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Biochar

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Interaction between biochar particle size and soil salinity levels on soil properties and tomato yield

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Abstract

The enhancement of saline soil yield potential by biochar was well-documented, but the changes brought by biochar particle size on soil properties and crop performance are not well understood. To investigate the changes in soil properties and tomato yield due to biochar particle size under varying salt stress, we conducted a pot experiment in China Northwest's solar greenhouse. A total of nine treatments were applied, with three different salt amounts of [S0 (no salt), S1 (0.3% dry weight), and S2 (0.6% dry weight)], and three biochar treatments of B0, B1, and B2 (0, 0.5% of large particles and 0.5% of small particles). Adding biochar did not significantly affect the measured soil chemical properties, except for pH, total nitrogen (TN), and Ca^{2+}. Specifically, the addition of biochar significantly increased soil pH and TN, while reduced soil Ca^{2+} content likely due to biochar selective adsorption of Ca^{2+}. Biochar particle size had opposite effects on tomato yield under varying salt stress levels. Compared to S0, the yield under B1 was 19.1% and 36.5% higher, whereas under B2, the yield was 33.1% and 44.2% lower for S1 and S2, respectively. Under no salt stress, small-size biochar increased yield by 51.0% compared to B0, largely due to the improved soil water and nutrient status. These results are of great value for developing better strategies for adding biochar with appropriate properties into saline soils to achieve greater productivity gains.

Highlights

- Biochar addition significantly reduced soil Ca^{2+} by 16.7–37.9%, while there was no significant difference in the other cations.
- Large-size biochar alleviated salt stress and improved tomato yield by promoting salt leaching and enhancing soil nutrients.
- Small particle size biochar exacerbated salinity stress and reduced tomato yield under higher salinity treatments.
- Small particle size biochar boosted tomato yield in soils without salinity stress.

Keywords Biochar, Particle, Tomato, Yield, Soil physicochemical

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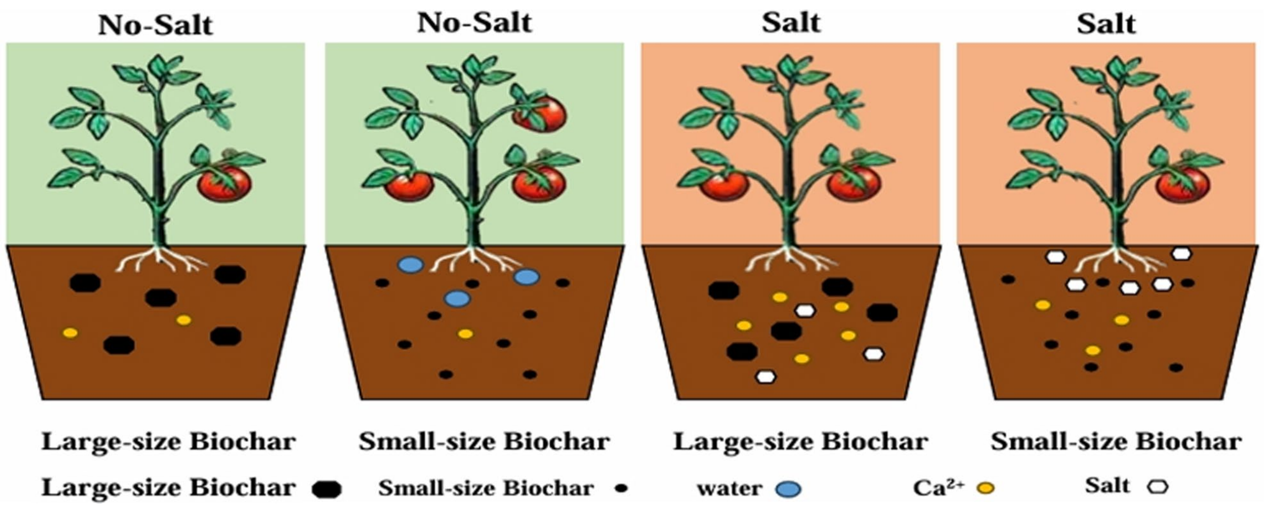
Graphical Abstract



1 Introduction

Under aerobic or anaerobic conditions, biochar is formed by the high-temperature decomposition of biomass and organic waste (Ahmad et al. 2014). With its unique chemical, physical, and biological characteristics, such as high organic carbon content, low bulk density, and large surface areas, biochar has been widely used in various fields in recent years (Xie et al. 2022). Biochar, as a sustainable soil amendment, improved soil properties and promoted plant growth. For example, Ng et al. (2023) found that biochar boosted soil water retention by 15%, reduced infiltration by 13%, and improved soil structure. Guo et al. (2023) reported that 10% biochar increased soil nitrogen, phosphorus, and potassium by 100%, 200%, and 31%, respectively, and raised LAI (Leaf Area Index) of shrubs by 51%. Liao et al. (2024) noted biochar enhanced soil fertility and water use and further promoted plant growth and photosynthesis.

Globally, soil salinization poses a significant challenge to sustainable agriculture and land use (Mahmoodabadi et al. 2013). Saline soils degraded the inherent properties of soil, causing nutrient deficiencies and suppressing microbial activity, thereby impacting crop growth. This degradation occurred due to the relatively high concentrations of soluble salts they contained (Ors et al. 2021; Yan et al. 2015). High salt content reduced soil osmosis, hindered the absorption of water by the roots, and led to lower crop yields (Zhao et al. 2020a).

Recent studies highlighted the potential of biochar to mitigate soil salinity and boost crop yields (Wang et al. 2022). Rich in nutrients, biochar replaced inorganic fertilizers in saline soils and boosted crop yields (Zhang et al. 2024). By enhancing porosity and water retention while reducing bulk density, biochar improved saline soil properties (Zhou et al. 2024). It also leached soluble salts and lowered electrical conductivity (EC) and exchangeable sodium, which boosted productivity (Yue et al. 2016). Biochar further regulated soil microbes and promoted carbon sequestration and nutrient availability, especially in rice (Zhao and Grossart 2024). Research showed that biochar increased leaf water content, chlorophyll levels, and regulated antioxidant enzymes (SOD, CAT, and POD), reduced MDA and proline, thus eased oxidative and osmotic stress to promote tomato growth (Kul et al. 2021). It also enhanced stomatal density and conductance in potatoes, reduced abscisic acid (ABA) production, and mitigated salt stress (Akhtar et al. 2015).

Previous studies have shown that whether or how much biochar addition could improve crop yield depended on properties of biochar, such as feedstock source, temperature and duration of pyrolysis, particle size, etc. (Cha et al. 2016; Mikajlo et al. 2024). Among those factors, biochar particle size was particularly influential on soil hydraulic properties. Edeh and Mašek (2022) noted that biochar with varying particle sizes affected soil water retention by modifying soil pore structure, porosity, and aggregate formation. The impact on water retention was determined by the interaction between the biochar, soil, and water. Specifically, large particle size biochar increased soil macroporosity, enhancing water infiltration and airflow, which helped retain water and supported plant water uptake. It also reduced surface crusting and maintained soil permeability. Conversely, smaller biochar particles increased soil microporosity, which improved water retention, enhanced soil organic matter, and altered soil chemistry to aid plant growth. Therefore, large particle size biochar was more suitable for improving soil structure and reducing surface crust in soils like calcareous sandy soils. In contrast, small-particle biochar was ideal for coarse soils, which benefited from increased microporosity and organic matter content, thereby improving water retention (Ibrahim et al. 2017; de Jesus et al. 2019). Therefore, biochar of large particles was expected to be more effective in enhancing leaching of soil soluble salts, while small-sized biochar might have accumulated salt content in the root zone when applied to saline soils. Indeed, Tang et al. (2023) found that smaller particles increased soil EC due to reduced porosity, hindering salt leaching.

