Soil Environ. 45(1): 21-32, 2026
DOI: doi.org/10.25252/SE/2026/253985
Online ISSN: 2075-1141
Print ISSN: 2074-9546

Effect of two straw biochar amendments on reducing soil salinity, enhancing soil fertility, and improving winter wheat yield

Shahrukh Khan[1], Punhoon Khan Korai[2], Shakal Khan Korai[1*], Shengnan Li[1], Muhammad Qasim[3], Muhammad Usama Younas[4], Liting Yang[5], Zameer Hussain Jamali[6,7] and Xiaoshan Wang[1*]
[1]College of Animal Science and Technology, Yangzhou University, Yangzhou 225009, China
[2]Department of Soil Science, Faculty of Agriculture, Lasbela University of Agriculture, Water and Marine Sciences, Uthal 90150, Balochistan, Pakistan
[3]Microelement Research Center, College of Resources and Environment, Huazhong Agricultural University, Wuhan, Hubei-430070, China
[4]Key Laboratory of Plant Functional Genomics of the Ministry of Education, Jiangsu Key Laboratory of Crop Genomics and Molecular Breeding, Agricultural College of Yangzhou University, Yangzhou 225009, China
[5]Jiangsu Yancheng Wetland Rare Birds National Nature Reserve, Yancheng 320900, China
[6]College of Crop Cultivation and Tillage, Yangzhou University, Yangzhou 225009, China
[7]Department of Agroecosystems, Faculty of Agriculture and Technology, University of South Bohemia in Ceske Budejovice, Branišovská 1645/31A, 37005, Ceske Budejovice, Czech Republic

[Received:** November 22, 2025 **Accepted:** February 25, 2026 **Published Online:** March 10, 2026**]

Abstract

Salt stress is a major constraint to global crop production, particularly under intensifying climate pressures, and identifying effective soil amendments is critical for sustaining productivity in salt-affected agroecosystems. This study evaluated the effects of two straw-derived biochars viz. maize straw biochar (MBC) and wheat straw biochar (WBC) on soil salinity, soil fertility, and winter wheat performance using a pot experiment with a salt-affected Entisol from central China. Biochars were applied at 2% and 5% (w/w) prior to winter wheat sowing, and soil and plant samples were collected before planting and at harvest to assess changes in soil pH, total salt content, Na^+ concentration, soil organic carbon (SOC), nutrient availability, plant growth traits, yield components, and tissue ion composition. Both MBC and WBC significantly reduced soil salinity indicators, including soil pH, total salt content, and Na^+ concentration, with stronger effects observed at the 5% application rate. Biochar application increased SOC, total nitrogen, available phosphorus, and available potassium, while soil cation exchange capacity remained unchanged. Wheat growth, root development, yield components, and biomass were significantly enhanced under biochar treatments, particularly with WBC at 5%. In addition, biochar reduced Na^+ accumulation and increased K^+, Ca^{2+}, and Mg^{2+} concentrations in wheat roots and leaves, indicating improved ionic balance under salt stress. Overall, straw-derived biochar especially wheat straw biochar at higher application rates effectively mitigated salt stress and improved soil fertility and winter wheat productivity under the non-leaching pot conditions of this study. These findings highlight the potential of straw biochar as a sustainable amendment for improving crop performance in salt-affected soils while providing a value-added pathway for crop residue utilization.

Keywords: Salt-affected soil, Sodium stress, Soil nutrients, Root growth, Biochar amendment, Sustainable agriculture

Introduction

Crop residues, including wheat and maize straw, are potential sources of nutrients for crop production. The release of nutrients through crop residue decomposition increases the availability of mineral nutrients and soil organic matter content, which in turn improves soil fertility and helps sustain agricultural productivity (Singh & Rengel, 2007; Kumari *et al*., 2019; Hossain *et al*., 2020; Fu *et al*., 2021). However, incorporating crop residues into the soil can create challenges, such as hindering the use of cultivation equipment (Bhuvaneshwari *et al*., 2019; Shinde *et al*., 2022), promoting the spread of residue-borne crop diseases (Kerdraon *et al*., 2019; Abalos *et al*., 2022), and

---

***Email:** xswang@yzu.edu.cn

Cite This Paper: Khan, S., P.K. Korai, S.K. Korai, S. Li, M. Qasim, M.U. Younas, L. Yang, Z.H. Jamali and X. Wang. 2026. Effect of two straw biochar amendments on reducing soil salinity, enhancing soil fertility, and improving winter wheat yield. *Soil Environ*. 45(1): 21-32.

inhibiting seed germination and plant growth due to the production of phytotoxins (Raaijmakers *et al.*, 2009; Chaudhary *et al.*, 2019). Moreover, decomposition of crop residues quickly releases carbon (C) fixed through photosynthesis back into the atmosphere (Qiao *et al.*, 2014), and can increase the loss of native soil organic carbon (SOC) due to the positive priming effect (Guenet *et al.*, 2018), thereby contributing to CO_2 emissions from terrestrial ecosystems (Langley *et al.*, 2009; Varney *et al.*, 2023; Zhang *et al.*, 2023). Converting straw residues into biochar provides an alternative management pathway that can retain a larger fraction of biomass carbon in a more stable form while recycling nutrients back to agricultural soils. Because biochar properties depend strongly on feedstock (e.g., wheat vs. maize straw) and pyrolysis conditions. Different straw-derived biochars may vary in their effectiveness for improving soil functions and crop performance.

Soil salinity is a serious constraint on arable-land productivity because it can disrupt soil physical structure and suppress microbial activity (Graber *et al.*, 2010; Ud Din *et al.*, 2023). As a result, salinization is now recognized as a worldwide problem that reduces crop yield and can also compromise food quality (El Sabagh *et al.*, 2020; Khondoker *et al.*, 2023). The area of salt-affected farmland is still increasing, often driven by inefficient water use, inadequate drainage, and inappropriate irrigation practices; these trends are frequently reported in countries such as Australia, Pakistan, China, and Indonesia (Sharma & Singh, 2017; Basak *et al.*, 2022; Kebede, 2023). In saline and sodic soils, excess soluble salts and exchangeable Na^+ can restrict plant water uptake and nutrient acquisition, degrade soil aggregation, and ultimately reduce crop productivity. Winter wheat is widely cultivated and is sensitive to salinity during early growth and grain formation; therefore, strategies that improve soil conditions and reduce salt stress are critical for stabilizing wheat yield in salt-affected regions.

To slow or prevent further salinization, several management approaches have been promoted, including water-saving strategies, improved irrigation scheduling, effective drainage systems, and adjustments in cropping patterns (Cuevas *et al.*, 2019; Haj-Amor *et al.*, 2022). Where soils are already affected, remediation commonly relies on chemical amendments (e.g., plaster or gypsum) and the incorporation of organic materials to reduce salinity impacts and improve soil conditions (Bello *et al.*, 2021). In China, these concerns are especially pressing because climate change is intensifying both drought pressure and the risk of salinity buildup, particularly across northern agricultural zones (Maheshwari *et al.*, 2022; Ud Din *et al.*, 2023). Accordingly, reclaiming salt-affected soils and preventing new salinization have become key priorities within China's agricultural planning (Kumar *et al.*, 2022; Gang *et al.*, 2024). Overall, there is growing emphasis on developing low-cost, sustainable, and scalable solutions that can alleviate salt stress and support stable crop production (Shokat & Großkinsky, 2019; Johnson & Puthur, 2021; Ashraf & Munns, 2022).

Biochar has been increasingly investigated as an organic amendment for salt-affected soils because it can influence soil chemical and physical properties that are directly related to salinity stress and fertility. Potential mechanisms include (i) increasing soil organic carbon and improving aggregation, (ii) supplying ash-derived base cations and nutrients, (iii) enhancing ion exchange and retaining plant-available nutrients, and (iv) reducing Na^+ stress by promoting Na^+ displacement and improving the soil's ionic balance.

