

Article

Soil Salinity, Nutrient Availability, and Sunflower Productivity in Coastal Saline–Alkali Land in Response to Different Irrigation Quotas and Biochar Application Rates

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Abstract

For many countries, the reclamation of coastal saline–alkali land is of great significance for ensuring food security. However, systematic research on the effects of leaching irrigation and biochar application on the “soil–crop” system in coastal areas remains scarce. This study investigated the effects of three irrigation quotas (8, 16, and 24 mm per application, applied once every 10 days) and four biochar rates (0, 3, 5, 7 t·ha^{−1}, from composite biomass) on soil salinity, available nutrients, and yield and quality of sunflower in coastal saline–alkali soils of Jiangsu, China. The experiment used a completely randomized block design with three replications. The results showed that soil salinity under all treatments exhibited a consistent decline–rebound–decline pattern over the growing season, with the lowest values occurring around 55 days after sowing and peaking around 95 days. The combined application of water and biochar enhanced salt reduction, with the highest irrigation and biochar levels achieving the greatest desalination effect. Biochar application increased soil available phosphorus and potassium contents, with average increases of 19.6% and 13.3% under the highest biochar rate compared with the control, while available nitrogen showed no clear response to any treatment. Crop yield responded nonlinearly to water and biochar inputs: under low irrigation, yield increased continuously with biochar addition, whereas under medium or high irrigation, yield plateaued at the moderate biochar rate (5 t·ha^{−1}), with no further gains from additional biochar or water. Regarding seed quality, linoleic acid content generally increased with higher water and biochar levels, oleic acid decreased, and crude fat remained unaffected. Based on a balanced consideration of yield, quality, salt reduction, and water conservation, the combination of 16 mm irrigation per application and 5 t·ha^{−1} biochar is recommended as the optimal amelioration strategy for coastal saline–alkali land.



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Keywords: coastal saline–alkali land; sunflower; yield; biochar; irrigation rate; soil nutrients

1. Introduction

Soil salinity affects approximately 800 million hectares of arable land worldwide. Currently, the total area of saline–alkali land globally is approximately 1.125 billion hectares [1]. In China, the total area of saline–alkali land reaches 36.3 million hectares, of which 1.1 million hectares is developable coastal saline–alkali land [2]. Due to urban expansion, the

amount of arable land available in China is gradually shrinking. Under these circumstances, undeveloped coastal saline–alkali land needs to be incorporated into the agricultural production system to support urban food supply and ensure national food security.

Saline–alkali soil is characterized by high salinity, a compacted texture, poor permeability, and nutrient deficiency and must be reclaimed before crops can be grown [3,4]. Irrigation is considered one of the effective measures for reclaiming saline–alkali soil. Heng [5] found that leaching through irrigation wells reduced soil salinity in the 0–80 cm layer from $16 \text{ dS}\cdot\text{m}^{-1}$ to $3 \text{ dS}\cdot\text{m}^{-1}$, resulting in a significant improvement in the microbial community. A five-year sub-mulch drip irrigation trial showed that, as the duration of irrigation increased, salinity declined continuously overall, reaching non-salinized levels after five years, thereby promoting crop growth and effectively increasing yield [6].

Biochar is a soil amendment characterized by a high specific surface area, abundant functional groups, and a porous structure. Through a meta-analysis, Zhang et al. [7] demonstrated that, following the application of biochar, the pH of saline–alkali soil decreased by 2.2% and soil salinity decreased by 9.6%, with Na^+ , Cl^- , and HCO_3^- concentrations decreasing by 12.5%, 23.4%, and 17.7%, respectively, whereas K^+ , Mg^{2+} , and Ca^{2+} concentrations increased by 28.2%, 20.2%, and 18.8%, respectively, effectively improving the soil ion composition. Xie et al. [8] used nano-biochar for soil amelioration and found that its application promoted salt leaching more effectively, primarily owing to its smaller particle size and larger specific surface area compared with other types of biochar. Furthermore, the application of appropriate amounts of biochar has been found to increase crop yield, improve quality, and simultaneously enhance antioxidant enzyme activity and osmotic regulation capacity in crops while reducing membrane lipid peroxidation, thereby improving crop tolerance to salinity and alkalinity stress [9–11].

The amelioration of saline–alkali land has evolved from single-measure approaches toward the integrated application of multiple technologies. Existing studies have shown that the combined application of organic fertilizers and soil conditioners reduced soil pH and electrical conductivity by 1.3–3.7% and 14–20%, respectively, while increasing the 1000-grain weight of rice by 4–7% [12]. Optimizing the irrigation rate and replacing 30% of chemical nitrogen fertilizers with organic fertilizers increased maize yield by 7.14% [13]. When slightly saline water ($2 \text{ g}\cdot\text{L}^{-1}$) was applied in combination with maize straw biochar ($10 \text{ t}\cdot\text{ha}^{-1}$), winter wheat yield increased by 17.7% compared with the control [14]. The use of drip irrigation in combination with desulfurization gypsum, biochar, and a microbial fertilizer resulted in water savings of 20–30%, while maize yield remained at a high level and water use efficiency improved significantly [15]. Combining drip irrigation flushing with subsurface drainage reduced soil electrical conductivity in saline–alkali land from $8\text{--}15 \text{ dS}\cdot\text{m}^{-1}$ to $4\text{--}8 \text{ dS}\cdot\text{m}^{-1}$, with desalination rates reaching 25.8–35.2% [16]. Winter irrigation with frozen saline water ($9.59 \text{ g}\cdot\text{L}^{-1}$) combined with spring plastic mulching reduced the electrical conductivity of coastal saline–alkali soil to $0.94 \text{ dS}\cdot\text{m}^{-1}$, yielding better results than any single amelioration measure [17].

