bacterial community structure and promoted an increase in the content of Proteobacteria. On the other hand, Gao et al (2019)<sup>35</sup> reported that the use of biochar also affected community structure, including the abundance of Bacteroidetes and other communities. This is also consistent with the results of this experiment (Fig. 1), which indicate that biochar directly or indirectly affects the soil environment for peanut growth, thereby affecting peanut growth.

### The effect of biochar on peanut stress resistance

Peanuts grow in saline alkali soil and are first subjected to environmental resistance such as salt alkali stress and oxidative stress. There have been numerous reports demonstrating that the application of biochar can enhance plant stress resistance, including an increase in peroxidase activity<sup>36,37</sup>. In this study, the use of biochar significantly increased the activity of three peroxidase scavenging enzymes (Fig. 6), indicating that the use of biochar promotes peanut resistance to salt alkali stress by increasing enzyme activity. On the other hand, free proline, as a common osmotic regulator, significantly increases under biochar treatment, enhancing peanut resistance to osmotic stress<sup>38,39</sup>. At the same time, the decrease in malondialdehyde content, which characterizes



**Fig. 4.** Biochar affects soil enzymes activities (A–D). PB2 represents 2% addition of biochar, PB3 represents 3% addition of biochar. Data were expressed as mean  $\pm$  SD ( $n = 3$ ).

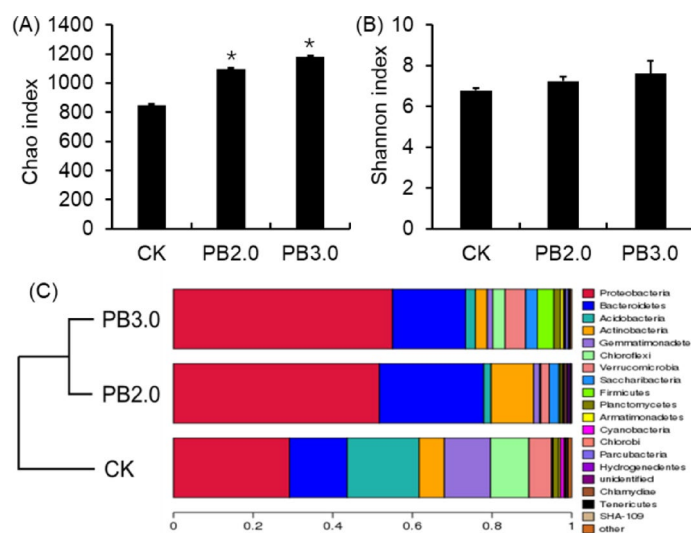


**Fig. 5.** Biochar affects peanut enzymes activities (A–E). PB2 represents 2% addition of biochar, PB3 represents 3% addition of biochar. Data were expressed as mean  $\pm$  SD ( $n = 3$ ).

the degree of cell membrane damage, further indicates that the use of biochar can significantly improve the environmental resistance of peanuts to salt alkali stress and promote their growth in saline alkali soil<sup>40</sup>.

## Conclusion

The use of biochar can improve the growth of peanuts in saline alkali soil, mainly by improving soil physical and chemical properties and enhancing soil fertility levels. At the same time, the application of biochar also promotes the increase of peanut peroxidase activity, which ensures the resistance of peanuts to saline alkali stress. However, the conclusion of this experiment is based on greenhouse pot experiments, and we hope to conduct more experiments in the field in the future.



**Fig. 6.** The biochar affects the microbial composition of peanut roots. (A) Chao index; (B) Shannon index; (C) The Species composition..

### Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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### References