Most biochar studies have been conducted under short-term (i.e., several weeks to a few months) laboratory incubation conditions (Farkas *et al.*, 2018; Igalavithana *et al.*, 2019; Leng *et al.*, 2019). However, laboratory settings can differ significantly from field conditions, limiting the applicability of such findings to real-world agriculture. Therefore, it is crucial to examine changes in soil properties induced by biochar application under field conditions for a better understanding of its impact on soil fertility (Korai *et al.*, 2018; Diatta *et al.*, 2020; Alkharabsheh *et al.*, 2021). In addition to incubation studies, pot experiments provide a controlled way to link biochar-induced changes in soil salinity-related indicators (e.g., EC and sodicity indices such as ESP/SAR) with crop growth and yield responses. Importantly, comparisons among biochars derived from different straw feedstocks under the same soil and management conditions can clarify whether "straw biochar" effects are consistent or feedstock-specific.

The effects of biochar on plant growth are highly variable ranging from positive to neutral or even negative while the underlying mechanisms remain unclear. The structure and properties of biochar, influenced by feedstock type and pyrolysis temperature, play essential roles in the interactions at the biochar-soil-plant interface. These interactions may contribute to mitigating climate change and supporting plant development. Additionally, novel applications of biochar as a pathogen control agent have recently emerged (Poveda *et al.*, 2021; Bhatt *et al.*, 2024). For salt-affected soils, these properties are especially relevant because they govern ash alkalinity, nutrient release, surface functional groups, and sorption/ion-exchange behavior, which collectively determine the amendment's capacity to reduce salinity stress and enhance fertility. Therefore, studies that explicitly compare wheat straw biochar and maize straw biochar while tracking soil salinity indices, fertility parameters, and crop yield components are needed to provide mechanistic and agronomically meaningful evidence.

We hypothesized that incorporating wheat and maize straw into the soil could enhance soil fertility, while applying biochar derived from wheat and maize straw with equivalent carbon content could alleviate salt stress. Therefore, in this study we have evaluated the effects of two straw biochar amendments (wheat straw biochar and maize straw biochar) on (i) reducing soil salinity/sodicity indicators, (ii) improving soil fertility-related properties, and (iii) enhancing winter wheat growth and yield in a pot experiment using salt-affected soil.

Materials and Methods

Soil sampling and Experimental site description

Soil used for the pot experiment was collected from a salt-affected agricultural field located in Kangzhuang Village (34°32′N, 115°30′E), Liangyuan District, Shangqiu Municipality, Henan Province, China. The region lies within a semi-arid to semi-humid agroecological zone where soil salinization is a persistent constraint to cereal production. The experiment was conducted in 2017, and climatic data for the experimental year, including temperature and precipitation, were obtained from the nearest meteorological station to characterize the prevailing growth conditions. Surface soil (0–20 cm), corresponding to the main rooting zone of wheat, was collected using a composite sampling approach. The soil was air-dried, gently crushed, and passed through a 2-mm sieve prior to pot preparation.

Initial soil physicochemical and salinity characterization

Prior to treatment application, soil samples were analyzed to establish baseline physicochemical properties and salinity status. Soil pH (H_2O) was measured in a soil–water suspension using a glass electrode pH meter. Soil salinity was assessed by determining total salt content (g kg^{-1}) following standard gravimetric procedures. Soil sodium (Na^+) concentration was measured after extraction using ammonium acetate and quantified by flame photometry. Soil total organic carbon (TOC) was determined using the dichromate oxidation method, and total nitrogen (TN) was measured using the Kjeldahl digestion method. Cation exchange capacity (CEC) was determined using the ammonium acetate (NH_4OAc) extraction method. These baseline measurements provided the reference values presented in Table 1 and were used to evaluate changes in soil properties following wheat cultivation under different biochar treatments.

Biochar preparation and characterization

Two straw-derived biochars, wheat straw biochar (WBC) and maize straw biochar (MBC), were used in the pot experiment. Both biochars were produced by slow pyrolysis of air-dried straw feedstocks at temperatures between 400 and 500 °C under oxygen-limited conditions. After pyrolysis, the biochars were allowed to cool under an inert atmosphere and then ground and sieved to a particle size of <1 mm to ensure homogeneous mixing with soil in the pot experiment. Prior to application, the physicochemical properties of both biochars were characterized. Biochar pH was measured in a biochar–water suspension, while total organic carbon (TOC) and total nitrogen (TN) were determined using standard analytical methods. Total salt content and cation exchange capacity (CEC) of the biochars were also measured to support interpretation of biochar-induced changes in soil salinity and fertility. The key properties of the wheat and maize straw biochars, together with those of the experimental soil, are summarized in Table 1.

Experimental design and Biochar treatments

The pot experiment was conducted using a completely randomized design. Five treatments were established: An unamended control (CK), maize straw biochar applied at 2% (MBC 2) and 5% (MBC 5, w/w on a soil mass basis), and wheat straw biochar applied at 2% (WBC 2) and 5% (WBC 5). Each treatment was replicated four times, resulting in a total of 20 experimental units. Biochar application rates were selected to represent moderate and high amendment levels commonly used in pot experiments investigating soil salinity remediation and fertility improvement. The rates of 2% and 5% (w/w) correspond to approximately 20–50 t ha^{-1} under field-equivalent conditions, allowing assessment of dose-dependent responses of soil properties and wheat performance.

Pot preparation and crop establishment

Plastic pots (25 cm diameter × 30 cm height; 10 L capacity) were filled with 8 kg of air-dried and sieved soil. The required amounts of wheat straw biochar or maize straw biochar were thoroughly mixed with the soil prior to pot filling to ensure uniform distribution. Control pots received

Table 1: Physico-chemical properties of the topsoil and biochar used in the pot experiment

Sample	pH (H_2O)	TOC (g kg^{-1})	TN (g kg^{-1})	Salt (g kg^{-1})	CEC (cmol kg^{-1})
Soil	8.3	5.01	0.8	13.23	22.31
MBC	9.6	404.3	10.4	32.45	19.21
WBC	9.1	465.3	11.4	40.98	15.46

Note: TOC, total organic carbon; TN, total nitrogen; CEC, cation exchange capacity; MBC, maize biochar; WBC, wheat biochar.

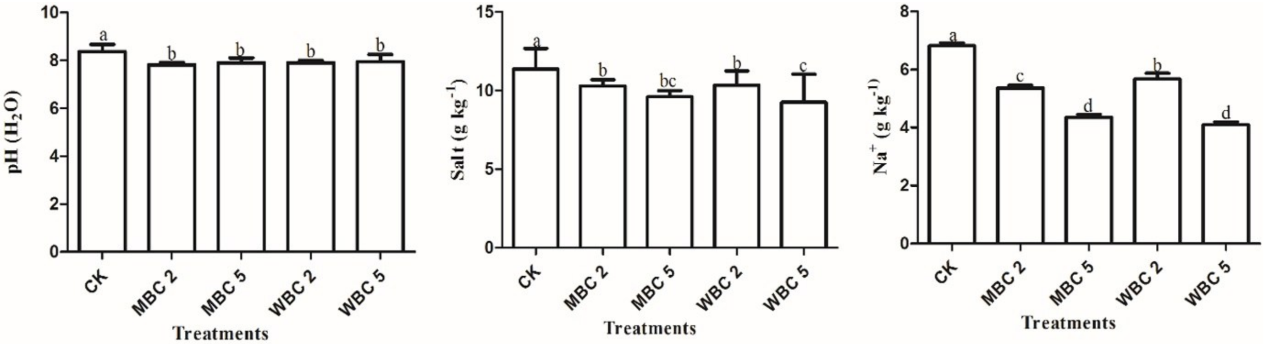

Figure 1: Effects of straw biochar treatments on soil pH, total salt content (g kg^{-1}), and Na^+ concentration (g kg^{-1}). Bars represent means ± SD (n = 4). Different letters indicate significant differences among treatments ($p < 0.05$)