In summary, current research on the integrated amelioration of saline–alkali land through multiple measures has primarily focused on combinations such as “organic fertilizer + soil conditioner,” “slightly saline water irrigation + biochar,” “irrigation leaching + soil conditioner,” and “subsurface drainage + irrigation leaching.” However, for coastal saline–alkali land of a specific soil type, limited attention has been given to the synergistic regulation of fixed irrigation quotas combined with modified biochar. Moreover, the application of FeCl_3 -modified composite biochar in saline soils has been largely confined to laboratory adsorption experiments, and its field-scale desalination efficacy, as well as its effects on sunflower yield and quality, remains unclear. In this study, field experiments were conducted on coastal saline–alkali land using the salt-tolerant plant sunflower as the

test plant, with varying irrigation rates and biochar application rates. We hypothesized that the application of biochar and irrigation quotas in coastal saline–alkali soil could regulate soil water–salt conditions and available nutrient status, thereby improving sunflower yield and quality, with an optimal water–biochar combination expected within a certain range. The objectives were to (1) elucidate the dynamics of soil salinity and available nutrients under different water–biochar treatments, (2) evaluate the interactive effects of irrigation and biochar on sunflower yield and quality, and (3) perform a multi-objective trade-off analysis among desalination rate, yield, quality, and water input so as to recommend the optimal water–biochar combination that balances salt reduction, stable yield, and water conservation.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted from May to October 2025 in Jianggang Town, Dongtai City, Yancheng, Jiangsu Province, China. Jianggang Town is located in the southeastern part of Dongtai City. It borders the towns of Xinjie, Sancang, and Touzao to the west; Chuan Dong Farm in Shanghai and Xin Cao Farm in Jiangsu Province to the north; Laobagang Town in Hai'an City to the south; and the Yellow Sea to the east. The town is situated on the coastal plain north of the Yangtze River Delta, with a generally flat and open terrain. The area has a monsoon climate transitioning from the northern subtropical zone to the warm temperate zone, characterized by distinct seasonal changes, abundant precipitation, and favorable sunlight conditions. From 2014 to 2024, the mean annual temperature was 15.2 °C, with a mean annual precipitation of 1065.2 mm and a mean annual sunshine duration of approximately 2064.5 h. The basic physicochemical properties (salinity, etc.) of the 0–80 cm soil layer in the experimental area are presented in Table 1. Moreover, the area has a flat topography and a shallow water table, fluctuating between 1.0 and 1.5 m during the growing season. The subsurface drainage system (buried at a depth of 1.5 m with a 20 m spacing) was installed in the field. The agronomic practices, including weeding, were uniformly applied, and no supplemental light, heat, or CO₂ was provided.

Table 1. Soil physical and chemical properties.

Soil Depth /cm	pH	Moisture Content/%	Bulk Density /(g·cm ^{−3})	Organic Matter /(g·kg ^{−1})	Electrical Conductivity /(ms·cm ^{−1})	Available Nitrogen /(mg·kg ^{−1})	Available Phosphorus /(mg·kg ^{−1})	Available Potassium /(mg·kg ^{−1})
0–20	8.31	24.2	1.45	8.33	4.63	58.2	8.9	152.3
20–40	8.17	23.8	1.47	8.36	4.92	62.1	8.7	161.0
40–60	8.65	24.6	1.51	8.02	3.09	57.5	8.7	150.2
60–80	9.13	27.5	1.44	7.55	2.82	51.0	7.1	148.6

In 2025, the year of the experiment, the monthly mean maximum temperature ranged from 10 to 34 °C, whereas the monthly mean minimum temperature ranged from −2 to 25 °C. Overall, the climate exhibited the characteristics of a continental climate, with hot summers and cold winters. Temperatures were lowest in January and February (a monthly mean maximum of 10 °C and a minimum of −2 to −1 °C) and highest in July (a monthly mean maximum of 34 °C and a minimum of 25 °C). The mean wind speed ranged from 5.9 to 17.4 km·h^{−1}, with relatively higher wind speeds from spring to early summer (March–May and July) and the lowest in winter (December). The precipitation distribution exhibited the typical characteristic of concurrent rainfall and heat. The total annual precipitation was approximately 1281.2 mm, concentrated from May to September,

during which cumulative precipitation reached 1116 mm, accounting for 87.1% of the annual total. Precipitation was highest in September (340 mm) and lowest in January (4.2 mm) (Figure 1).

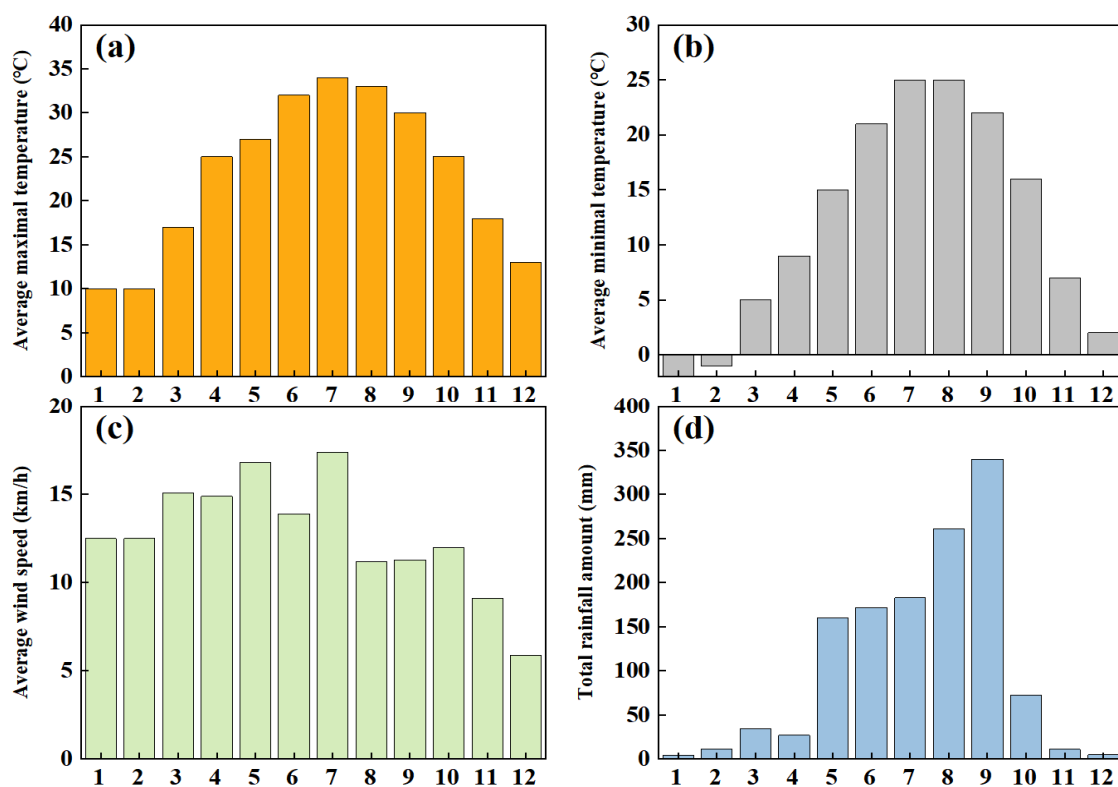


Figure 1. Temperature, wind speed, and precipitation for the year of the experiment ((a–d) were maximal temperature, minimal temperature, wind speed, and precipitation respectively).