The functional performance of biochar when added to soils was significantly influenced by its particle size. Smaller particles were more efficient in promoting nutrient mineralization and release, enhancing soil nutrient cycling (Sigua et al. 2014). This efficiency was credited to the larger reactive surface provided for interactions, which not only promoted soil nutrient cycling, but also further improved soil ecology by influencing microbial community structure (such as fungi and gram-negative bacteria) (Zhao et al. 2020b). Studies indicated that varying biochar particle sizes greatly enhanced soil physicochemical characteristics and nutrient availability, benefiting plant growth and physiological activities (Ali et al. 2019). In particular, Zeeshan et al. (2020) observed that in heavy metal-contaminated soil, biochar particles <3 mm significantly increased tomato height, yield, and chlorophyll content. Although larger particles also had positive effects, the smaller ones were more effective due to their larger surface area, which reduced nutrient loss. Liao and Thomas (2019) noted that plant responses to biochar size varied by species: ryegrass preferred larger particles for improved soil porosity and aeration, while velvetleaf benefited from smaller particles due to higher water retention and pH. These findings highlighted the significance of accounting for particle size effects on soil properties and plant growth when using biochar, and the strategic importance of selecting the right particle size biochar for different environments and crop types. Until present, research on biochar particle size effects on the properties of saline soils, and the interaction of biochar of different particle sizes and salinity levels are limited, and the mechanisms regulating the interactions between biochar properties, including but not limited to particle size, soil properties (including salinity), environment, and crops are not fully understood.

Extensive research supports that biochar addition enhances soil properties in saline conditions and subsequently promotes crop yield. Even though considerable endeavors have been dedicated to the benefits of biochar derived at various pyrolysis temperatures, there is a gap in understanding how biochar particle influences plant growth and productivity in saline environments. Therefore, the study aimed to examine how biochar of different particle sizes, when applied across a range of soil salinity levels, would affect soil characteristics, the productivity and quality of tomatoes cultivated in a greenhouse from northwestern China.

2 Design and methodology

2.1 Experimental arrangement

We carried out a pot experiment at the National Field Scientific Observation and Research Station on Efficient Water Use of Oasis Agriculture in Wuwei, Gansu Province of Northwest China. The research site is situated at 37°52′20″ N latitude and 102°50′50″ E longitude, at an elevation of 1581 m. Tomato plants of a local variety "Fenxi" (*Solanum lycopersicum*) were used. Tomato seeds were germinated in a composite substrate (pH 6.7, 5% vermiculite, 25% perlite) under 70–80% humidity. Seedlings with 3–4 leaves were transplanted on July 19, 2021, into pots placed in a solar greenhouse. The pots used in the research measured 24.5 cm across the top, 21 cm across the bottom, and stood 25 cm in height. The soil utilized in this experiment was obtained from a maize field that had been subjected to long-term monoculture, ensuring the fundamental characteristics of soil were relatively stable. After collection, the soil was sun-exposed for approximately one week. Subsequently, the dried soil was crushed and sieved to obtain a uniform consistency. For the experimental treatments, the processed soil was then thoroughly mixed with salt and biochar. Additionally, a multi nutrient fertilizer with an N:P:K ratio of 15:15:15 was included, calculated at a rate of 0.75 t hm^{-1}. The soil and fertilizer were mixed thoroughly using shovel before placed in pots. Soil analysis determined it to be sandy loam, with sand, silt, and clay making up 62.8%, 20.3%, and 16.9% respectively.

Nine distinct treatments were included in the experiment, combining three salinity levels (S0, S1, and S2) and three biochar treatments (B0, B1, B2). Salinity levels were created by adding salts (NaCl, $MgSO_4$, $CaSO_4$ in a 2:2:3 ratio) at 0, 0.3%, and 0.6% of dry weight into soil. The experimental treatments for biochar included no biochar (B0), biochar particles > 2 mm (B1), and particles < 2 mm (B2), both at 0.5% of soil dry weight. Biochar was

Table 1 Soil and biochar properties

Propertie	Soil	Biochar
pH_{H2O}	8.37	9.42
$EC_{1:5}$ (dS m^{-1})	379.8	6793
Organic matter (g kg^{-1})	11.65	846.13
CEC (cmol kg^{-1})	8.72	67.10
TN (g kg^{-1})	0.69	28.97
TC (g kg^{-1})	16.51	444.11
C/N	23.93	15.33

produced from corn straw by pyrolysis at 400 °C for 10 h, was provided by Intellect, Integration & Connection Co., Ltd (Nanjing, China). Table 1 shows the properties of the biochar and soil used in the study. Each treatment had three replicates, totaling 27 pots. In the S0B0 treatment, irrigation was done when soil moisture fell to 50% of field capacity, with other treatments receiving the same water volume. Irrigation occurred approximately every 6 days during the seedling stage and every 3 days during the fruit expansion stage, with a total water application of 890 mm per pot over the growth period.

2.2 Data collection

At the end of the experiment, the potted soil was systematically divided into two distinct layers for sampling. Each layer was approximately 10 cm thick. The overall soil properties for each pot were determined by averaging the measurements from the two layers. Each soil sample was divided into four parts. One part was used to measure gravimetric SWC (Soil water content) by weighing method. Another part was first air-dried, sieved through a 1 mm sieve, then mixed thoroughly with deionized water at ratio of 1:5. The mixture was filtered through filter paper (9 cm, medium speed) for measuring EC, pH, and cation concentrations (Chen et al. 2023a, b). EC, pH and cation concentrations were assessed using a conductivity meter (FE38, MTI, Switzerland), a pH meter (FE28, MTI, Switzerland), and ICP-OES (Optima, PE, USA), respectively. The third part of 10 g fresh soil sample was mixed thoroughly with 1 M KCl (50 ml) solution, then filtered through filter paper for measuring nitrate nitrogen (NO_3^-) and ammonium nitrogen (NH_4^+) content. The remaining part of the soil was used to measure TN after digestion with the Kjeldahl method. Soil NO_3^-, NH_4^+, and TN were measured using a continuous flow autoanalyzer following the protocols in the manual of the instrument (Auto Analyzer 3, BL, Germany). All properties were measured in triplicates.

Starting from the seedling stage, the height of the tomatoes, from the base to the highest point, was recorded every 7 days, for a total of 18 measurements. On the day after an irrigation event during fruit ripening stage, leaf physiological parameters were measured at the third fully expanded leaf (one per pot). Chlorophyll content index (CCI) was measured at five random points on the leaf using a chlorophyll meter (SPAD-502Plus, KMI, Japan), and the average was used. Photosynthesis parameters including net photosynthetic rate (A), stomatal conductance (gs), intercellular CO_2 concentration (C_i), and transpiration rate (Tr) were determined on the same leaf between 09:00 and 11:00 am using a portable gas exchange system (Li-6400XT, LC, USA) (Du et al. 2022). Midday leaf water potential (Ψleaf) was assessed using a pressure chamber (1505D; PMS, USA). Leaf thickness was measured with vernier calipers. Fresh leaves were weighed and then placed in a oven at 70 °C until a constant weight was achieved to determine the leaf water content (LWC). All parameters were measured on one leaf per pot with three replicates.