Table 2: Basic properties of topsoil under two types of biochar treatments in salt-stressed conditions

Treatment	SOC (g kg^{-1})	CEC (cmol kg^{-1})	TN (g kg^{-1})	AP (mg kg^{-1})	AK (g kg^{-1})
CK	6.68 ± 0.3 d	26.41 ± 0.0 a	0.82 ± 0.0 d	30.2 ± 0.0 e	0.169 ± 0.1 d
MBC 2	7.42 ± 0.8 c	26.25 ± 0.1 a	1.15 ± 0.1 c	31.4 ± 0.1 d	0.193 ± 0.0 cd
MBC 5	8.67 ± 0.7 b	26.34 ± 0.1 a	1.35 ± 0.0 b	38.8 ± 0.5 b	0.397 ± 0.1 bc
WBC 2	8.17 ± 0.2 b	26.41 ± 0.2 a	1.52 ± 0.1 ab	32.5 ± 0.1 c	0.322 ± 0.1 b
WBC 5	9.53 ± 0.3 a	26.32 ± 0.1 a	1.55 ± 0.1 a	45.9 ± 0.9 a	0.600 ± 0.6 a

SOC, soil organic carbon; CEC, cation exchange capacity; TN, total nitrogen; AP, available phosphorus; AK, available potassium; CK, control; MBC 2, maize straw biochar at 2%; MBC 5, maize straw biochar at 5%; WBC 2, wheat straw biochar at 2%; WBC 5, wheat straw biochar at 5%. Values are means ± SD (n = 4). Different letters indicate significant differences among treatments ($p < 0.05$).

soil without biochar amendment. After pot preparation, seeds of winter wheat (*Triticum aestivum* L.) were sown, and seedlings were thinned after emergence to maintain five uniform plants per pot across all treatments. All pots were maintained under natural light conditions during the experimental period. Soil moisture was regularly monitored and maintained near field capacity to avoid both drought and waterlogging stress, ensuring that plant responses were primarily associated with biochar-induced changes in soil properties under salt-stressed conditions.

Nutrient and irrigation management

To avoid nutrient deficiency and ensure comparable growth conditions among treatments, all pots received a uniform nutrient supply during the experimental period. A modified Hoagland nutrient solution was applied at regular intervals to provide essential macro- and micronutrients (Arnon, 1950). This approach was adopted to minimize nutrient limitation and to ensure that observed plant responses were primarily attributable to biochar-induced changes in soil salinity and fertility rather than differences in nutrient availability. Irrigation was applied using deionized water to maintain soil moisture near field capacity throughout the experiment. Water was supplied uniformly to all treatments, and the number of irrigation events and approximate volume per pot were kept consistent across treatments to avoid confounding effects of water stress.

Leaching Conditions

No intentional leaching was allowed during the experiment. Pots were designed without drainage collection, and irrigation was carefully controlled to avoid water percolation and loss of soluble salts. This experimental setup was adopted to simulate salt accumulation conditions commonly observed in salt-affected soils with limited drainage and to enable assessment of biochar effects on soil salinity and ion dynamics under non-leaching conditions.

Plant growth and yield measurements

Wheat plants were harvested 100 days after sowing, corresponding to the active growth stage under pot conditions. At harvest, plant growth parameters were recorded, including plant height, tiller number per plant, leaf area, and shoot fresh weight. Root traits, including root length and root fresh weight, were also measured after carefully washing roots free of adhering soil. Yield-related parameters were determined at maturity. Grain number per spike and 1000-grain weight were recorded to assess yield formation under different biochar treatments. In addition, shoot dry weight and root dry weight were measured after oven-drying plant samples at 70 °C to constant weight. All growth and yield data were expressed on a per-plant or per-pot basis, consistent with the experimental design and statistical analysis.

Statistical analysis

All experimental data were subjected to analysis of variance (ANOVA) to assess the effects of biochar type and application rate on soil properties and wheat growth and yield parameters. When significant differences were detected, treatment means were compared using the Least Significant Difference (LSD) test at a significance level of $p < 0.05$. Statistical analyses were performed using SPSS software (version 22.0) (MILLS, 2003; Gray & Kinnear, 2012). Results are presented as mean ± standard deviation (SD) based on four replicates per treatment.

Results

Effects of straw biochar on soil pH, salt content, and Na^+ concentration

Changes in soil salinity indicators (pH, total salt content, and Na^+ concentration) under different biochar treatments are shown in Figure 1. Compared with the control (CK), all biochar treatments significantly reduced soil pH, total salt content, and Na^+ concentration ($p < 0.05$). Soil pH decreased by 7.0%, 5.9%, 5.9%, and 5.3% in the MBC 2%, MBC 5%, WBC 2%, and WBC 5% treatments, respectively. Total salt content declined by 15.0%, 23.2%, 14.3%, and 27.9%, while

Table 3: Effect of two straw biochar treatments on growth characteristics of wheat plants under salt-stressed conditions

Treatment	Plant Height (cm)	Tiller Number/Plant	Leaf Area (cm)	Shoot Fresh Weight/Plant
CK	67.08 ± 0.9 d	2.41 ± 0.1 d	26.53 ± 0.1 e	10.28 ± 0.1 e
MBC 2	79.11 ± 0.5 c	5.39 ± 0.1 c	30.36 ± 0.2 d	30.64 ± 1.0 d
MBC 5	83.47 ± 0.5 b	7.79 ± 0.3 b	31.96 ± 0.1 c	41.24 ± 0.7 b
WBC 2	82.71 ± 1.4 b	5.56 ± 0.2 c	34.44 ± 0.3 b	35.84 ± 0.2 c
WBC 5	90.77 ± 2.6 a	8.11 ± 0.1 a	44.57 ± 0.3 a	60.53 ± 0.5 a

Note: CK, control; MBC 2, maize biochar 2%; MBC 5, maize biochar 5%; WBC 2, wheat biochar 2%; WBC 5, wheat biochar 5%. Different letters in each column indicate significant differences ($p < 0.05$) between the biochar treatments. Values in each column indicate mean ± SD (n=4).

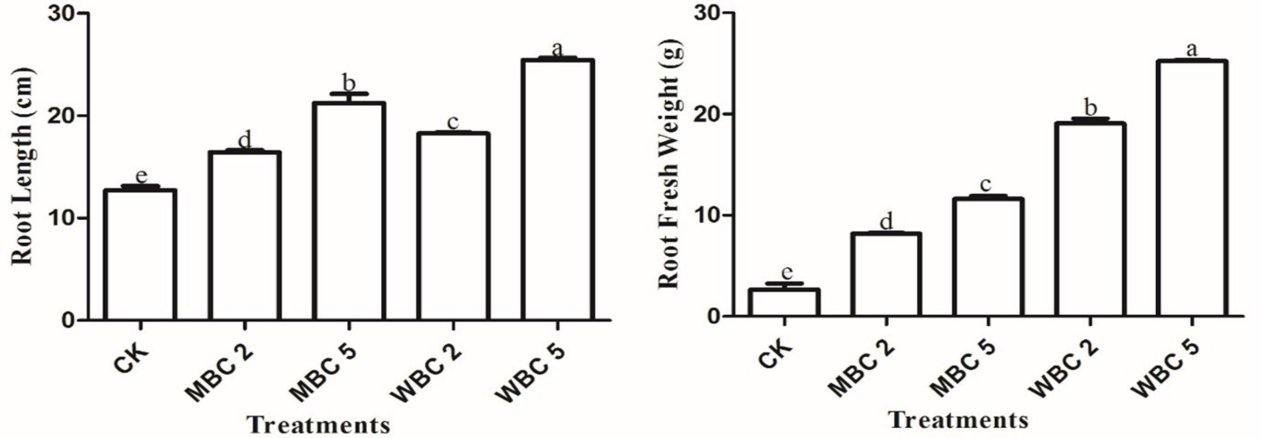

Figure 2: Effects of straw biochar treatments on root length and root fresh weight of winter wheat. Bars represent means ± SD (n = 4). Different letters indicate significant differences among treatments ($p < 0.05$)

Na^+ concentration decreased by 27.2%, 56.8%, 20.1%, and 66.3% under the same treatments. In general, higher biochar application rates resulted in greater reductions in soil salinity indicators, and wheat straw biochar exhibited a stronger effect than maize straw biochar.