2.2. Experimental Design

This study used the sunflower (*Helianthus annuus* L.) as the test plant, with the growing period spanning from 2 June to 18 October 2025. The specific growth stages included the seedling stage, the budding stage, the full-bloom stage, and the maturity/harvest stage, as shown in Table 2. On 31 May, a single flood irrigation event was applied at a rate of 50 mm to leach salts from the soil (which was not included in the seasonal irrigation amount).

Table 2. Stages of sunflower growth.

Growth Stage	Seedling Stage	Budding Stage	Full-Blooming Stage	Maturity Stage
Period	2 June–23 July	24 July–20 August	21 August–7 September	8 September–18 October
Irrigation Times	5	3	1	4

Local agricultural technology is relatively advanced, and farmers have a high income level, generally accepting the use of smart automated systems for scheduled, metered irrigation. Therefore, this study employed three irrigation rates, namely 8 mm (I1), 16 mm (I2), and 24 mm (I3), which were applied once every 10 days starting on 11 June. The final irrigation procedure was applied on 9 October (130 days after sowing). Considering material availability and practicality, a composite biomass feedstock consisting of 50% rice straw, 30% reed, and 20% poplar sawdust was used (the high cellulose content of rice straw improves carbon yield and porosity; the high lignin content of reed enhances the structural stability and degradation resistance of the biochar, and the high lignin content of poplar

sawdust further strengthens the carbon skeleton and promotes the formation of hierarchical porosity). The feedstock was impregnated with a 5% ferric chloride solution at a solid-to-liquid ratio of 1:10 and then pyrolyzed at 600 °C for 2 h to produce the biochar used in the experiment. FeCl₃ modification was selected because the iron oxides loaded on the biochar surface can simultaneously adsorb Na⁺, Cl[−], and phosphate via ligand exchange and electrostatic attraction. During pyrolysis, most Cl[−] ions are volatilized as HCl, leaving limited residuals [18,19]. The basic properties of the biochar were as follows: pH: 7.8, EC: 3.5 dS·m^{−1}, total carbon: 58.4%, total nitrogen: 0.9%, C/N ratio: 64.9, total phosphorus: (as P₂O₅) 1.8%, total potassium (as K₂O): 4.2%, ash content: 28.5%, CEC: 16.8 cmol·kg^{−1}, and specific surface area: 132 m²·g^{−1}. The experimental design included four biochar application rates, namely 0 t·ha^{−1} (B0), 3 t·ha^{−1} (B1), 5 t·ha^{−1} (B2), and 7 t·ha^{−1} (B3), all applied as a single dose before sowing. The specific experimental design is presented in Table 3.

Table 3. Experimental treatment.

Irrigation	Biochar	Irrigation Quota (mm)	Irrigation Frequency (d)	Total Irrigation Amount	Biochar Application Rate (t/ha)	Application Method
I1	B0	8	10	104	0	Applied in a single application before sowing
I1	B1	8		104	3	
I1	B2	8		104	5	
I1	B3	8		104	7	
I2	B0	16		208	0	
I2	B1	16		208	3	
I2	B2	16		208	5	
I2	B3	16		208	7	
I3	B0	24		312	0	
I3	B1	24		312	3	
I3	B2	24		312	5	
I3	B3	24		312	7	

In the experimental design, a no-sunflower control was not included because the study objective was focused on the yield and quality responses of the sunflower under different water–biochar management practices, rather than isolating the effect of the sunflower itself on soil salinity. Regarding the absence of a no-irrigation control, it was mainly because zero irrigation is not a local practice and would make it impossible to obtain meaningful yield data.

The experiment employed a randomized complete block design, with each plot measuring 6 m × 8 m (48 m²), comprising a total of 36 plots (Figure 2). Each treatment was completely randomly assigned to one plot and replicated three times. Each plot was surrounded by 1 m wide buffer strips, and adjacent plots were separated by ridges with a 60 cm deep plastic barrier installed between them to prevent lateral water and salt movement. Sunflower plants were spaced 60 cm between rows and 40 cm within rows. Irrigation was applied through an underground sprinkler system. Fertilization was based on our previous study [20], with 120 kg N·ha^{−1}, 85 kg P₂O₅·ha^{−1}, and 160 kg K₂O·ha^{−1} of fertilizer applied. Additionally, 25% of the nitrogen was derived from the chemical fertilizer (urea) and 75% was derived from the organic fertilizer produced by Nanjing Mingzhu Fertilizer Co., Ltd. (Nanjing, China) (containing 2.3% N, 1.2% P₂O₅, and 1.3% K₂O). The shortfall in phosphorus and potassium from the organic fertilizer was supplemented with triple superphosphate and potassium chloride.

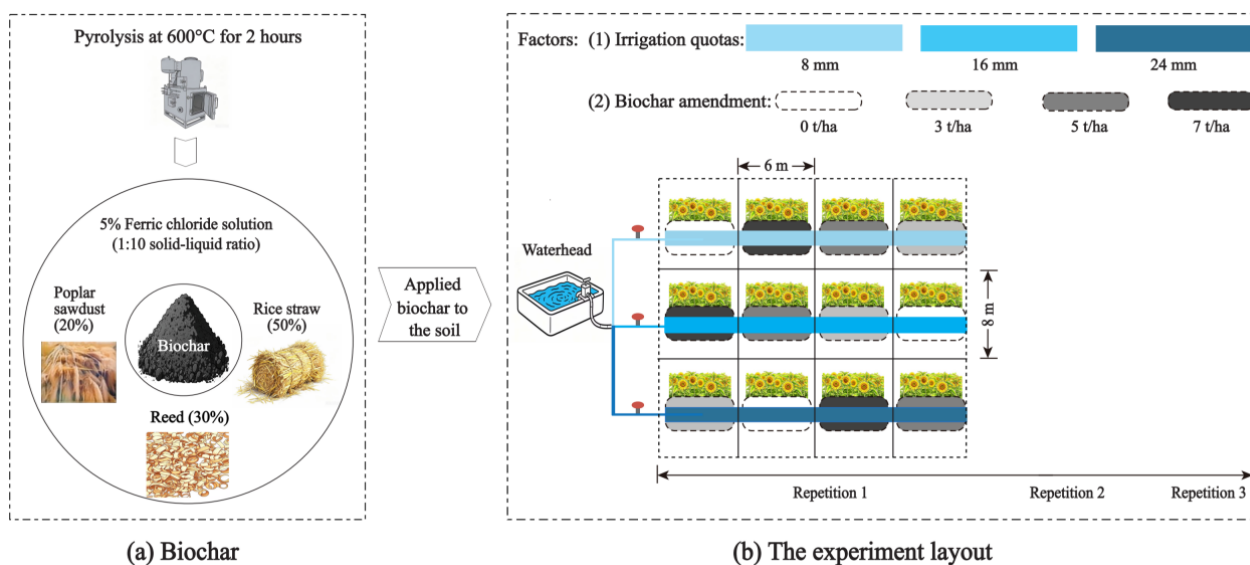


Figure 2. Experimental setup.