Upon fruit ripening, tomatoes from each pot were harvested to evaluate fresh yield and quality. Fruit quality was assessed by measuring the fruit shape index (SI), color index (CI), firmness (Fn), and total soluble solids (TSS). From each pot, three fruits were collected using a completely random sampling method. Fruit size was recorded using calipers, ensuring precise dimensions. The shape index of the fruits was derived by dividing the length of fruit by its width. The CI was determined using a spectrophotometer (SP60, XI, USA), that provided three color space coordinates (L, a, and b). CI was calculated using the formula:

$$CI = 2000\frac{a}{L\sqrt{a^2 + b^2}}$$

where L indicates lightness (0–100). The a value spans from green to red (−100 to +100), while the b value varies from blue to yellow (−100 to +100) (Chen et al. 2013). Fn and TSS were measured using a firmness tester (FHR-5, TEW, Japan) and a handheld refractometer (ATAGO, PCT, Japan), respectively.

2.3 Data analysis

The mean differences in soil properties, tomato physiological parameters, plant height, yield, as well as fruit quality characteristics across the different treatments were analyzed using two-way ANOVA. We established a threshold of 0.05 and employed Duncan's multiple range test to evaluate the significance of the data. These analyses were executed with SPSS (20.0, SI, USA), offering a full range of statistical tools for our research requirements. Additionally, the plotting of graphs and

Table 2 Soil physicochemical properties at different biochar addition rates in different salinity levels at the end of the experiment

		Soil water content (cm^3 cm^{-3})	$EC_{1:5}$ (μS cm^{-1})	pH	Na^+ (mg g^{-1})	K^+ (mg g^{-1})	Ca^{2+} (mg g^{-1})	Mg^{2+}	SAR	NH_4^+	NO_3^-	Total nitrogen
B0	S0	0.09 cd	530.53c	8.32ab	0.06d	0.18ab	0.20de	0.06de	0.63d	1.22a	99.11a	0.79ab
	S1	0.08 cd	1123.55ab	8.12 cd	0.23c	0.19ab	0.54b	0.16bc	1.45c	1.35a	125.64a	0.76b
	S2	0.15a	1464.05a	8.06d	0.48a	0.20ab	0.81a	0.22a	2.47ab	1.08a	95.45a	0.69c
B1	S0	0.07d	583.77c	8.39a	0.07d	0.21ab	0.31cde	0.11cde	0.54d	1.59a	114.57a	0.85a
	S1	0.10bcd	1128.77ab	8.11 cd	0.23c	0.24a	0.45bc	0.14bc	1.53c	1.45a	150.18a	0.83ab
	S2	0.14ab	1372.58a	8.15 cd	0.33bc	0.18ab	0.60b	0.17ab	1.88bc	1.02a	125.65a	0.81ab
B2	S0	0.11bc	459.00c	8.38a	0.06d	0.17b	0.15e	0.05e	0.75d	0.87a	86.14a	0.81ab
	S1	0.09 cd	1006.17b	8.24bc	0.21c	0.19ab	0.38bcd	0.12bcd	1.51c	1.11a	142.13a	0.83ab
	S2	0.09 cd	1443.43a	8.20bc	0.41ab	0.15b	0.50bc	0.17abc	2.55a	1.12a	117.02a	0.84a
ANOVA												
Salt (S)		**	***	***	***	ns	***	***	***	ns	ns	ns
Biochar (B)		ns	ns	*	ns	ns	*	ns	ns	ns	ns	***
S×B		*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

SAR is sodium adsorption ratio. S: Salt (0, 1, 2 represent 0, 0.3, 0.6% of soil dry weight salts); B: Biochar (0, 1, 2 represent 0%, 0.5% large-particle biochar, and 0.5% small-particle biochar). Different letters within the same column indicate significant differences between treatments at $p < 0.05$; 'ns' indicates non-significant; *, **, *** denote significance at $p < 0.05$, <0.01, and <0.001 levels, respectively

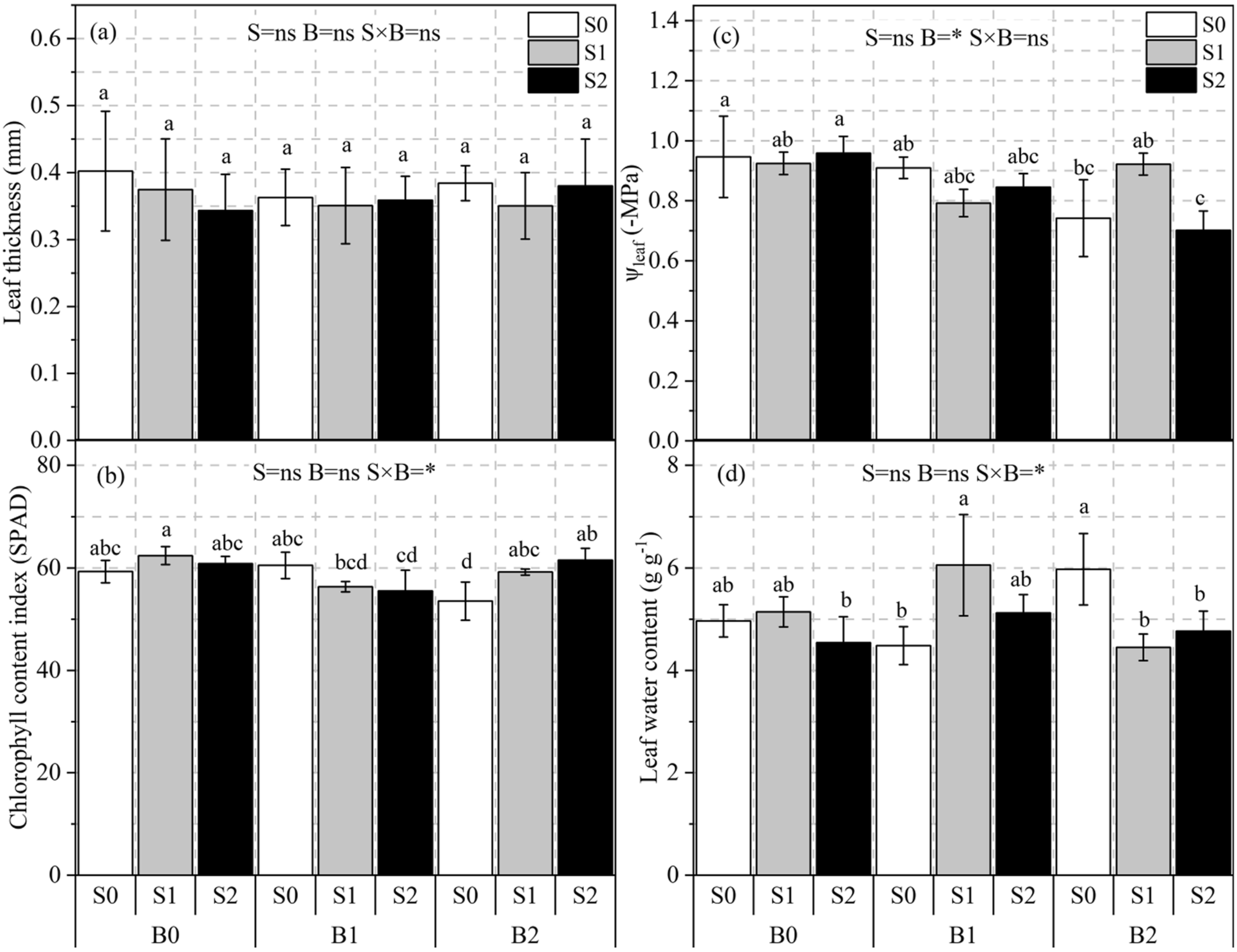


Fig. 1 Effects of different treatments on leaf physiological indexes at ripe stage, including Leaf thickness (**a**), CCI (**b**), Ψ_{leaf} (**c**), and Leaf water content (**d**). S0: No salts, S1: 0.3% w/w salts, S2: 0.6% w/w salts; B0: no biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar. Different letters in each figure indicate significant differences between treatments at $p < 0.05$; '*ns*' indicates non-significant and * denotes significance at $p < 0.05$ level

PCA were conducted using Origin (2023, OL, USA), enabling precise visualization and sophisticated analysis of the data.