Effects of straw biochar on soil organic carbon and nutrient status

Soil organic carbon and nutrient status responded positively to straw biochar application under salt-stressed conditions (Table 2). Compared with the control (CK), SOC increased across all biochar treatments, rising from 6.68 g kg^{-1} in CK to 7.42 g kg^{-1} (MBC 2), 8.67 g kg^{-1} (MBC 5), 8.17 g kg^{-1} (WBC 2), and 9.53 g kg^{-1} (WBC 5). The highest SOC value was observed under WBC 5, indicating the strongest carbon improvement at the higher wheat biochar rate. Total nitrogen (TN) also increased significantly following biochar application. TN rose from 0.82 g kg^{-1} in CK to 1.15 g kg^{-1} (MBC 2), 1.35 g kg^{-1} (MBC 5), 1.52 g kg^{-1} (WBC 2), and 1.55 g kg^{-1} (WBC 5), with wheat biochar treatments producing the highest TN levels. Available phosphorus (AP) and available potassium (AK) increased significantly in biochar-amended soils relative to CK. AP increased from 30.2 mg kg^{-1} in CK to 31.4 mg kg^{-1} (MBC 2), 38.8 mg kg^{-1} (MBC 5), 32.5 mg kg^{-1} (WBC 2), and 45.9 mg kg^{-1} (WBC 5), with WBC 5 showing the greatest enhancement. A similar trend was observed for AK, which increased from 0.169 in CK to 0.193 (MBC 2), 0.397 (MBC 5), 0.322 (WBC 2), and 0.600 (WBC 5). In contrast, CEC did not differ significantly among treatments, remaining stable across all biochar types and application rates. Overall, wheat straw biochar particularly at the 5% application rate produced the strongest improvements in SOC and nutrient availability under salt stress.

Effects of straw biochar on wheat growth and Root traits

Application of straw biochar significantly enhanced wheat growth characteristics under salt-stressed conditions (Table 3; Figure 2). Compared with the control (CK), all biochar treatments resulted in marked increases in plant height, tiller number, leaf area, and shoot fresh weight. The magnitude of improvement generally increased with higher biochar application rates. Plant height increased from 67.08 cm in CK to 79.11 cm (MBC 2), 83.47 cm (MBC 5), 82.71 cm (WBC 2), and 90.77 cm (WBC 5). Similarly, tiller number per plant increased substantially across treatments, with the highest value observed under WBC 5. Leaf area also expanded significantly in biochar-amended soils, reaching a maximum of 44.57 cm^2 in the WBC 5 treatment. Shoot fresh weight showed pronounced increases following biochar application.

Compared with CK (10.28 g $plant^{-1}$), shoot fresh weight increased to 30.64 g (MBC 2), 41.24 g (MBC 5), 35.84 g (WBC 2), and 60.53 g (WBC 5). Root traits responded similarly to biochar amendment (Figure 2). Root length increased from 12 cm in CK to 16 cm (MBC 2), 22 cm (MBC 5), 18 cm (WBC 2), and 25 cm (WBC 5). Root fresh weight also increased markedly across treatments, with the highest value recorded under WBC 5, followed by WBC 2, MBC 5, and MBC 2. Overall, wheat straw biochar produced stronger improvements in both shoot and root growth than maize straw biochar, particularly at the higher application rate.

Effects of straw biochar on wheat yield components and biomass

Straw biochar application significantly improved wheat yield components and biomass production under salt-stressed conditions (Figures 3 and 4). Compared with the control (CK), all biochar treatments increased the number of grains per spike and 1000-grain weight, with the magnitude of response generally increasing with application rate. The number of grains per spike increased markedly relative to CK, with increases observed in all biochar treatments. Similarly, 1000-grain weight was significantly enhanced by biochar application, reaching the highest value under the WBC 5% treatment. Overall, wheat straw biochar produced greater improvements in yield components than maize straw biochar at comparable application rates (Figure 3).

Biochar amendment also significantly increased wheat biomass accumulation (Figure 4). Both shoot dry weight and root dry weight were significantly higher in biochar-treated soils than in the control. Among the treatments, WBC 5% resulted in the highest shoot and root dry weights, followed by WBC 2%, MBC 5%, and MBC 2%, while CK consistently showed the lowest biomass values. The observed trends were consistent for both aboveground and belowground biomass, indicating that straw biochar application, particularly wheat straw biochar at higher rates, substantially enhanced wheat growth and dry matter accumulation under saline conditions.

Effects of straw biochar on mineral ion accumulation in wheat roots and leaves

Straw biochar application significantly influenced the accumulation of mineral ions in wheat roots and leaves under salt-stressed conditions (Table 4). Compared with the control (CK), all biochar treatments significantly reduced Na^+ concentrations in both roots and leaves, with the magnitude of reduction increasing with higher application rates. Root Na^+ concentration decreased from 10.2 mg g^{-1} DW in CK to

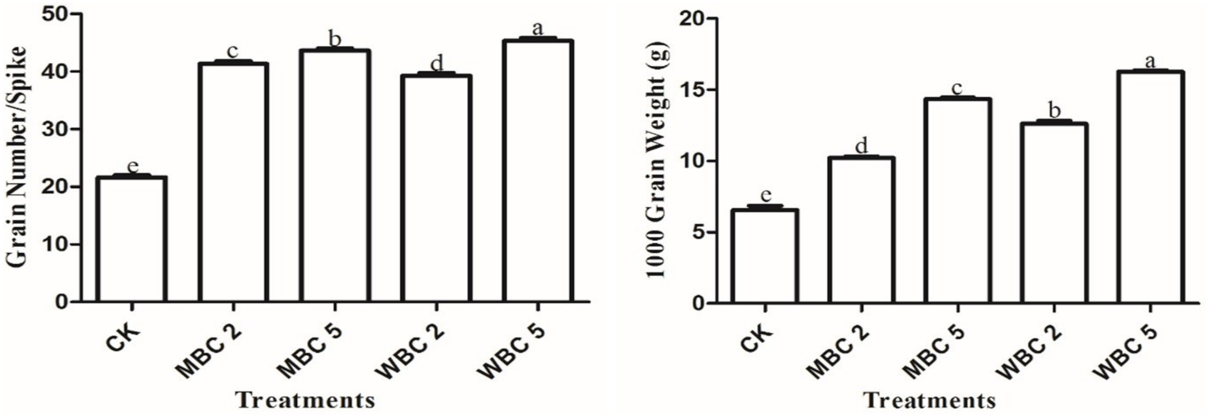

Figure 3: Effects of straw biochar treatments on grain number per spike and 1000-grain weight (g) of winter wheat. Bars represent means ± SD ($n = 4$). Different letters indicate significant differences among treatments ($p < 0.05$)