2.3. Measurements and Methods

Soil electrical conductivity (bulk EC, $\text{ms}\cdot\text{cm}^{-1}$) in the plow layer was monitored throughout the entire growth period of the sunflower. A soil conductivity meter (WET-2, Delta-T Devices Ltd., Cambridge, UK) was used to measure EC within a 1 m wide strip directly above and parallel to the main underground irrigation pipeline, following the five-point sampling method. The sensor was calibrated with standard buffer solutions prior to each measurement. Measurements were taken at 0–20 cm depth on the 5th day after each irrigation (i.e., the midpoint of the 10-day interval), when soil moisture conditions were comparable across treatments. The first measurement was taken on June 6, and the last was taken on October 14. The salt reduction rate was calculated as follows: salt reduction rate (%) = $(\text{initial EC} - \text{final EC}) / \text{initial EC} \times 100$. The initial EC was determined on the 5th day after sowing, and the final EC was determined at harvest (135 days after sowing). Both values were the averages of three replications per treatment.

Soil available nutrients: On October 14 (135 days after sowing), topsoil samples were collected using the five-point sampling method. After thorough mixing, the available nitrogen, phosphorus, and potassium contents were determined by the alkaline hydrolysis diffusion method, the $0.5 \text{ mol}\cdot\text{L}^{-1} \text{ NaHCO}_3$ extraction–molybdenum–antimony colorimetric method, and the ammonium acetate extraction–flame photometric method, respectively [21].

Crop yield and quality: Yield was determined at sunflower maturity. The central four rows (each 6 m long) in each plot were harvested as the sampling area, with a harvest area of 14.4 m^2 . Border rows 0.5 m from each end of the rows were excluded. All sunflower heads within the sampling area were collected, air-dried, threshed, and weighed. A random subsample of 500 seeds was taken to determine the 100-seed weight, and seed moisture content was measured and adjusted to the standard 14% moisture content. Plot yield was calculated as follows: $(\text{t}\cdot\text{ha}^{-1}) = [\text{total fresh seed weight (kg)} \times (1 - \text{measured moisture content}) / (1 - 14\%)] / \text{harvest area (m}^2) \times 10,000$. Among the sunflower quality indicators, palmitic acid (%), oleic acid (%), linoleic acid (%), and stearic acid (%) were determined by gas chromatography, whereas crude fat (%) was determined after extraction with an ionic liquid solvent [22,23].

2.4. Data Analysis

Soil nutrients, yield, and quality results were analyzed by two-way ANOVA to evaluate the main effects of irrigation, biochar, and their interaction. Differences among treatments were tested for significance at the 0.05 level using Duncan's multiple range test in SPSS 17.0 software. Duncan's multiple range test was suitable for pairwise comparisons of multiple treatment combinations in agricultural field experiments, offering a balance between controlling Type I error and minimizing false negative risk, and is widely adopted in crop cultivation and soil amelioration research.

3. Results and Discussion

3.1. EC and EC Decline Rate

The EC values in each treatment exhibited a distinct “decline–rebound–decline” pattern over the treatment period (Figure 3). The highest values were observed 5 days after sowing, ranging from 4.2 to 4.5 $\text{ms}\cdot\text{cm}^{-1}$, and then declined to a minimal level at around 55 days. The lowest value of 2.3 $\text{ms}\cdot\text{cm}^{-1}$ was observed in the I3B3 group. Subsequently, EC values rebounded rapidly between 55 and 95 days (a period characterized by high temperatures and frequent rainfall), peaking at around 95 days at 3.6–4.6 $\text{ms}\cdot\text{cm}^{-1}$. Thereafter, EC values declined again with time, dropping to 2.2–3.2 $\text{ms}\cdot\text{cm}^{-1}$ by 135 days.