3 Results

3.1 Soil properties

Our study examined how various biochar and different salinity gradients impact the physicochemical characteristics of soil (Table 2). The synergistic influence of salt and biochar notably impacted SWC, once the experiment was finished. In the absence of biochar (B0) and with the application of large-particle biochar (B1), the SWC levels were considerably higher under the S2 treatment relative to other salt treatments, demonstrating the distinct influence of this salt concentration on soil moisture. Conversely, when small-particle biochar (B2) was used, the SWC remained consistent across all three salt treatments. This interaction did not markedly alter other soil qualities. Biochar was found to notably influence pH, Ca^{2+}, and TN levels. Overall, incorporating biochar into the soil resulted in increased pH and TN, while it reduced Ca^{2+} concentration. Specifically, the average pH for the treatments was 8.17 in B0, 8.22 in B1, and 8.27 in B2. The TN in the soil experienced a rise, varying from a minimum of 2.41% to a maximum of 22.56%, after biochar was introduced. In comparison to B0, the treatments B1 and B2 led to a reduction in Ca^{2+} content by 12 and 34%, respectively. The majority of the soil attributes were markedly influenced by the salinity treatments, with soil Na^{+}, Ca^{2+}, Mg^{2+}, EC, and SAR all increasing in response to higher salinity levels. However, there were no substantial changes in soil NO_3^{-} and NH_4^{+} concentrations.

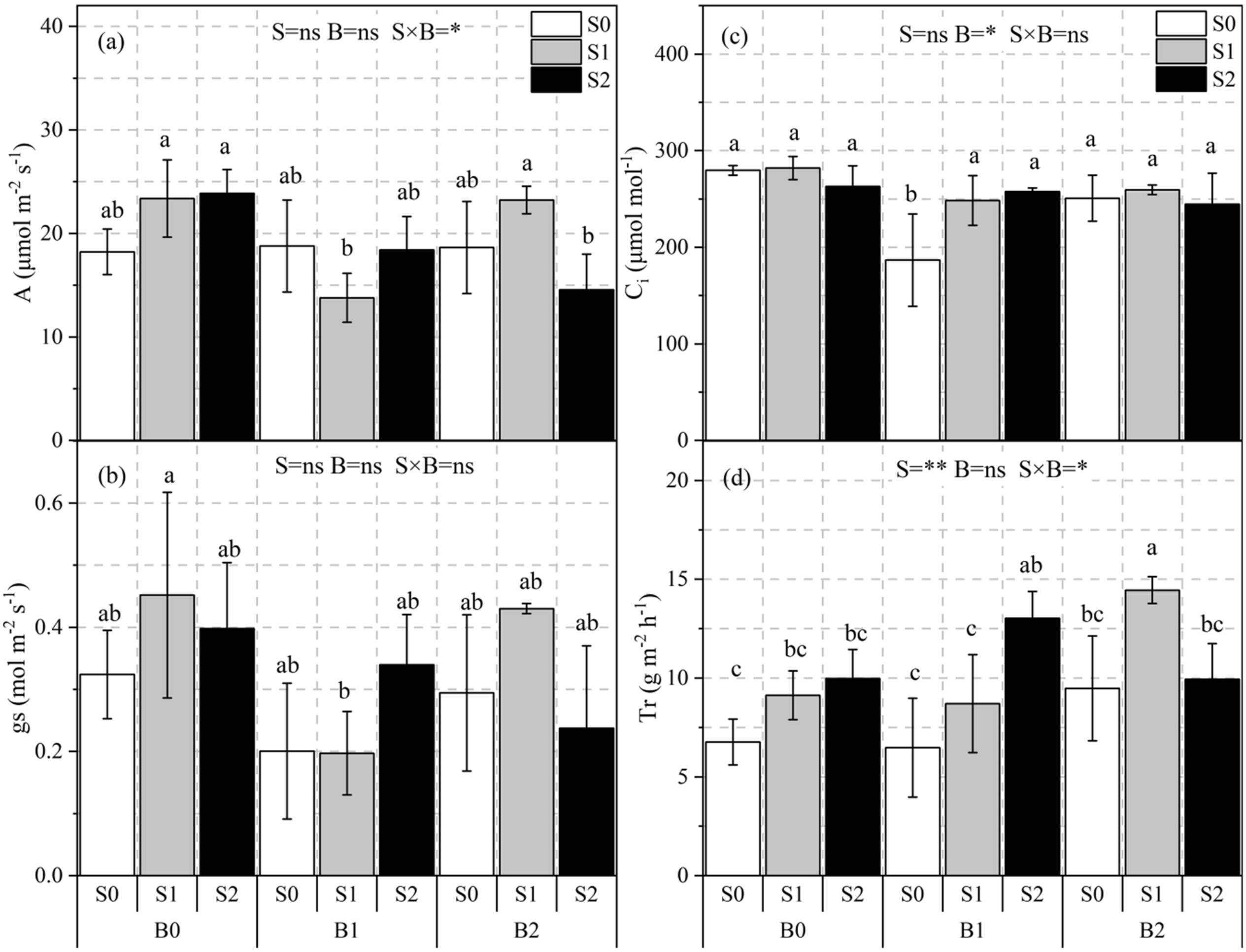


Fig. 2 Measurements of photosynthetic rate (**a**), stomatal conductance (**b**), intercellular CO_2 concentration (**c**), and transpiration rate (**d**) at ripe stage. S0: No salts, S1: 0.3% w/w salts, S2: 0.6% w/w salts; B0: no biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar

3.2 Plant physiological parameters

In this study, the physiological and photosynthetic indexes of tomato leaves were evaluated at the ripe stage of tomatoes. CCI and LWC were notably influenced owing to the collective impact of salt and biochar (Fig. 1b, d). Under B0 and B1, the three salinity treatments had similar CCI, while under B2, CCI was significantly higher for S1 and S2 than for S0. In terms of LWC, S1 and S2 tended to have larger values than S0 under B1, while the opposite was true under B2. Overall, the addition of biochar significantly increased Ψ_{leaf} (Fig. 1c), especially for B2 under S0 and S2 treatments. The changes in leaf thickness were not significant.

Tomato photosynthetic rate and transpiration rate showed significant responses to the interaction between salt and biochar (Fig. 2a, d). As the size of biochar particles varied, salinity levels had different impacts on tomato photosynthesis rate (A) and transpiration rate (Tr). Under B0, both A and Tr tended to increase with salinity, while under B2, A and Tr both first increased from S0 to S1, then decreased from S1 to S2. However, for B1, A decreased from S0 to S1, but increased from S1 to S2, while Tr increased consistently with higher salinity. Under S0 treatment, A and Tr showed no significant differences among biochar treatments, but larger particle biochar reduced A, and small particle biochar increased Tr under S1 significantly. For S2, B2 significantly reduced A. Largely, salt and biochar did not lead to any notable changes in gs and C_i of leaves (Fig. 2b, c), except that S0B1 had lower Ci of leaves than the other treatments.