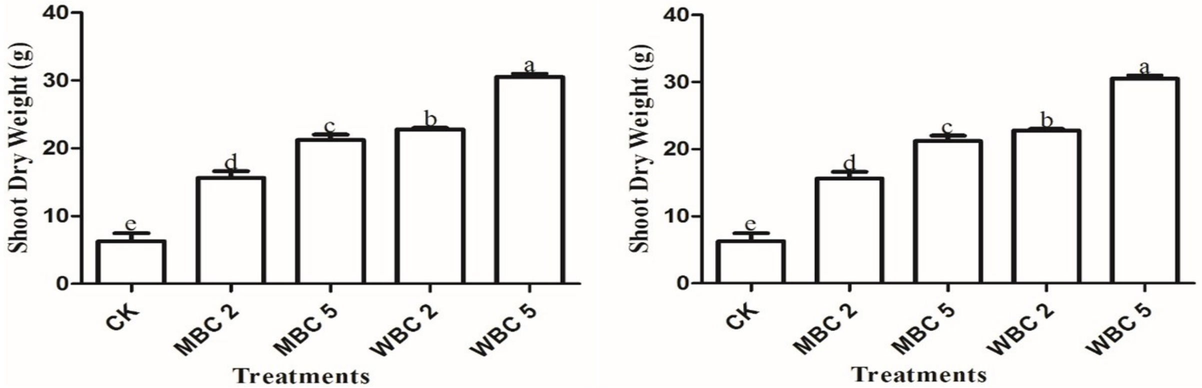

Figure 4: Effects of straw biochar treatments on shoot dry weight and root dry weight (g) of winter wheat. Bars represent means ± SD ($n = 4$). Different letters indicate significant differences among treatments ($p < 0.05$)

Table 4: Effect of two straw biochar treatments on sodium, potassium, calcium, and magnesium contents of wheat plants under salt-stressed conditions

Treatment	Root Na^+ (mgg^{-1} DW)	Leaf Na^+ (mgg^{-1} DW)	Root K^+ (mgg^{-1} DW)	Leaf K^+ (mgg^{-1} DW)	Root Ca^{2+} (mgg^{-1} DW)	Leaf Ca^{2+} (mgg^{-1} DW)	Root Mg^{2+} (mgg^{-1} DW)	Leaf Mg^{2+} (mgg^{-1} DW)
CK	10.2 ± 0.13 e	13.0 ± 0.15 e	15.4 ± 0.20 e	17.4 ± 0.30 e	10.1 ± 0.05 e	9.19 ± 0.56 e	5.52 ± 0.26 e	5.22 ± 0.34 e
MBC 2	9.27 ± 0.05 d	12.1 ± 0.09 d	17.3 ± 0.17 d	19.3 ± 0.20 d	15.2 ± 0.10 d	13.4 ± 0.45 d	7.37 ± 0.17 d	7.07 ± 0.30 d
MBC 5	8.36 ± 0.14 c	11.2 ± 0.17 c	19.3 ± 0.14 c	21.3 ± 0.50 b	17.3 ± 0.10 c	16.3 ± 0.30 c	10.3 ± 0.15 c	9.97 ± 0.50 c
WBC 2	6.39 ± 0.20 b	9.29 ± 0.20 b	22.4 ± 0.33 b	24.4 ± 0.67 c	19.3 ± 0.08 b	18.3 ± 0.80 b	12.5 ± 0.10 b	12.1 ± 0.45 b
WBC 5	5.28 ± 0.06 a	8.18 ± 0.10 a	25.8 ± 0.22 a	27.1 ± 0.90 a	22.4 ± 0.11 a	21.5 ± 0.50 a	14.3 ± 0.14 a	14.0 ± 0.49 a

Note: CK, control; MBC 2, maize biochar 2%; MBC 5, maize biochar 5%; WBC 2, wheat biochar 2%; WBC 5, wheat biochar 5%. Different letters above the blocks indicate significant differences ($p < 0.05$) between the biochar treatments. Values represent the mean ± SD (n = 4).

9.27 mg g^{-1} (MBC 2), 8.36 mg g^{-1} (MBC 5), 6.39 mg g^{-1} (WBC 2), and 5.28 mg g^{-1} (WBC 5). A similar pattern was observed in leaves, where Na^+ concentration declined from 13.0 mg g^{-1} DW in CK to 12.1 mg g^{-1} (MBC 2), 11.2 mg g^{-1} (MBC 5), 9.29 mg g^{-1} (WBC 2), and 8.18 mg g^{-1} (WBC 5). In contrast, the concentrations of K^+, Ca^{2+}, and Mg^{2+} in both roots and leaves increased significantly following biochar application. The highest concentrations of these beneficial cations were consistently observed under the WBC 5% treatment, followed by WBC 2%, MBC 5%, and MBC 2%. Overall, wheat straw biochar, particularly at the higher application rate, resulted in the strongest reduction of Na^+ accumulation and the greatest enhancement of K^+, Ca^{2+}, and Mg^{2+} concentrations in wheat tissues under saline conditions.

Discussion

Salt stress, through osmotic and ionic mechanisms, poses a major threat to crop growth in salt-affected croplands (Alkharabsheh *et al.*, 2021; Basak *et al.*, 2022). Salinity, primarily dominated by sodium ions (Na^+), causes soil compaction and increased bulk density, which reduces pore size and hinders salt leaching, root penetration, and seed germination (Ud Din *et al.*, 2023; Sun *et al.*, 2024). Biochar, a porous and carbon-rich organic material, possesses favorable characteristics that can improve soil physical properties (Korai *et al.*, 2018). When derived from crop residues or straw, biochar can enhance soil aggregation and increase porosity, which is evidenced by a reduction in soil bulk density. In the present study, this salinity-alleviation effect was reflected by the significant declines in soil total salt content and soil Na^+ concentration under biochar treatments, with the strongest reductions observed at the 5% application rate particularly for wheat straw biochar (Figure 1).

Due to its highly porous structure and large surface area, biochar can significantly improve the water-holding capacity of sandy soils (Korai *et al.*, 2018; Alghamdi, Alkhasha & Ibrahim, 2020; Li *et al.*, 2021). The application of straw-based biochar as a key component of compost may contribute to more effective removal of soluble salts. Additionally, biochar amendment can help form blocky soil structures and aggregates, which can block the upward movement of salts via capillary action. These mechanisms support the use of straw biochar in facilitating salt leaching and reducing salt stress during seed germination and crop development (Malik *et al.*, 2023; Duan *et al.*, 2024; Liu *et al.*, 2024). However, because this pot study was conducted under a non-leaching setup (Section 2.7), the observed decreases in soil salt content and Na^+ concentration (Figure 1) are more plausibly attributed to biochar-driven changes in salt distribution and ionic retention within the soil matrix (e.g., reduced upward movement and improved salt buffering), rather than physical salt removal via drainage. Consistent with this, soil pH decreased slightly under all biochar treatments relative to CK (Figure 1), indicating that the amendments modified the soil chemical environment under saline conditions.

Improved crop growth and yield in salt-stressed soils often begin with better seed germination and consistent growth through to maturity. Yield reduction under salt stress is well-documented (Keshavarzi *et al.*, 2011; Rath & Rousk, 2015; Bhattarai *et al.*, 2020; Kaiwen *et al.*, 2020; Basak *et al.*, 2022; Singh *et al.*, 2022). Various studies have reported positive (Qurashi & Sabri, 2011; Thomas *et al.*, 2013; Hasanuzzaman & Fujita, 2022; Duan *et al.*, 2024), insignificant (Fahad *et al.*, 2018; Woolf *et al.*, 2018), or even negative (Ashraf & Munns, 2022) effects of biochar application on crop growth and yield, especially when applied in large quantities. In the current study, wheat growth and yield-related traits improved consistently across all biochar treatments, with the greatest responses under WBC 5%. Specifically, biochar increased plant height, tiller number, leaf area, shoot fresh weight, and root traits (Table 3; Figure 2), and also enhanced yield components (grain number per spike and 1000-grain weight) as well as shoot and root dry biomass (Figures 3–4).

Salt stress can negatively impact seed germination and plant survival rates. High osmotic pressure, limited moisture and oxygen availability, and toxicity from exchangeable sodium can restrict seedling establishment and yield (Guo, Shi & Yang, 2009; Hailu & Mehari, 2021). Although a reduction in soil salinity generally promotes seed germination, this trend was not evident in the current pot study. Nevertheless, the application of straw biochar may enhance germination and radicle growth (Das & Biswas, 2022). Korai et al., (2018) observed that straw biochar improved the physiological performance of rice and wheat, although such effects may not be consistently observed across all crop species. Because seed germination was not directly measured in this experiment, the improvement in wheat performance is better supported by the measured responses in vegetative growth, root development, and yield components (Table 3; Figures 2–4), together with the concurrent reductions in soil salinity indicators (Figure 1).