- Hassani, A., Azapagic, A. & Shokri, N. Global predictions of primary soil salinization under changing climate in the 21st century. *Nat. Commun.* **12**, 6663. <https://doi.org/10.1038/s41467-021-26907-3> (2021).
- Zhang, X. et al. Biochar addition combined with daily fertigation improves overall soil quality and enhances water-fertilizer productivity of cucumber in alkaline soils of a semi-arid region. *Geoderma* **363**, 114170 (2020).
- Rengasamy, P. Soil processes affecting crop production in salt-affected soils. *Funct. Plant. Biol.* **37**, 613–620 (2010).
- Lehmann, J., Gaunt, J. & Rondon, M. Biochar sequestration in terrestrial ecosystems: A review. *Mitig. Adapt. Strateg. Glob. Change.* **11**, 403e427 (2006).
- Bera, T. et al. Influence of select bioenergy by-products on soil carbon and microbial activity: a laboratory study. *Sci. Total Environ.* **653**, 1354e1363 (2019).
- Olmo, M., Villar, R., Salazar, P. & Albuquerque, J. A. Changes in soil nutrient availability explain biochar's impact on wheat root development. *Plant. Soil.* **399** (1e2), 333e343 (2016).
- Karer, J., Wimmer, B., Zehetner, E., Kloss, S. & Soja, G. Biochar application to temperate soils: effects on nutrient uptake and crop yield under field conditions. *Agric. Food Sci.* **22**, 390e403 (2013).
- Huang, M., Zhang, Z., Zhu, C., Zhai, Y. & Lu, P. Effect of Biochar on sweet corn and soil salinity under conjunctive irrigation with brackish water in coastal saline soil. *Sci. Hort.* **250**, 405–413 (2019).
- Bera, T., Purakayastha, T. J., Patra, A. K. & Datta, S. C. Comparative analysis of physicochemical, nutrient, and spectral properties of agricultural residue biochars as influenced by pyrolysis temperatures. *J. Mater. Cycles Waste Manag.* **20**, 1115e1127 (2017).
- Peng, X., Ye, L. L., Wang, C. H., Zhou, H. & Sun, B. Temperature- and duration-dependent rice straw-derived biochar: characteristics and its effects on soil properties of an ultisol in Southern China. *Soil. Tillage Res.* **112**, 159e166 (2011).
- Sohi, S. P., Krull, E., Lopez-Capel, E. & Bol, R. A review of Biochar and its use and function in soil. *Adv. Agron.* **105**, 47e82 (2010).
- Ahmad, M. et al. Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere* **99**, 19e23 (2014).
- Ahmad Bhat, S. et al. Application of Biochar for improving Physical, Chemical, and hydrological soil properties: A systematic review. *Sustainability* **14** (17), 11104. <https://doi.org/10.3390/su141711104> (2022).
- Schmidt, H. P. et al. Biochar and biochar-compost as soil amendments to a vineyard soil: influences on plant growth, nutrient uptake, plant health and grape quality. *Agric. Ecosyst. Environ.* **191**, 117e123 (2014).
- Sun, Z. et al. Effect of Biochar on aerobic processes, enzyme activity, and crop yields in two sandy loam soils. *Biol. Fertil. Soils* **50**, 1087–1097 (2014).
- Huang, M., Zhang, Z., Zhai, Y., Lu, P. & Zhu, C. Effect of straw Biochar on soil properties and wheat production under saline water irrigation. *Agronomy* **9** (8), 457 (2019).
- Zhou, Z. et al. Treatment of the saline-alkali soil with acidic corn stalk Biochar and its effect on the sorghum yield in Western Songnen plain. *Sci. Total Environ.* **797**, 149190 (2021).
- Lehmann, J. A handful of carbon. *Nature* **447**, 143–144. <https://doi.org/10.1038/447143a> (2007).
- McLaughlin, H. et al. Carbon capture utilization and storage in review: sociotechnical implications for a carbon reliant world. *Renew. Sust. Energ. Rev.* **177**, 113215. <https://doi.org/10.1016/j.rser.2023.113215> (2023).
- Guo, M., Uchimiya, S. M. & He, Z. Agricultural and environmental applications of biochar: advances and barriers. In *SSSA Special Publications* (eds Guo, M. et al.) 495–504 (SSSAJ, 2015).
- Ma, L. et al. Continuous application of Biochar increases 15 N fertilizer translocation into soil organic nitrogen and crop uptake in drip-irrigated cotton field. *J. Soils Sediments.* **23**, 1204–1216. <https://doi.org/10.1007/s11368-022-03416-4> (2023).
- Khan, Z. et al. *Chemical and Biological Enhancement Effects of Biochar on Wheat Growth and Yield Under Arid Field Conditions* (Sustainability, 2021).