3.3 Plant height, yield, and fruit quality

Figure 3 shows the changes in tomato plant height over time under different treatments. The ANOVA analysis showed that during the seedling stage, plant height was mainly influenced by salinity levels, with the order of S0 > S1 > S2. After the seedling stage, both salinity and

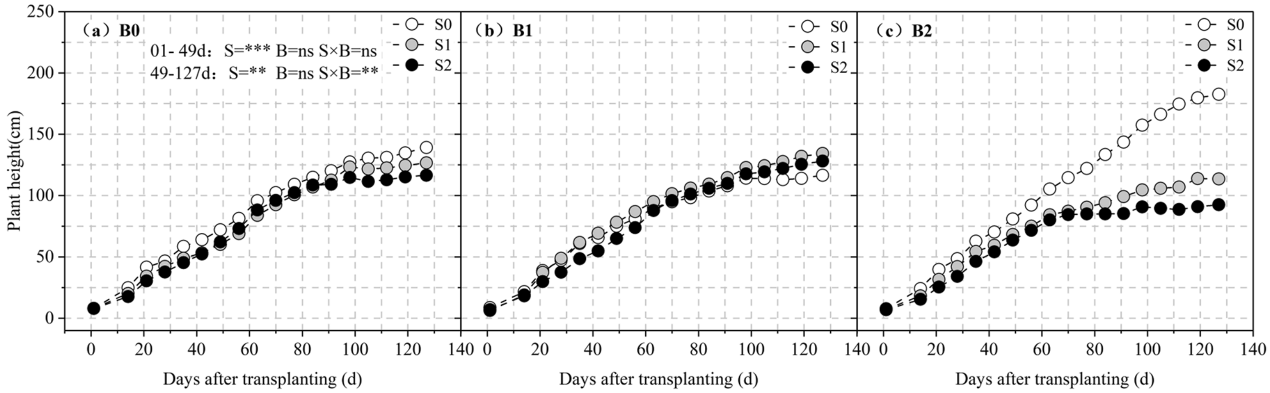


Fig. 3 Changes in plant height over time during the growth period under different salinity and biochar treatments. B: Biochar treatments; B0 (**a**), B1 (**b**), B2 (**c**). S0: No salts, S1: 0.3% w/w salts, S2: 0.6% w/w salts; B0: no biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar

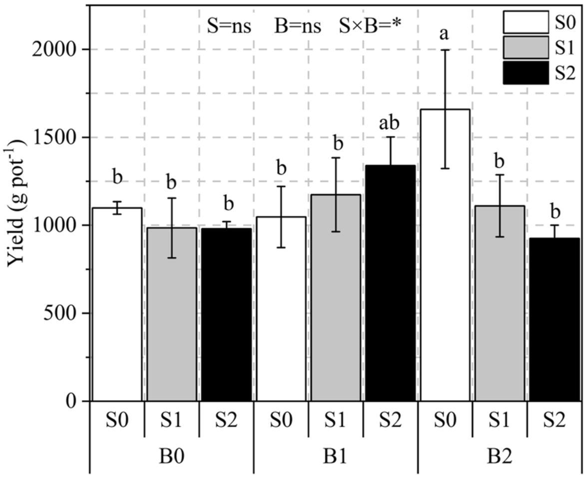


Fig. 4 Effects of different treatments on tomato yield. S0: No salts, S1: 0.3% w/w salts, S2: 0.6% w/w salts; B0: no biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar

biochar treatments affected plant height. Plant height showed a decrease as salinity increased in both the B0 (no biochar) and B2 (small-particle biochar) treatments. When large-particle biochar (B1) was added, greater tomato plant height was found under the S1 and S2 salinity conditions, compared to the B0 treatment, indicating that B1 treatment could alleviate the detrimental impacts of salinity, thereby promoting development of the tomato.

Figure 4 illustrates the impact of salinity and biochar on tomato yield, and the interaction between them was found significant ($p < 0.05$). Yield decreased under B0 and B2 as salinity increased, although the difference between S0, S1, and S2 under B0 was not statistically significant due to a relatively large standard deviation under B0S1. In B2, yield under S1 and S2 was both significantly lower than S0, by 33.05% and 44.17%, respectively, while the difference between S1 and S2 was not significant. On the contrary, under B1, yield increased with salinity, with S1 and S2 having 12% and 18% higher yield than S0, respectively. However, the yield difference between S0, S1, and S2 under B1 was not statistically significant with $p > 0.05$.

Prior to fruit harvest, we assessed fruit quality indicators, including SI, CI, Fn, and TSS, as shown in Fig. 5. Only fruit TSS responded to the interaction between salinity and biochar. In the B0 and B2 treatments, TSS increased with salinity, with S2B2 showing about 1.49 times higher TSS than S0B2. In contrast, TSS decreased with salinity in the B1 treatment, with little difference between the S1 and S2 treatments. CI and Fn indices showed no significant changes.

3.4 Interrelationships between tomato parameters and soil properties

We conducted a correlation analysis to explore the connections between yield, growth, physiological, quality, and soil physicochemical properties under various treatments, as shown in Fig. 6. The analysis revealed that yield had significant positive correlations with LWC, SWC, and pH, having correlation values of 0.42, 0.39, and 0.39, respectively. Additionally, yield exhibited negative correlations with most soil ion contents, such as EC, Na^+, and Ca^{2+}. Yield was also significantly positively correlated with plant height, and the relationship between plant height and both physiological and soil properties mirrored that of yield. Among leaf physiological parameters, the chlorophyll content index (CCI) exhibited negative correlations with LWC and leaf water potential (Ψleaf), with correlation coefficients of −0.45 and −0.47, respectively. Although the photosynthetic rate (A) was negatively correlated with Ψleaf and LWC (with a coefficient of −0.44), most photosynthetic indices showed positive correlations, ranging from 0.49 to 0.91. Soil pH was considerably negatively related to indicators such as EC, Na^+,