The increased grain yield and total aboveground biomass following the application of two types of biochar during the wheat growing season, and the lack of a continued increase in a subsequent season in this pot study, indicate the potential of biochar incorporation in boosting crop production. The incorporation of biochar and crop residues not only supplies nutrients (Hussain *et al.*, 2017; Sarkar *et al.*, 2018; Sarwar *et al.*, 2023) but also improves soil conditions that support plant growth. Nitrogen immobilized by microbes during residue decomposition may be released later to meet increased crop N demands, thereby enhancing synchronization between nutrient supply and crop requirements, and promoting higher yields (Kushwaha et al., 2000). However, straw incorporation may reduce plant N uptake and barley yield due to prolonged microbial N immobilization (Liu *et al.*, 2019; Fontaine *et al.*, 2024). In this study, soil nutrient status increased substantially following biochar application, particularly under WBC 5%, as shown by the increases in TN, AP, and AK (Table 2). These changes in soil fertility were accompanied by improved ionic nutrition within the plant: Na^+ concentrations declined in both roots and leaves, while K^+, Ca^{2+}, and Mg^{2+} increased (Table 4), indicating enhanced ionic balance under salt stress. This coordinated shift lower Na^+ accumulation together with higher essential cations provides direct support for the improved growth and yield traits observed under biochar amendment (Table 3; Figures 2–4).

The impact of biochar on crop yield depends not only on the properties of the biochar itself (Blanco-Canqui, 2013) but also on soil fertility, pH, and crop species (Alkharabsheh *et al.*, 2021; Abukari *et al.*, 2022). The observed improvements in crop traits and yield in this study may be due to the higher nutrient availability in low-temperature-produced biochar, which tends to retain more extractable cations and nutrients. In contrast, high-temperature biochar offers greater carbon stability but fewer available nutrients (Zhang, Voroney & Price, 2015; Nan *et al.*, 2021; Wang *et al.*, 2022). Differences between the two straw biochars were also evident: wheat straw biochar generally produced stronger effects than maize straw biochar at comparable rates, including greater reductions in soil salt content and Na^+ (Figure 1), higher SOC and nutrient availability (Table 2), stronger increases in plant growth and biomass (Table 3; Figures 2–4), and a more favorable tissue ion profile (Table 4). Notably, despite clear improvements in SOC and nutrient availability, soil CEC remained statistically unchanged across treatments (Table 2). This outcome is consistent with the relatively short duration of the pot experiment and the fact that the measured CEC reflects the bulk soil exchange complex, which may not shift detectably over a single season even when carbon inputs increase.

In sum, salt-stressed soils were effectively reclaimed through the application of two types of straw biochar, which improved soil structure for root development, preserved nitrogen, enhanced phosphorus and potassium availability, and facilitated the leaching of soluble salts. These combined effects created a favorable environment for wheat growth under salt stress. Overall, the present findings demonstrate that straw biochar amendments particularly wheat straw biochar at 5% reduced soil salinity indicators (salt content and Na^+), improved soil fertility (TN, AP, AK, and SOC), promoted root development, enhanced plant ionic balance (lower Na^+ and higher $K^+/Ca^{2+}/Mg^{2+}$), and ultimately increased wheat yield components and biomass under salt stress (Tables 2–4; Figures 1–4). Given the non-leaching pot design, these benefits are most consistent with biochar-mediated improvement of soil chemical buffering and plant ion regulation rather than salt removal via drainage.

Conclusions

The application of wheat straw biochar (WBC) and maize straw biochar (MBC) in a pot experiment with salt-affected soil improved soil conditions and winter wheat performance. Compared with the control, all biochar treatments reduced soil salinity indicators, including soil pH, total salt content, and soil Na^+ concentration (Figure 1), with the strongest reductions generally observed under WBC at 5%. Biochar addition also increased soil fertility parameters, particularly SOC, total nitrogen, available phosphorus, and available potassium (Table 2), while soil CEC remained unchanged across treatments. These improvements were accompanied by enhanced wheat growth and root development (Table 3; Figure 2), increased yield components and biomass (Figures 3–4), and a more favorable tissue ion profile characterized by reduced Na^+ and increased K^+, Ca^{2+}, and Mg^{2+} in roots and leaves (Table 4). Overall, straw-derived biochar especially wheat straw biochar applied at 5% showed greater effectiveness than maize straw biochar in mitigating salt stress and improving soil fertility and wheat productivity under the experimental conditions. Because the experiment was conducted under a non-leaching pot setup, the observed benefits are most consistent with improved soil chemical buffering and enhanced plant ion regulation rather than salt removal via drainage. These findings support the use of straw biochar as a practical amendment for improving crop performance in salt-affected soils while providing a value-added pathway for crop residue utilization.

Funding

This work was supported by the National Key R & D Program of China (NO. 2022YFE0113400).

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest.

Authors' contributions

SKK, XW and PKK conceived and designed the study, supervised the research, and provided critical revisions to the manuscript. SK and SKK conducted the experiments and were involved in data collection and curation. SL and MQ contributed to data analysis, visualization, and manuscript drafting. LY, MUY, and ZHJ contributed to methodology development, literature review, and manuscript editing. All authors reviewed and approved the final version of the manuscript.

References

Abalos, D., S. Recous, K. Butterbach-Bahl, C. De Notaris, T.F. Rittl, C.F.E. Topp, S.O. Petersen, S. Hansen, M.A. Bleken and R.M. Rees. 2022. A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues. *Science of The Total Environment* 828: 154388.

Abukari, A., J.S. Kaba, E. Dawoe and A.A. Abunyewa. 2022. A comprehensive review of the effects of biochar on soil physicochemical properties and crop productivity. *Waste Disposal and Sustainable Energy* 4: 343–359.

Alghamdi, A.G., A. Alkhasha and H.M. Ibrahim. 2020. Effect of biochar particle size on water retention and availability in a sandy loam soil. *Journal of Saudi Chemical Society* 24: 1042–1050.

Alkharabsheh, H.M., M.F. Seleiman, M.L. Battaglia, A. Shami, R.S. Jalal, B.A. Alhammad, K.F. Almutairi and A.M. Al-Saif. 2021. Biochar and its broad impacts on soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy* 11: 993.

Arnon, D.I. 1950. Dennis Robert Hoagland: 1884–1949. *Science* 112: 739–742.

Ashraf, M. and R. Munns. 2022. Evolution of approaches to increase the salt tolerance of crops. *Critical Reviews in Plant Sciences* 41: 128–160.

Basak, N., A.K. Rai, A. Barman, S. Mandal, P. Sundha, S. Bedwal, S. Kumar, R.K. Yadav and P.C. Sharma. 2022. Salt affected soils: Global perspectives.p. 107-129. In: *Soil Health and Environmental Sustainability: Application of Geospatial Technology*. P.K. Shit, P.P. Adhikari, G.S. Bhunia and D. Sengupta (eds). SpringerCham.

Bello, S.K., A.H. Alayafi, S.G. Al-Solaimani and K.A.M. Abo-Elyousr. 2021. Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy* 11: 1735.

Bhatt, B., S.K. Gupta, S. Mukherjee and R. Kumar. 2024. A comprehensive review on biochar against plant pathogens: Current state-of-the-art and future research perspectives. *Heliyon* 10(17): e37204.

Bhattarai, S., D. Biswas, Y.-B. Fu and B. Biligetu. 2020. Morphological, physiological, and genetic responses to salt stress in alfalfa: A review. *Agronomy* 10: 577.