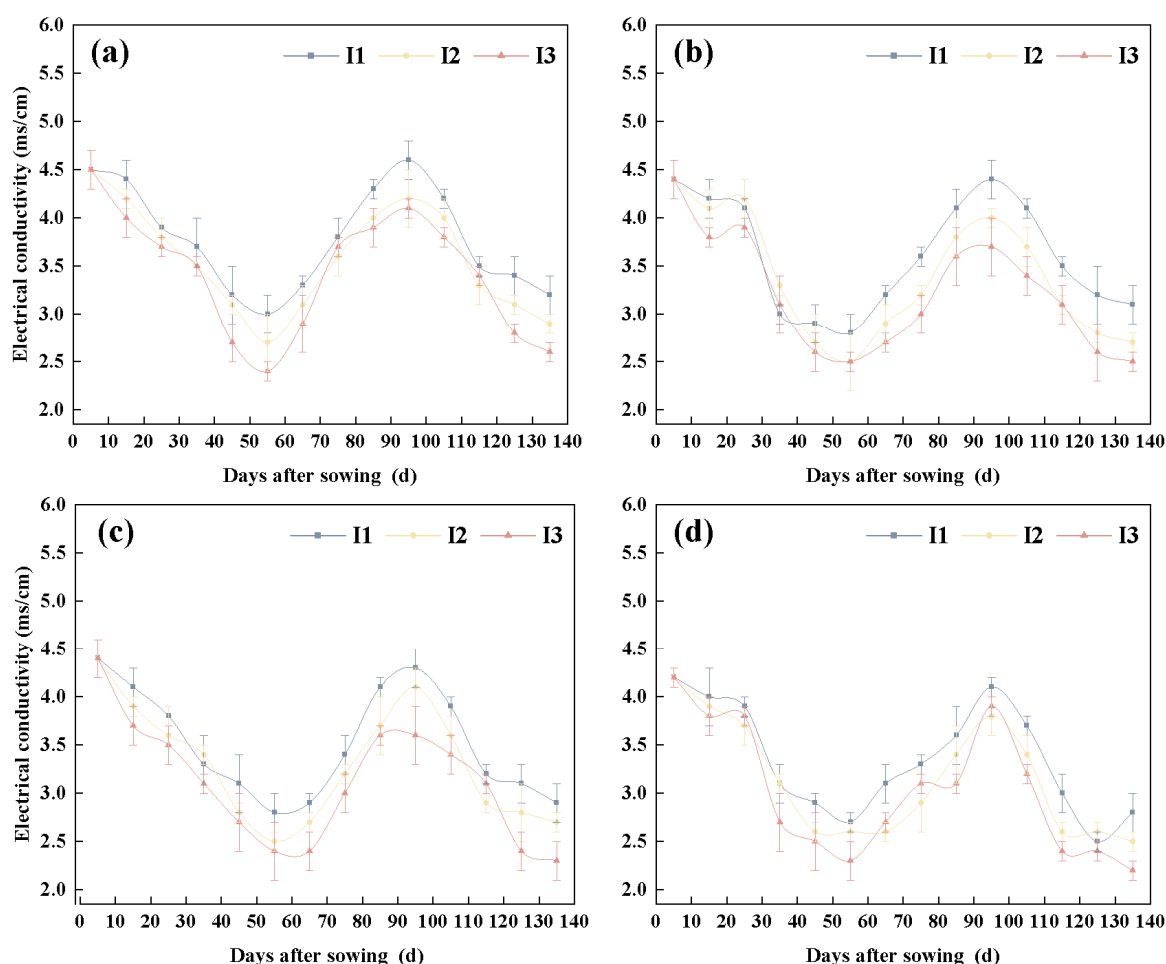


Figure 3. Dynamics of soil electrical conductivity over time. (a–d) are the results based on biochar application rates of 0, 3, 5, and 7 $\text{t}\cdot\text{ha}^{-1}$, respectively. I1, I2, and I3 denote irrigation rates of 8, 16, and 24 mm per application, respectively. Data are presented as means $\pm$ SD.

Obvious differences were observed among the biochar treatments, with B0 exhibiting the highest overall values, B1 and B2 falling in the middle, and B3 showing generally lower values. These results indicated that increasing the biochar application rate suppressed EC values. At the same biochar application rate, the different irrigation rates (I1, I2, and I3) also influenced EC values, with higher irrigation rates resulting in lower EC values.

EC dynamics were driven by the combined effects of irrigation, rainfall, evaporation, and biochar. Although rainfall was the major water input during the growing season, it was identical across all treatments. Therefore, the inter-treatment differences in EC were primarily determined by the gradient effects of irrigation and biochar.

The salt reduction rate in each treatment increased significantly with higher biochar application and irrigation rates (Figure 4). At the same biochar application rate, the salt reduction rate under the I3 treatment was significantly higher ($p < 0.05$) than those under the I2 and I1 treatments. Across different biochar application rates, the B2I3 treatment exhibited the highest salt reduction rate (approximately 47.8%), followed by treatment I3B3 (approximately 47.6%), whereas the B0I3 treatment showed the lowest rate (approximately 42.3%). These results indicated that both biochar application and irrigation rates significantly enhanced the salt reduction effect. Moreover, both the irrigation quota and the biochar application rate had highly significant effects on the salt reduction rate ($p < 0.01$), whereas their interactive effect was not significant.

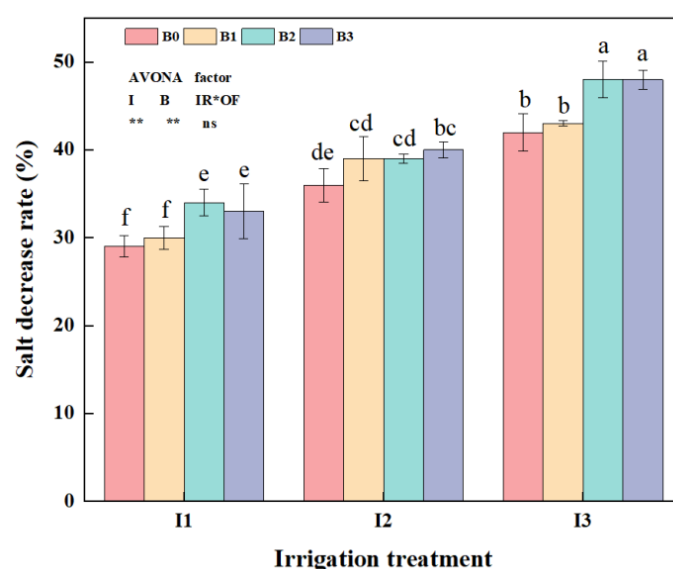


Figure 4. Salt reduction rates under different irrigation and biochar application rates. I1, I2, and I3 denote irrigation rates of 8, 16, and 24 mm per application, respectively. B0, B1, B2, and B3 denote biochar application rates of 0, 3, 5, and 7 t·ha^{−1}, respectively. Data are presented as means ± SD. Different letters above the bars indicate significant differences among treatments at the 0.05 level. ** and ns mean that the experimental treatment has extremely (0.01) and no significant effect on the indicator.

3.2. Crop Yield

The different treatments had a significant effect on yield (Figure 5). Under the same irrigation regime, yield generally increased with increasing biochar application. However, when the biochar application rate increased from B2 to B3, the increase in yield was not significant ($p > 0.05$). This pattern was observed across all three irrigation regimes. Overall, among the biochar treatments, sunflower yield was highest under the B3 treatment, reaching 3.37–3.86 t·ha^{−1}. At the same biochar application rate, yield was generally highest under the I2 regime. Under the I2 treatment combined with the B2 and B3 biochar application rates, the yield ranged from 3.68 to 3.86 t·ha^{−1}, with a seasonal irrigation

amount of 208 mm (258 mm including the 50 mm pre-sowing leaching event), a salt reduction rate of 38.6–40.5%, and a water productivity of 1.43–1.50 kg·m⁻³, demonstrating generally favorable overall performance. The irrigation quota or biochar application rate had a highly significant effect on the yield ($p < 0.01$), whereas their interactive effect was not significant.

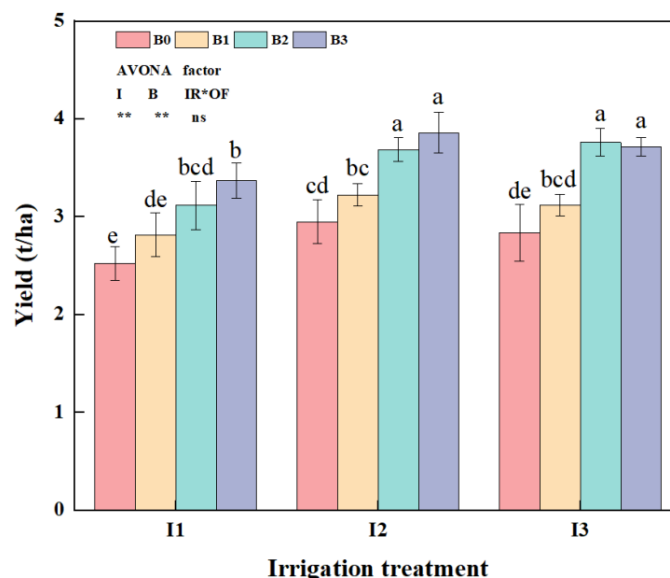


Figure 5. Effects of different irrigation and biochar application rates on sunflower yield. I1, I2, and I3 denote irrigation rates of 8, 16, and 24 mm per application, respectively. B0, B1, B2, and B3 denote biochar application rates of 0, 3, 5, and 7 t·ha⁻¹, respectively. Data are presented as means $\pm$ SD. Different letters above the bars indicate significant differences among treatments at the 0.05 level. ** and ns mean that the experimental treatment has extremely (0.01) and no significant effect on the indicator.