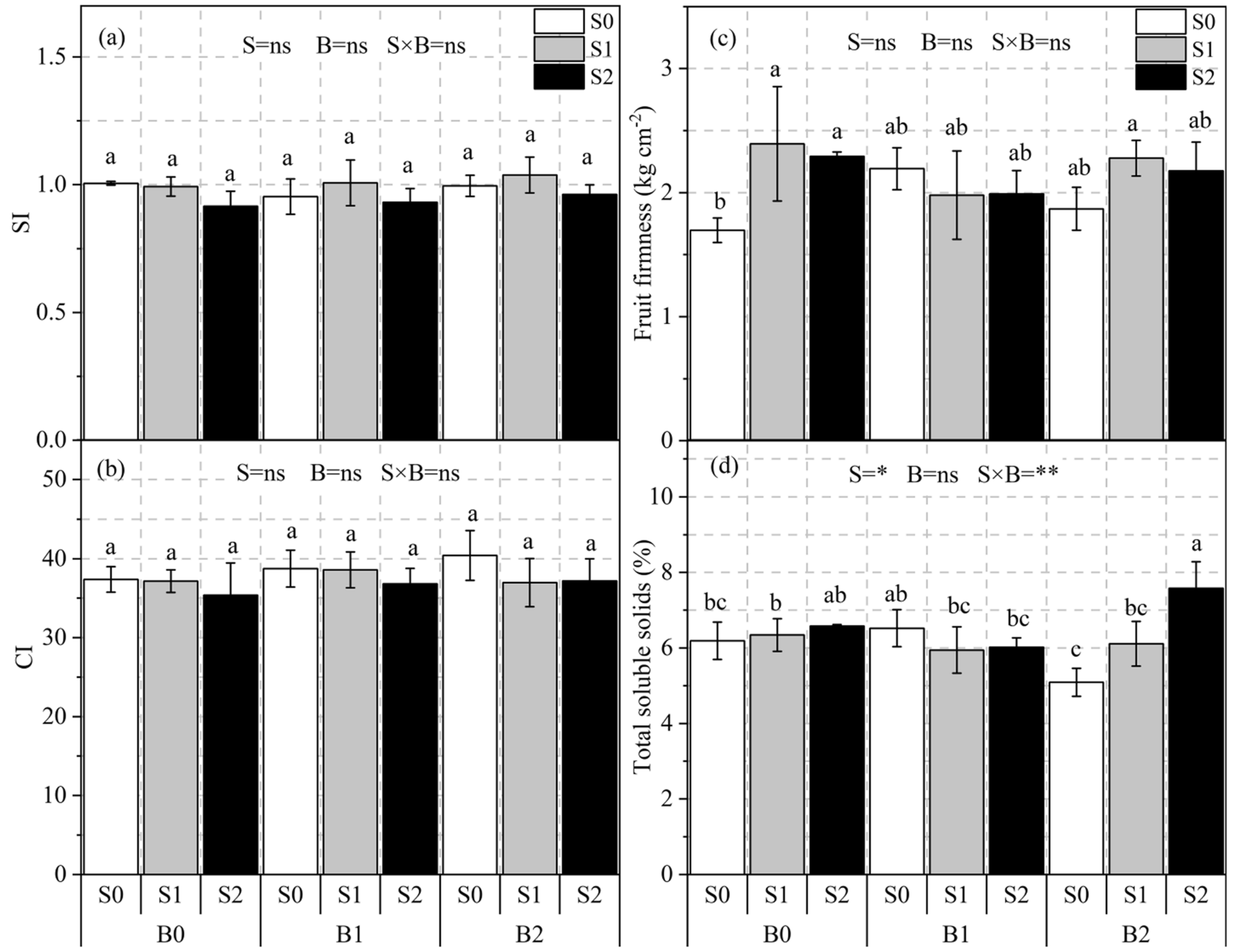


Fig. 5 Effects of different treatments on tomato fruit quality, including SI (**a**), CI (**b**), Fn (**c**), and TSS (**d**). B0: no biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar; S0: No salts, S1: 0.3% w/w salts, S2: 0.6% w/w salts

and Ca^{2+}, while the levels of soil cation contents were positively correlated with one another. NO_3^- and N_{Soil} exhibited positive correlations with soil EC and cations. Additionally, yield was significantly negatively correlated with TSS, with a correlation coefficient of −0.66.

3.5 Principal component analysis (PCA)

To further explore the possible interrelationships between yield and soil parameters, we performed PCA on soil indicators under different biochar treatments, respectively (Fig. 7). In all instances, the bulk of the variance within the data was explained by the first two principal components, PC1 and PC2. Specifically, they accounted for 78.5%, 78.1%, and 82.1% of the variance for B0, B1, and B2, respectively. This level of explanation was deemed adequate to capture the variability among the variables analyzed (Beyzi et al. 2019). These findings suggest that PC1 and PC2 provide a comprehensive summary of the underlying patterns in the dataset, allowing for meaningful interpretation and comparison across different conditions. SWC was strongly correlated with PC2, while soil EC was significantly positively correlated with PC1. In the B0 and B1 treatments, we noticed that the vector of SWC was biased in the negative direction, whereas it was more closely aligned with the positive direction of PC2 in the B2 treatment.

Linear regression was used to fit PC1 and PC2 to tomato yield; results were shown in Table 3. PC1 and yield was negatively correlated under B2 treatments. For PC2, it was negatively correlated with yield under B1 treatment. As can be seen from the R^2 values of the models, the model fit value for the B2 treatment (0.893) was significantly higher than for B0 (0.129) and B1 (0.528), indicating that PC1 under the B2 treatment was able to better explain the yield variability. In the B0 treatment, neither PC1 nor PC2 showed a significant linear relationship with yield. However, as biochar addition rate increased, the relationship became more pronounced, the *p*-value for B0 is 0.66, for B1 it is 0.10, and for B2 it is 0.01.

By examining Table 3 and Fig. 7 together, it was observed that under the B0 treatment, there was an absence of any notable association between yield and the various soil properties; under B1 treatment, yield was mainly negatively correlated with PC2, where SWC (−0.37), K^+(0.60), NO_3^-(0.50) were the dominant variables; under B2 treatment, yield was mainly negatively correlated with PC1, and the most important soil variables in PC1 were EC (0.35), Ca^{2+}(0.36), Mg^{2+}(0.36) and the other ions.

4 Discussion

Biochar significantly alters the physical and chemical characteristics of soil (Wang et al. 2022). Among the measured soil properties, adding biochar significantly affected pH, Ca^{2+}, and TN. The incorporation of biochar is known to elevate soil pH, due to its alkaline nature. The pH of the soil increases with the addition of biochar, primarily due to the substantial amount of alkaline ash content inherent in the biochar (Yang et al. 2018; Hossain et al. 2020). Similarly, the TN levels in the soil also rise because biochar contains a certain amount of nitrogen. This finding is consistent with the results of other studies (Zhang et al. 2021a, 2021b). The effect of biochar on soil ion content is complex and varies with experimental conditions. For example, Duan et al. (2021) investigated the incorporation of biochar into saline soils with high Na^+ content, discovering that biochar, particularly when acidified, adsorbed Na^+ while releasing K^+, Ca^{2+}, and Mg^{2+} ions. Ge et al. (2023) demonstrated that applying saline plant-derived biochar in acidic soils effectively increased soil cation content owing to the elevated concentrations of alkaline cations present in the biochar. Dos Santos et al. (2022) observed that incorporating biochar into clay soils with high cation content (Na^+, Ca^{2+}, Mg^{2+}) reduced soil stickiness and increased leaching of these ions, while it raised soil K^+ levels due to the high K^+ content of biochar. In our research, due to the low application rate, biochar did not markedly impact soil properties other than pH, Ca, and TN. In this study, we added biochar at a rate of 0.5% which was lower than those rates used in most studies. He et al. (2020) added biochar at rates of 0.1, 2, 2.5, 5, and 10% (w/w) in saline-alkaline soils, finding significant effects on soil physicochemical properties only at the 2 and 2.5% levels.