23. Tang, M. et al. Straw returning measures enhance soil moisture and nutrients and promote cotton growth. *Agron. Basel*. <https://doi.org/10.3390/agronomy13071850> (2023).
24. Wu, X., Wang, D., Riaz, M., Zhang, L. & Jiang, C. Investigating the effect of Biochar on the potential of increasing cotton yield, potassium efficiency and soil environment. *Ecotox Environ. Safe*. **182**, 109451. <https://doi.org/10.1016/j.ecoenv.2019.109451> (2019).
25. Batool, A. et al. Potential of soil amendments (biochar and gypsum) in increasing water use efficiency of *Abelmoschus esculentus* L. Moench. *Front. Plant. Sci.* **6**, 733 (2015).
26. Haddad, S., Mowrer, J. & Thapa, B. Biochar and compost from cotton residues inconsistently affect water use efficiency, nodulation, and growth of legumes under arid conditions. *J. Environ. Manage.* <https://doi.org/10.1016/j.jenvman.2022.114558> (2022).
27. Xiao, Q. et al. Soil amendment with bio-char increases maize yields in a semi-arid region by improving soil quality and root growth. *Crop Pasture Sci.* **67**, 495–507 (2016).
28. Piscitelli, L., Rivier, P. A., Mondelli, D., Miano, T. & Joner, E. J. Assessment of addition of Biochar to filtering mixtures for potential water pollutant removal. *Environ. Sci. Pollut Res.* **25**, 2167–2174 (2018).
29. Rasa, K. et al. How and why does Willow Biochar increase a clay soil water retention capacity? *Biomass Bioenergy*. **119**, 346–353 (2018).
30. Saha, A., Basak, B. B., Gajbhiye, N. A., Kalariya, K. A. & Manivel, P. Sustainable fertilization through coapplication of Biochar and chemical fertilizers improves yield, quality of *andropogon paniculata* and soil health. *Ind. Crop Prod.* **140**, 111607 (2019).
31. Tu, C. et al. Biochar and bacteria inoculated Biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil[J]. *Environ. Int.* **137**, 105576. <https://doi.org/10.1016/j.envint.2020.105576> (2020).
32. Chen, H. et al. Biochar improves sustainability of green roofs via regulate of soil microbial communities. *Agriculture* **11**, 620 (2021).
33. Gross, A., Bromm, T. & Glaser, B. Soil organic carbon sequestration after Biochar application: A global meta-analysis. *Agronomy* **11**, 2474 (2021).
34. Montes, K., RiosPino, N. J. P. & Gustavo, A. Alberto. *Response of Rhizobacterial Community To Biochar Amendment in Coal Mining Soils with Brachiaria Decumbens as Pioneer Plant*[J] Vol. 29 (Soil & Sediment Contamination, 2020). 1a4.
35. Gao, Y. et al. Biochar Suppresses Bacterial Wilt of Tomato by Improving Soil Chemical Properties and Shifting Soil Microb. *Community*[J] *Microorganisms*, 7(12).DOI:<https://doi.org/10.3390/microorganisms7120676>. (2019).
36. Ran, T. et al. Biochar nanoparticles alleviate salt stress in tomato (*Solanum lycopersicum*) seedlings[J]. *Environ. Sci. Nano*, **10** (7), 1800–1811 (2023).
37. Karabay, U. et al. Does Biochar alleviate salt stress impact on growth of salt-Sensitive crop common Bean[J]. *Communications in soil science and plant analysis*, 52. (2021). <https://doi.org/10.1080/00103624.2020.1862146>
38. Kamran, M. A., Bibi, S. & Chen, B. Preventative effect of crop straw-derived Biochar on plant growth in an arsenic polluted acidic ultisol[J]. *Sci. Total Environ.* **812**, 151469–. <https://doi.org/10.1016/j.scitotenv.2021.151469> (2022).
39. Zhu, Y. et al. Effects of Biochar and biofertilizer on cadmium-contaminated cotton growth and the antioxidative defense system[J]. *Sci. Rep.* (1). <https://doi.org/10.1038/S41598-020-77142-7> (2020).
40. Wang, P. et al. Combined application of desulfurization gypsum and Biochar for improving Saline-Alkali soils: A strategy to improve newly reclaimed cropland in coastal Mudflats[J]. *Land* (2012), **12**(9). (2023). <https://doi.org/10.3390/land12091717>

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Conceptualization, Zhang.ZL and Tian.D.; methodology, Wang.YC, Zhong.XH.and Chen.P; resources, Zhang.X and Yang.M.; writing—original draft preparation, Zhang.ZL and Tian.D and Liu.T.; writing—review and editing, Zhang.X and Yang.M.; All authors have read and agreed to the published version of the manuscript.

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## Declarations

## Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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