3.3. Available Nutrients in Soil

The irrigation quota had a highly significant ($p < 0.01$) effect on the available nitrogen and potassium; the biochar application rate had a highly significant ($p < 0.01$) effect on the available phosphorus and potassium, whereas their interactive effect was not significant on the three indicators.

Different treatments had varying effects on the available nutrient contents in the soil (Figure 6). For available nitrogen, the mean values under the I1, I2, and I3 levels were 71.53–75.37 mg·kg⁻¹, 66.93–69.07 mg·kg⁻¹, and 66.30–68.13 mg·kg⁻¹, respectively, showing no clear trend with changes in the biochar application rate.

For available phosphorus, under the same irrigation rate, the available phosphorus content generally increased with increasing biochar application. Under the I1, I2, and I3 levels, the highest available phosphorus values were observed in the B3 treatment, at 10.87 mg·kg⁻¹, 10.90 mg·kg⁻¹, and 10.33 mg·kg⁻¹, respectively, all of which were significantly higher than those in the corresponding B0 treatment ($p < 0.05$). At the same biochar application rate, the available phosphorus content under the I1 treatment was generally the highest, ranging from 9.70 to 10.87 mg·kg⁻¹, slightly higher than that under the I2 and I3 treatments.

Available potassium was also significantly affected by the irrigation and biochar treatments. Similar to available phosphorus, under the same irrigation rate, the available potassium content generally increased with increasing biochar application. The highest available potassium values across the three irrigation rates were observed in the B3 treatment, at 181.33 mg·kg⁻¹, 172.33 mg·kg⁻¹, and 166.33 mg·kg⁻¹, respectively, all of which

were significantly higher than those in the corresponding B0 treatment. Under the same biochar application rate, the available potassium content under the I1 treatment remained at a relatively high level, ranging from 160.37 to 181.33 mg·kg⁻¹.

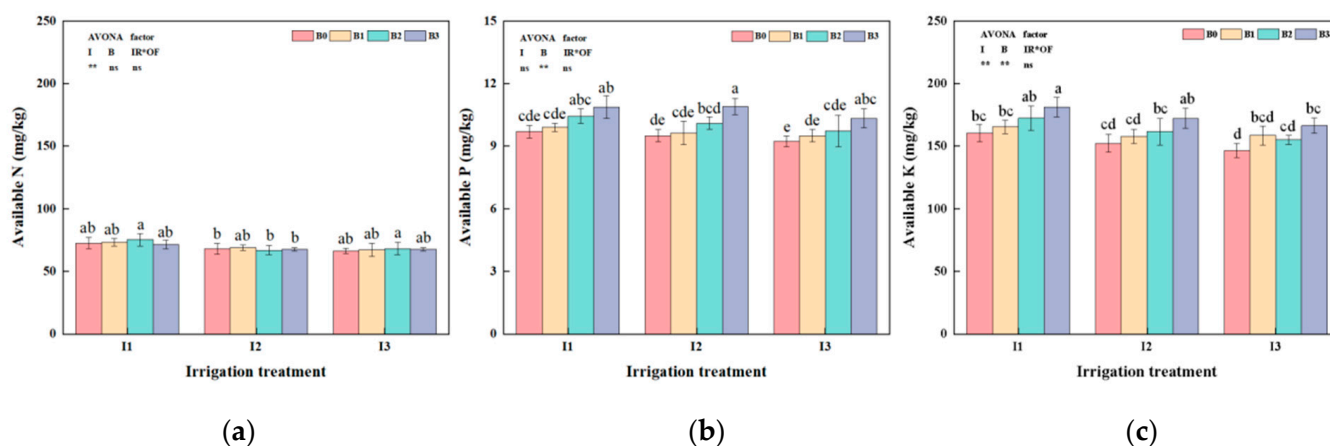


Figure 6. Effects of different irrigation and biochar application rates on available nutrients in the plow layer. Subfigures (a–c) show the available nitrogen, phosphorus, and potassium contents, respectively. I1, I2, and I3 denote irrigation rates of 8, 16, and 24 mm per application, respectively; B0, B1, B2, and B3 denote biochar application rates of 0, 3, 5, and 7 t·ha⁻¹, respectively. Data are presented as means $\pm$ SD. Different letters above the bars indicate significant differences among treatments at the 0.05 level. ** and ns mean that the experimental treatment has extremely (0.01) and no significant effect on the indicator.

3.4. Relationship Between Yield, Salinity and Available Nitrogen

A positive correlation was observed between yield and the salt reduction rate across all irrigation levels, with the strongest correlation at the I3 level ($r = 0.71$, $n = 12$, $p < 0.05$), followed by I2 ($r = 0.60$, $n = 12$, $p < 0.05$), and the weakest at I1 ($r = 0.27$, $n = 12$, $p > 0.05$). In contrast, the correlation between available nitrogen content and yield was generally weak, with no significant linear relationship.

3.5. Crop Quality

The palmitic acid content ranged from 5.83% to 6.92% overall. No significant differences were observed among treatments at the I1 level ($p > 0.05$), and no clear relationship was found between palmitic acid content and biochar application under the I2 and I3 regimes (Table 4). The oleic acid content ranged from 19.47% to 23.17% and decreased with increasing irrigation rate or biochar application. The highest oleic acid content was observed in the I1B0 treatment, reaching 23.2%, although the difference from I1B1 was not significant ($p > 0.05$). The trend of the linoleic acid content was opposite to that of oleic acid: as the irrigation rate or biochar application increased, linoleic acid content generally increased. When biochar application increased from B0 to B1, linoleic acid content rose significantly ($p < 0.05$). However, the increase from B1 to B3 was not significant ($p > 0.05$). Stearic acid content ranged from 4.55% to 6.13% and generally decreased with increasing irrigation rate or biochar application. Crude fat content ranged from 22.67% to 25.07%, with no significant differences observed among most treatments ($p > 0.05$). In summary, irrigation and biochar exerted more pronounced regulatory effects on the oleic and linoleic acid contents of sunflower seeds.