In this study, Ca^{2+} was the only ion that was markedly influenced by biochar treatment. Hailegnaw et al. (2019) discovered that biochar modulated soil Ca^{2+} content contingent upon the soil initial Ca^{2+} concentration. Specifically, in soils with low Ca^{2+} levels, the incorporation of biochar would elevate Ca^{2+} concentrations, while in soils already rich in Ca^{2+}, biochar addition would lead to a diminution of soil Ca^{2+} content. They suggested that the decrease in Ca^{2+} could be due to biochar forming aggregates with Ca^{2+} and soil organic matter, reducing exchangeable Ca^{2+}. Another possibility is that biochar adsorbs Ca^{2+} on its surface, decreasing its exchangeable form (Novak et al. 2009). In our investigation, soil Ca^{2+} might be within the range of relatively higher concentration as mentioned by Hailegnaw et al. (2019), especially for treatments with salt addition. For treatments of S1 and S2, $CaSO_4$ was added into soils, probably leading to relatively high Ca content. The reduction in Ca^{2+} was more pronounced for B2 than for B1 in this study (B1 reduced by 16.7–25.9% compared to B0, B2 reduced by 25.0–38.2% compared to B0), indicating that small particle biochar could help form more aggregates and adsorb more Ca because of its more extensive surface area (Chen et al. 2022).

Tomato growth was supposed to be inhibited and yield was supposed to decrease with increasing salt content for treatments without biochar. Nonetheless, this study found no notable variation in tomato yield among the three salt treatments, even though the yields in S1 and S2 were numerically lower than in S0. This may be due to the salt-tolerant tomato variety used, which could withstand the adverse impacts of salt stress to some extent (Guo et al. 2022). Therefore, alterations in soil salinity were found not to correlate significantly with tomato yield under B0 (as shown in Table 3 and Fig. 7). Furthermore, salt stress considerably impaired the capacity of tomato roots of absorbing water and nutrients owing to osmotic pressure and toxic ion accumulation This led to reduced root water use efficiency and elevated SWC in salt soils (Li et al. 2023; Zhao et al. 2020a).

Large-size and small-size biochar has been found to affect soil pore structure differently in saline soils, leading to greater variation in ion adsorption capacity and nutrient release, in turn significant differences in plant development (Tang et al. 2023). Relative to small-particle, large-particle biochar has more complete internal porosity, greater macroscopic pores, and better soil aeration, but reduced water retention capacity (WRC) and ions adsorption capacity (Villagra-Mendoza and Horn 2018). Adding large-particle biochar in saline soils could alleviate salinity stress by facilitating the leaching of salts, and improving soil nutrients status. The addition of large-particle biochar increased soil macropores and improved pore connectivity, providing better pathways for salt ions to leach away from the root zone, thereby reducing the risk of ion accumulation that

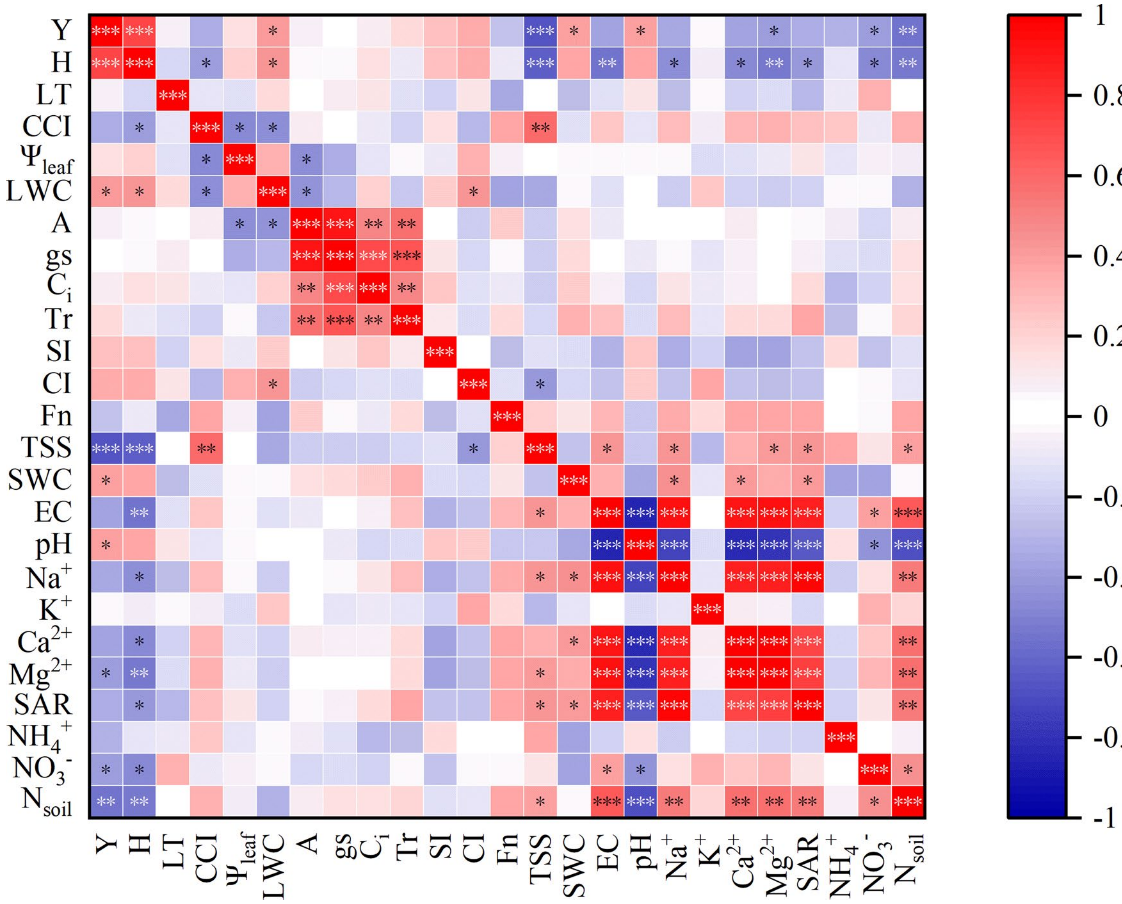


Fig. 6 Correlation analysis heat map between various indexes. Y was plant yield; H was plant height; SWC was soil water content; SAR was sodium adsorption ratio

might affect plant growth and yield negatively (An et al. 2023). In our study, by the end of the experiment, EC in S2B1 decreased by 6.25% and 4.91%, and Na^+ decreased by 31.25 and 19.51%, compared to S2B0 and S2B2, respectively. Indeed, EC and most ion contents in this study were found not to affect tomato growth and yield significantly when large-particle biochar was added, indicating there were no substantial ion accumulations within the root zone under the treatment. In addition, the improved soil nutrient status could be another factor leading to greater yield under B1, as evidenced by stronger correlation between soil K^+ and NO_3^- with yield, and overall greater K^+ and NO_3^- content under S1B1 and S2B1 than the other treatments.

EC and most ions contents could explain almost the total yield variation under B2 ($R2 = 0.89$), indicating that salt accumulation around the roots was the main element factor leading to yield reduction with increasing salinity. Instead of the increased macroporosity and reduced WRC from large particle biochar, small particle size biochar increases soil microporosity and reduces soil aeration, and its extensive specific surface area and fine powder structure increase the soil WRC (Chen et al. 2023a, b). The addition of small-particle biochar to saline soil increased micropores, but reduced pore connectivity and aeration, limiting water and nutrient flow, trapping more ions in the root zone, and exacerbating the harmful effects of salinity on plants (Liu et al. 2017; Tang et al. 2023).

Interestingly, small-particle biochar under S0 conditions resulted in the highest yield among all treatments included in the study. In environments without salt stress, small-particle biochar can markedly improve the soil capacity of effectively holding and storing crucial water and nutrients. Those retained resources become more readily available for plant uptake, which can effectively promote and support crop growth. Previous studies also indicated that small-particle biochar enhances soil characteristics and boosts agricultural productivity in non-saline conditions (Głąb et al. 2016).