Bhuvaneshwari, S., H. Hettiarachchi and J.N. Meegoda. 2019. Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health* 16: 832.

Chaudhary, A., R.S. Chhokar, D.B. Yadav, V.K. Sindhu, H. Ram, S. Rawal, R.S. Khedwal, R.K. Sharma and S.C. Gill. 2019. In-situ paddy straw management practices for higher resource use efficiency and crop productivity in Indo-Gangetic Plains of India. *Journal of Cereal Research* 11: 172–198.

Cuevas, J., I.N. Daliakopoulos, F. del Moral, J.J. Hueso and I.K. Tsanis. 2019. A review of soil-improving cropping systems for soil salinization. *Agronomy* 9: 295.

Das, R. and S. Biswas. 2022. Influence of abiotic stresses on seed production and quality. In *Seed Biology Updates,* J.C. Jimenez-Lopez (ed.). IntechOpen. DOI: 10.5772/intechopen.106045

Diatta, A.A., J.H. Fike, M.L. Battaglia, J.M. Galbraith and M.B. Baig. 2020. Effects of biochar on soil fertility and crop productivity in arid regions: A review. *Arabian Journal of Geosciences* 13: 1–17.

Duan, S., A.A. Al-Huqail, I.M. Alsudays, M. Younas, A. Aslam, A.N. Shahzad, M.F. Qayyum, M. Rizwan, Y. Alhaj Hamoud and H. Shaghaleh. 2024. Effects of biochar types on seed germination, growth, chlorophyll contents, grain yield, sodium, and potassium uptake by wheat under salt stress. *BMC Plant Biology* 24: 487.

Fahad, S., M.Z. Ihsan, A. Khaliq, I. Daur, S. Saud, S. Alzamanan, W. Nasim, M. Abdullah, I.A. Khan and C. Wu. 2018. Consequences of high temperature under changing climate optima for rice pollen characteristics: Concepts and perspectives. *Archives of Agronomy and Soil Science* 64: 1473–1488.

Farkas, É., V. Feigl, K. Gruiz, E. Vaszita, É. Ujaczki, I. Fekete-Kertész, M. Tolner, C.M. Horváth, Z. Berkl and N. Uzinger. 2018. Microcosm incubation study for monitoring the mid-term effects of different biochars on acidic sandy soil applying a multiparameter approach. *Process Safety and Environmental Protection* 120: 24–36.

Fontaine, S., L. Abbadie, M. Aubert, S. Barot, J.M.G. Bloor, D. Derrien, O. Duchene, N. Gross, L. Henneron and X. Le Roux. 2024. Plant–soil synchrony in nutrient cycles: Learning from ecosystems to design sustainable agrosystems. *Global Change Biology* 30: e17034.

Fu, B., L. Chen, H. Huang, P. Qu and Z. Wei. 2021. Impacts of crop residues on soil health: A review. *Environmental Pollutants and Bioavailability* 33: 164–173.

Gang, N.I., F. Gu, H.M. Burrill, J. Li, J. Zhang and F. Zhang. 2024. Saline-alkali soil reclamation and utilization in China: Progress and prospects. *Frontiers of Agricultural Science and Engineering* 11.

Graber, E.R., Y. Meller Harel, M. Kolton, E. Cytryn, A. Silber, D. Rav David, L. Tsechansky, M. Borenshtein and Y. Elad. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil* 337: 481–496.

Gray, C.D. and P.R. Kinnear. 2012. *IBM SPSS Statistics 19 Made Simple*. Psychology Press.

Guenet, B., M. Camino-Serrano, P. Ciais, M. Tifafi, F. Maignan, J.L. Soong and I.A. Janssens. 2018. Impact of priming on global soil carbon stocks. *Global Change Biology* 24: 1873–1883.

Guo, R., L. Shi and Y. Yang. 2009. Germination, growth, osmotic adjustment and ionic balance of wheat in response to saline and alkaline stresses. *Soil Science and Plant Nutrition* 55: 667–679.

Hailu, B. and H. Mehari. 2021. Impacts of soil salinity and sodicity on soil-water relations and plant growth in dry land areas: A review. *Journal of Natural Sciences Research* 12: 1–10.

Haj-Amor, Z., T. Araya, D.-G. Kim, S. Bouri, J. Lee, W. Ghiloufi, Y. Yang, H. Kang, M.K. Jhariya and A. Banerjee. 2022. Soil salinity and its associated effects on soil microorganisms, greenhouse gas emissions, crop yield, biodiversity and desertification: A review. *Science of The Total Environment* 843: 156946.

Hasanuzzaman, M. and M. Fujita. 2022. Plant responses and tolerance to salt stress: Physiological and molecular interventions. *International Journal of Molecular Sciences*23(9): 4810.

Hossain, M.Z., M.M. Bahar, B. Sarkar, S.W. Donne, Y.S. Ok, K.N. Palansooriya, M.B. Kirkham, S. Chowdhury and N. Bolan. 2020. Biochar and its importance on nutrient dynamics in soil and plant. *Biochar* 2: 379–420.

Hussain, M., M. Farooq, A. Nawaz, A.M. Al-Sadi, Z.M. Solaiman, S.S. Alghamdi, U. Ammara, Y.S. Ok and K.H.M. Siddique. 2017. Biochar for crop production: Potential benefits and risks. *Journal of Soils and Sediments* 17: 685–716.

Igalavithana, A.D., E.E. Kwon, M. Vithanage, J. Rinklebe, D.H. Moon, E. Meers, D.C.W. Tsang and Y.S. Ok. 2019. Soil lead immobilization by biochars in short-term laboratory incubation studies. *Environment International* 127: 190–198.

Johnson, R. and J.T. Puthur. 2021. Seed priming as a cost effective technique for developing plants with cross tolerance to salinity stress. *Plant Physiology and Biochemistry* 162: 247–257.

Kaiwen, G., X. Zisong, H. Yuze, S. Qi, W. Yue, C. Yanhui, W. Jiechen, L. Wei and Z. Huihui. 2020. Effects of salt concentration, pH, and their interaction on plant growth, nutrient uptake, and photochemistry of alfalfa leaves. *Plant Signaling and Behavior* 15: 1832373.

Kebede, F. 2023. Status, drivers, and suggested management scenarios of salt-affected soils in Africa. In R. Choukr-Allah & R. Ragab (Eds.), Biosaline Agriculture as a Climate Change Adaptation for Food Security. Cham: *Springer International Publishing* 259–284.

Kerdraon, L., V. Laval and F. Suffert. 2019. Microbiomes and pathogen survival in crop residues, an ecotone between plant and soil. *Phytobiomes Journal* 3: 246–255.

Keshavarzi, M.H.B., M.S.O. Rafsanjani, S.M. Moussavinik and M.Z. Abdin. 2011. Effect of salt stress on germination and early seedling growth of spinach. *Annals of Biological Research* 2: 490–497.

Khondoker, M., S. Mandal, R. Gurav and S. Hwang. 2023. Freshwater shortage, salinity increase, and global food production: A need for sustainable irrigation water desalination. *Earth* 4: 223–240.

Korai, P.K., X. Xia, X. Liu, R. Bian, M.O. Omondi, A. Nahayo and G. Pan. 2018. Extractable pool of biochar controls on crop productivity rather than greenhouse gas emission from a rice paddy under rice–wheat rotation. *Scientific Reports* 8: 802.

Kumar, R., A. Singh, A.K. Bhardwaj, A. Kumar, R.K. Yadav and P.C. Sharma. 2022. Reclamation of salt-affected soils in India: Progress, emerging challenges, and future strategies. *Land Degradation and Development* 33: 2169–2180.

Kumari, R., R. Singh and N. Kumar. 2019. Effect of crop residue management on soil organic carbon, soil organic matter and crop yield: An overview. *Journal of Applied and Natural Science* 11: 712.