Table 4. Effects of different irrigation rates and biochar application rates on crop quality.

Irrigation Quota	Biochar Application	Palmitic Acid (%)	Oleic Acid (%)	Linoleic Acid (%)	Stearic Acid (%)	Crude Fat (%)
I1	B0	5.83 ± 0.19 d	23.2 ± 0.21 a	64.9 ± 0.60 d	6.13 ± 0.24 a	23.7 ± 1.15 abc
	B1	5.90 ± 0.11 d	22.4 ± 1.11 ab	66.9 ± 1.45 bc	4.84 ± 0.24 fg	23.5 ± 0.62 bc
	B2	5.85 ± 0.13 d	21.2 ± 0.40 bcde	67.5 ± 0.55 abc	5.42 ± 0.04 cd	22.7 ± 0.56 c
	B3	5.92 ± 0.22 d	20.1 ± 0.80 efg	68.2 ± 1.00 ab	5.81 ± 0.06 ab	22.9 ± 0.61 c
I2	B0	6.10 ± 0.12 cd	22.3 ± 0.40 abc	65.9 ± 0.40 cd	5.73 ± 0.13 bc	25.1 ± 0.74 ab
	B1	6.25 ± 0.14 c	21.8 ± 1.25 bcd	67.1 ± 1.55 bc	4.78 ± 0.17 fg	25.2 ± 1.03 a
	B2	6.23 ± 0.11 c	21.1 ± 0.15 cdef	68.0 ± 0.46 ab	4.64 ± 0.20 fg	24.2 ± 1.05 abc
	B3	6.55 ± 0.12 b	20.5 ± 0.40 efg	68.4 ± 0.56 ab	4.55 ± 0.10 g	22.7 ± 0.59 c
I3	B0	6.92 ± 0.20 a	21.0 ± 0.60 def	66.1 ± 1.05 cd	5.98 ± 0.27 ab	24.9 ± 0.98 ab
	B1	6.88 ± 0.11 a	20.4 ± 0.80 efg	67.8 ± 0.80 ab	4.92 ± 0.11 ef	24.2 ± 0.90 abc
	B2	6.58 ± 0.15 b	19.9 ± 0.35 fg	68.3 ± 0.80 ab	5.19 ± 0.31 de	23.7 ± 0.56 abc
	B3	6.56 ± 0.11 b	19.5 ± 0.32 g	69.3 ± 0.55 a	4.74 ± 0.16 fg	23.1 ± 0.94 c

Note: I1, I2, and I3 denote irrigation rates of 8, 16, and 24 mm per application, respectively. B0, B1, B2, and B3 denote biochar application rates of 0, 3, 5, and 7 t·ha^{−1}, respectively. Data are presented as means ± SD. Different letters indicate significant differences among treatments at the 0.05 level.

4. Discussion

This study demonstrated that water–biochar treatment can effectively reduce soil salinity, with the highest water and biochar application rates yielding the best results. Irrigation primarily reduces salinity in the plow layer through leaching, a mechanism that has been widely confirmed by numerous studies. The mechanisms by which biochar reduces soil salinity likely involve two main aspects. First, biochar facilitates ion adsorption and exchange. Biochar possesses a high specific surface area and abundant oxygen-containing functional groups, possibly enabling it to directly adsorb salt ions such as Na⁺ from the soil solution through surface adsorption. Simultaneously, Ca²⁺ and Mg²⁺ released from the biochar might undergo ion exchange with Na⁺ on the surface of soil colloids, thereby reducing the exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) in the soil. Second, biochar might promote the leaching of salt ions. The porous structure of the biochar increases soil porosity (particularly in the 0.1–0.5 mm pore size range [24]) and water infiltration rates, thereby facilitating the downward migration of salt ions with irrigation water. Moreover, the porous structure prolongs the residence time of water in the soil, thereby improving salt leaching efficiency and reducing salt accumulation in the root zone. Jayanta [25] reported that, compared to the control treatment, the application of biochar increased the average soil hydraulic conductivity by up to 55.9%.

It is noteworthy that although the growing-season rainfall (1116 mm) was substantial, all treatments received identical rainfall; therefore, the inter-treatment differences in soil salinity should be attributed to the gradient effects of irrigation and biochar. The water balance comprised pre-sowing leaching (50 mm), seasonal irrigation (104/208/312 mm), and rainfall (1116 mm), totaling 1270/1374/1478 mm. Rainfall occurs as discrete precipitation events, during the intervals of which root-zone moisture may become insufficient; irrigation applied at fixed 10-day intervals provided a steady water supply, compensating for the temporal unevenness of rainfall. Under identical rainfall conditions, this targeted irrigation strategy, in synergy with biochar, produced the gradient effects.

Overall, the results of this study indicate that the application of biochar enhanced the levels of available nutrients in saline–alkali soils. This finding is consistent with the study by Jaffar et al., who reported that 2% plant-derived biochar promoted nutrient cycling by increasing the activity of soil urease, alkaline phosphatase, and acid phosphatase [26]. However, this study also found that the effect of biochar on soil available nutrients varied with the specific nutrient. In this study, no significant change was observed in available

nitrogen. This may be due to the offsetting effects of biochar's adsorption and fixation of NH_4^+ against its promotion of nitrogen mineralization or to the higher C/N ratio that may have induced short-term immobilization of inorganic nitrogen by microorganisms. In contrast, available phosphorus and potassium showed significant increases. This is partly because biochar itself is rich in soluble phosphorus and potassium, which directly replenished the soil's available phosphorus and potassium pools upon application, and partly because functional groups on the biochar surface can chelate and immobilize metal ions such as Fe^{3+} , Al^{3+} , and Ca^{2+} , thereby reducing the chemical fixation of phosphorus. In addition, its high cation exchange capacity allows it to adsorb and retain K^+ , thereby mitigating leaching losses [27]. A significant increase in available nitrogen content was observed in the biochar application trials; this may be because these experiments involved the application of both biochar and an organic fertilizer.

An increased irrigation rate or biochar application helped increase the linoleic acid content in sunflowers while reducing oleic and stearic acid levels, which is consistent with the findings of Yin [28]. This may be because higher water and biochar levels reduced soil salinity stress (Figures 3 and 4) and optimized nutrient supply (Figure 6), thereby activating oleic acid desaturase. This enzyme might promote the extensive conversion of oleic acid into linoleic acid and also facilitates the desaturation of stearic acid, leading to a decrease in oleic and stearic acid contents and a corresponding increase in linoleic acid content. Mostafa [29] found that drought stress inhibited lipid synthesis, adversely affecting sunflower seed quality and reducing overall economic value. Wu [30] reported that a total irrigation volume of 285 mm was optimal for improving sunflower quality, which is consistent with our findings (208–312 mm).