Concerning tomato quality, the study found that biochar had minimal influence on the SI and CI quality

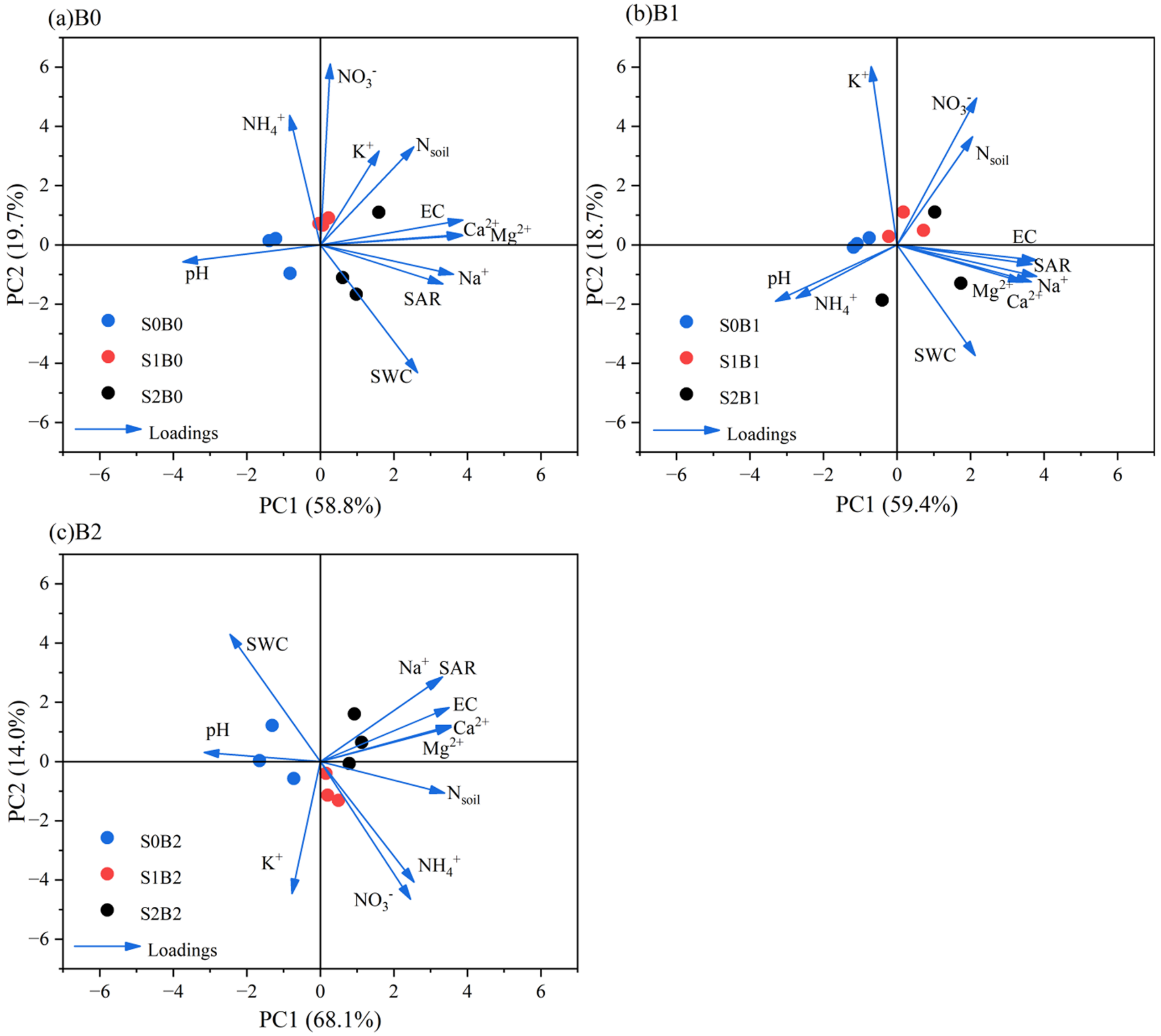


Fig. 7 Principal component analysis (PCA) of soil indexes under different salt treatments for B0 (**a**), B1 (**b**), and B2 (**c**), respectively

indices, which is in line with prior studies (Agbna et al. 2017; Wu et al. 2022). Interestingly, trend for TSS content was opposite to that of yield; tomatoes grown under lower yield conditions had lower water content and higher ion concentration, resulting in relatively better quality (Mitchell et al. 1991). This suggests that while biochar may not significantly alter certain quality indices, its impact on fruit TSS and overall quality could be influenced by yield levels.

Our results showed that large-sized biochar was more effective for ameliorating saline soils than small-sized biochar, while small-sized biochar might worsen salt stress and lead to yield reduction. In non-saline soils, however, small-sized biochar, with its better water retention, can improve crop yields significantly. Therefore, biochar with particles size >2 mm is expected

Table 3 The fitting equation, along with coefficient of determination (R^2), and *p*-value (*p*) from stepwise linear regression between tomato yield and two principal components (PC1 and PC2) derived from PCA of soil properties under B0, B1, and B2 treatments separately

Treatment	Regression model (y: tomato yield)	R^2	*p*
B0	Non-significant	0.129	0.661
B1	y = −155.41 PC2 + 1186.57	0.528	0.105
B2	y = −375.17 PC1 + 1231.8	0.893	0.010

B0: No biochar, B1: 0.5% large particles biochar, B2: 0.5% small particles biochar to perform better than smaller size particles, and better suited for application on saline soils for improving productivity and revenue of the land, or reclamation of marginal salinized land. For non-saline soils, biochar of relatively smaller particle (<2 mm) is better to be used as soil amendment for increase yield and soil carbon storage.

5 Conclusion

Using a northwest solar greenhouse as the study site, we investigated how various particle sizes of biochar, under different salt stress conditions, affect tomato growth, physiology, yield, and soil parameters. The findings indicated that, apart from soil pH, TN, and Ca^{2+}, most soil properties were not significantly altered by biochar application. Biochar enhanced soil pH and TN content attributable to its natural ash content. Additionally, the selective adsorption properties of biochar lead to a reduction in Ca^{2+} concentration within the soil. This reduction in Ca^{2+} was more pronounced with smaller particle-sized biochar, owing to its larger surface area. The combination of biochar size and salinity had varied effects on tomato yield: large-particle biochar improved yield in high-salinity soils by promoting salt leaching, whereas small-particle biochar reduced yield under high salinity. In non-saline conditions, small-particle biochar resulted in the highest yields. At present, what size of biochar is most suitable for certain type of soil with a given salinity level under field conditions, and long-term effects of applying biochar on soils were not clear. Further studies on the long-term effects on yield, as well as soil properties, from applying biochar of different particle sizes on saline soils under different field conditions are needed. In addition, the effects of combining biochar with other commonly-used soil amendments also need further study to achieve the highest possible production of saline soils.

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Author contributions

The conceptualization and design of the study were a joint effort by all authors. Wu Zhuqing and Zhou Zhengquan were responsible for data collection, while Wu Zhuqing conducted the data analysis and wrote the initial draft. All authors reviewed and provided comments on the draft multiple times. The final manuscript was read and approved by all authors.

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Availability of data and materials

The datasets generated and/or analyzed during the current study, as well as the materials used, are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study did not involve any human participants, animals, or sensitive data requiring ethical approval. Therefore, no ethics approval or consent to participate was necessary.

Consent for publication

All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing financial or non-financial interests to disclose.

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