Langley, J.A., D.C. McKinley, A.A. Wolf, B.A. Hungate, B.G. Drake and J.P. Megonigal. 2009. Priming depletes soil carbon and releases nitrogen in a scrub-oak ecosystem exposed to elevated CO_2. *Soil Biology and Biochemistry* 41: 54–60.

Leng, L., X. Xu, L. Wei, L. Fan, H. Huang, J. Li, Q. Lu, J. Li and W. Zhou. 2019. Biochar stability assessment by incubation and modelling: Methods, drawbacks and recommendations. *Science of The Total Environment* 664: 11–23.

Li, L., Y.-J. Zhang, A. Novak, Y. Yang and J. Wang. 2021. Role of biochar in improving sandy soil water retention and resilience to drought. *Water* 13: 407.

Liu, R., M. Tang, Z. Luo, C. Zhang, C. Liao and S. Feng. 2024. Straw returning proves advantageous for regulating water and salt levels, facilitating nutrient accumulation, and promoting crop growth in coastal saline soils. *Agronomy* 14: 1196.

Liu, Z., F. Gao, Y. Liu, J. Yang, X. Zhen, X. Li, Y. Li, J. Zhao, J. Li and B. Qian. 2019. Timing and splitting of nitrogen fertilizer supply to increase crop yield and efficiency of nitrogen utilization in a wheat–peanut relay intercropping system in China. *The Crop Journal* 7: 101–112.

Maheshwari, S., V. Kumar, G. Bhadauria and A. Mishra. 2022. Immunomodulatory potential of phytochemicals and other bioactive compounds of fruits: A review. *Food Frontiers* 3: 221–238.

Malik, Z., N. Malik, I. Noor, M. Kamran, A. Parveen, M. Ali, F. Sabir, H.O. Elansary, T.K.Z. El-Abedin and E.A. Mahmoud. 2023. Combined effect of rice-straw biochar and humic acid on growth, antioxidative capacity, and ion uptake in maize grown under saline soil conditions. *Journal of Plant Growth Regulation* 42: 3211–3228.

Mills, J.D. 2003. SPSS textbooks: A review for teachers. *Statistics Education Research Journal* 2: 59–70.

Nan, H., J. Yin, F. Yang, Y. Luo, L. Zhao and X. Cao. 2021. Pyrolysis temperature-dependent carbon retention and stability of biochar with participation of calcium: Implications to carbon sequestration. *Environmental Pollution* 287: 117566.

Poveda, J., Á. Martínez-Gómez, C. Fenoll and C. Escobar. 2021. The use of biochar for plant pathogen control. *Phytopathology* 111: 1490–1499.

Qiao, N.A., D. Schaefer, E. Blagodatskaya, X. Zou, X. Xu and Y. Kuzyakov. 2014. Labile carbon retention compensates for CO_2 released by priming in forest soils. *Global Change Biology* 20: 1943–1954.

Qurashi, A.W. and A.N. Sabri. 2011. Osmoadaptation and plant growth promotion by salt tolerant bacteria under salt stress. *African Journal of Microbiology Research* 5: 3546–3554.

Raaijmakers, J.M., T.C. Paulitz, C. Steinberg, C. Alabouvette and Y. Moënne-Loccoz. 2009. The rhizosphere: A playground and battlefield for soilborne pathogens and beneficial microorganisms. *Plant and Soil* 321: 341–361.

Rath, K.M. and J. Rousk. 2015. Salt effects on the soil microbial decomposer community and their role in organic carbon cycling: A review. *Soil Biology and Biochemistry* 81: 108–123.

El Sabagh, A., A. Hossain, C. Barutçular, M.A. Iqbal, M.S. Islam, S. Fahad, O. Sytar, F. Çiğ, R.S. Meena and M. Erman. 2020. Consequences of salinity stress on the quality of crops and its mitigation strategies for sustainable crop production: An outlook of arid and semi-arid regions. p. 503-533. In: Environment, Climate, Plant and Vegetation Growth, S. Fahad, M. Hasanuzzaman, M. Alam, H. Ullah, M. Saeed, I.A. Khan and M. Adnan (eds). Springer Nature Switzerland.

Sarkar, S.C., E. Wang, S. Wu and Z. Lei. 2018. Application of trap cropping as companion plants for the management of agricultural pests: A review. *Insects* 9: 128.

Sarwar, N., N. Abbas, O. Farooq, M. Akram, M.W. Hassan, K. Mubeen, A. Rehman, M. Shehzad, M. Ahmad and A. Khaliq. 2023. Biochar integrated nutrient application improves crop productivity, sustainability and profitability of maize–wheat cropping system. *Sustainability* 15: 2232.

Sharma, D.K. and A. Singh. 2017. Current trends and emerging challenges in sustainable management of salt-affected soils: A critical appraisal. p. 1-40. In: *Bioremediation of Salt Affected Soils: An Indian Perspective,* S. Arora, A.K. Singh and Y.P. Singh (eds.). Springer International Publishing AG 2017.

Shinde, R., D.K. Shahi, P. Mahapatra, C.S. Singh, S.K. Naik, N. Thombare and A.K. Singh. 2022. Management of crop residues with special reference to the on-farm utilization methods: A review. *Industrial Crops and Products* 181: 114772.

Shokat, S. and D.K. Großkinsky. 2019. Tackling salinity in sustainable agriculture—What developing countries may learn from approaches of the developed world. *Sustainability* 11: 4558.

Singh, B. and Z. Rengel. 2007. The role of crop residues in improving soil fertility. In P. Marschner & Z. Rengel (Eds.), Nutrient Cycling in Terrestrial Ecosystems. *Springer-Verlag, Berlin Heidelberg* 183–214.

Singh, P., K.K. Choudhary, N. Chaudhary, S. Gupta, M. Sahu, B. Tejaswini and S. Sarkar. 2022. Salt stress resilience in plants mediated through osmolyte accumulation and its crosstalk mechanism with phytohormones. *Frontiers in Plant Science* 13: 1006617.

Sun, W., M.H. Shahrajabian, Y. Kuang and N. Wang. 2024. Amino acids biostimulants and protein hydrolysates in agricultural sciences. *Plants* 13: 210.

Thomas, S.C., S. Frye, N. Gale, M. Garmon, R. Launchbury, N. Machado, S. Melamed, J. Murray, A. Petroff and C. Winsborough. 2013. Biochar mitigates negative effects of salt additions on two herbaceous plant species. *Journal of Environmental Management* 129: 62–68.

Ud Din, M.M., M.I. Khan, M. Azam, M.H. Ali, R. Qadri, M. Naveed and A. Nasir. 2023. Effect of biochar and compost addition on mitigating salinity stress and improving fruit quality of tomato. *Agronomy* 13: 2197.

Varney, R.M., S.E. Chadburn, E.J. Burke, S. Jones, A.J. Wiltshire and P.M. Cox. 2023. Simulated responses of soil carbon to climate change in CMIP6 Earth system models: The role of false priming. *Biogeosciences* 20: 3767–3790.

Wang, Z., H. Chen, Z. Zhu, S. Xing, S. Wang and B. Chen. 2022. Low-temperature straw biochar: Sustainable approach for sustaining higher survival of *Bacillus megaterium* and managing phosphorus deficiency in the soil. *Science of The Total Environment* 830: 154790.

Woolf, D., J. Lehmann, A. Cowie, M.L. Cayuela, T. Whitman and S. Sohi. 2018. Biochar for climate change mitigation. In R. Lal & B. A. Stewart (Eds.), Soil and Climate. *CRC Press, Boca Raton* 219–248.

Zhang, H., R.P. Voroney and G.W. Price. 2015. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil carbon and nitrogen transformations. *Soil Biology and Biochemistry* 83: 19–28.

Zhang, Q., J. Feng, J. Li, C. Huang, Y. Shen, W. Cheng and B. Zhu. 2023. A distinct sensitivity to the priming effect between labile and stable soil organic carbon. *New Phytologist* 237: 88–99.