Optimal irrigation levels are critical for sunflower yield. Salbas [31] found that improper irrigation affected sunflower leaf water status, which was positively correlated with the final seed yield. Yavuz [32] found that a 70 cm drip irrigation spacing combined with a moisture coefficient of 1.00 (full irrigation) resulted in a maximum sunflower yield of $5.70 \text{ t} \cdot \text{ha}^{-1}$. Our study also found a positive correlation between sunflower yield and irrigation rate. However, when the irrigation rate was increased from I2 to I3, sunflower yield did not change significantly and even decreased slightly, which may be due to the leaching of some nutrients from the plow layer caused by the higher irrigation rate. In this study, the reason why I2 promoted a high sunflower yield may be because this irrigation rate directly reduced soil salinity in the plow layer through leaching while simultaneously improving water use efficiency and nutrient availability, thereby creating a favorable water–salt environment for sunflower yield formation.

The findings of this study—that higher biochar application rates led to higher yields (highest under the B3 rate, $3.37\text{--}3.86 \text{ t} \cdot \text{ha}^{-1}$)—are consistent with the research by Tian et al. [33], who reported that biochar application resulted in yield increases ranging from 13.8% to 29.5%. The yield increase attributed to biochar application may be due to its direct improvement of soil physicochemical properties. First, biochar application helped improve the soil structure [34], promoted salt leaching, reduced salt stress on sunflower roots, and improved growing conditions for sunflowers. Second, biochar helped increase the retention of available nutrients (phosphorus and potassium, Figure 6) in the soil, laying the foundation for sunflower nutrient uptake and ultimately yield formation. We are more inclined to believe that the yield increase observed in this study stemmed from the reduction in soil salinity following biochar application. This is because, on the one hand, no significant change in available nitrogen (Figure 6)—which was considered a key factor in yield formation—was observed after biochar application. On the other hand, the correlation analysis (Figure 7) indicated a relatively stronger correlation between yield and the rate of salinity reduction.

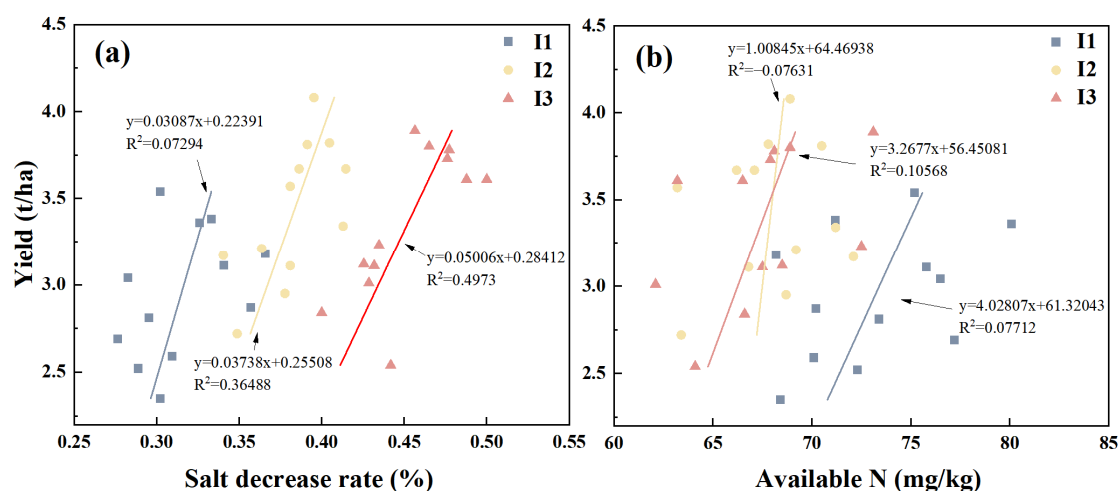


Figure 7. Correlations between yield and salt reduction rate (a), yield and available nitrogen (b).

The main limitations of this study include a single experimental site, a one-growing-season duration, substantial rainfall during the experiment, shallow groundwater influence, a lack of detailed water–salt balance data, and the absence of systematic monitoring of residual Fe/Cl. Consequently, the recommended strategy is primarily applicable to coastal saline–alkali lands with similar climatic and soil conditions, and further validation is required for regions with different rainfall patterns, groundwater levels, or soil textures. Additionally, potential ecological risks associated with residual chloride or iron from the modified biochar—affecting soil EC, phosphorus availability, and environmental safety—should be considered. Although the biochar used was derived from clean feedstocks with low heavy metal backgrounds, produced at 600 °C to degrade most organic contaminants, and FeCl₃ modification may immobilize certain heavy metals through complexation, these potential pollutants were not systematically monitored in this study. Future research should validate amelioration effectiveness under broader climatic and soil conditions, extend the observation period to assess long-term biochar effects, and strengthen systematic monitoring of the ecological safety of modified biochar in saline soils, with particular attention to residual Fe/Cl and their potential impacts on the soil environment and crop growth.

5. Conclusions

The water–biochar combination significantly reduced soil salinity, with desalination rates ranging from 42.6% to 47.8% across treatments. Following biochar application, there was a clear increase in available phosphorus and potassium (approximately 15–24% and 13–21% higher, respectively, compared to the control without biochar), whereas no significant effect on available nitrogen was observed ($p > 0.05$). This suggested that phosphorus and potassium were primarily regulated by direct biochar input, whereas nitrogen turnover relied more on soil mineralization processes and required independent management. Under low-water conditions, biochar exhibited a significant marginal yield-increasing effect, whereas under medium-to-high-water conditions, this effect tended to saturate once biochar application reached 5 t·ha^{−1}, and further increases in water and biochar inputs did not result in significant yield gains. Linoleic acid content ranged from 64.8% to 69.2% across treatments, showing an overall upward trend with increasing water and biochar levels. Oleic acid content ranged from 19.7% to 23.4%, exhibiting a downward trend. Based on a balanced consideration of yield, quality, salt reduction, and water conservation, the application of 16 mm of irrigation water combined with 5 t·ha^{−1} of biochar is recommended as an appropriate improvement measure. This approach can achieve efficient desalination (a

47.6% desalination rate) and a stable yield increase ($3.68 \text{ t} \cdot \text{ha}^{-1}$) while saving approximately 29% of water.

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