Journal of Soil Science and Plant Nutrition (2026) 26:5506–5522
https://doi.org/10.1007/s42729-026-03206-8

ORIGINAL PAPER

Biochar-Modified Sulfur and Licorice Root Extract Improve Rhizosphere Properties and Biochemical Adaptation in *Cucurbita pepo* Plants Under Salt Stress

Nasr M. Abdou[1] · Mohammed A. H. Gyushi[2] · Basma R. Abdel-Moatamed[3] · Ahmed R. Abd El-Tawwab[1]

Received: 24 July 2025 / Accepted: 10 March 2026 / Published online: 10 April 2026
© The Author(s) 2026

Abstract
Soil salinity critically threatens agricultural sustainability, particularly in squash production. This study evaluates integrated soil-plant strategies to mitigate salt stress, applying biochar-modified sulfur (BMS) as a soil amendment and licorice root extract (LRE) as a foliar treatment to enhance soil functionality and plant osmotic resilience. Two field experiments (2023–2024) employed a split-plot in randomized complete block design. Main plots tested BMS at 0 (BMS_0), 5 (BMS_5), and 10 (BMS_{10}) ton ha^{-1}; subplots received foliar LRE at 0% (LRE_0) or 1% (LRE_1). BMS_5 and BMS_{10} significantly ameliorated key physicochemical constraints of saline soils: reducing bulk density, saturated hydraulic conductivity, electrical conductivity (ECe), and pH, while increasing soil-water retention capacity, soil porosity, available water content, organic matter content, cation exchange capacity and nutrient availability (nitrogen, phosphorus and potassium) versus BMS_0. Synergistic BMS + LRE_1 treatments enhanced squash growth metrics, photosynthetic pigments, nutritional and water status, membrane integrity, and yield over (BMS_0 + LRE_0). However, leaf proline, phenolics, free amino acids and TSS were significantly reduced, under the same treatments, confirming improved salinity tolerance of squash plants. Combined BMS and LRE application sustainably enhances saline soil properties and fortifies plant biochemical resilience, optimizing squash productivity. This strategy offers a viable pathway for saline soil management in water-scarce agroecosystems.

Keywords Biochar · Sulfur · Licorice root extract · Salinity stress · Physio-biochemical responses · Yield · Squash

1 Introduction

In Egypt, squash (*Cucurbita pepo* L.) a key *Cucurbitaceae* species, holds critical importance as a summer vegetable cash crop, due to its high yield potential per unit area within a short growing season (Farrag et al., 2015). Globally, squash-a dual purpose crop is extensively used for nutrition and herbal remedies. It provides carbohydrates, fatty acids, essenitial minerals, alongside bioactive constituents (i.e. flavonoids, carotenoids, polysaccharides, tocopherols, alkaloids, terpenoids, phenols) (Enneb et al., 2020; Hashash Maher et al., 2017).

As a major abiotic stressor exacerbated by climate change, soil salinization significantly diminishes crop yield and quality (Hussaan et al., 2022; Munir et al., 2022). It adversely affects plants through interconnected osmotic and ionic stresses, causing a range of detrimental effects from cellular dehydration to metabolic dysfunction (Arif et al., 2020; Tedeschi et al., 2023). A key survival strategy

✉ Nasr M. Abdou
nma02@fayoum.edu.eg

Mohammed A. H. Gyushi
mah09@fayoum.edu.eg

Basma R. Abdel-Moatamed
bra11@fayoum.edu.eg

Ahmed R. Abd El-Tawwab
ara08@fayoum.edu.eg

[1] Soils and Water Department, Faculty of Agriculture, Fayoum University, Fayoum 63514, Egypt

[2] Horticulture Department, Faculty of Agriculture, Fayoum University, Fayoum 63514, Egypt

[3] Food Science and Technology Department, Faculty of Agriculture, Fayoum University, Fayoum 63514, Egypt

involves the metabolic synthesis of compatible osmolytes, including proline and sugars. This accumulation is a critical adaptation for maintaining cellular turgor, stabilizing membranes and proteins, and mitigating oxidative damage by reducing ROS levels (Ghanbari et al., 2023; Singh et al., 2022b). Hence salinity stress significantly impacts agricultural sustainability in particular squash crop.

Consequently, developing integrated strategies is crucial to mitigate salinity stress. Approaches such as soil amendments and antioxidant applications can ameliorate soil properties and enhance plant resilience (Abdou et al., 2024; Jin et al., 2018). For squash cultivation in saline soils, we propose that the synergistic use of biochar-modified sulfur (BMS) and licorice root extract (LRE) offers a cost-effective and eco-friendly strategy to enhance tolerance, growth, and yield under adverse conditions.

Biochar—acarbon-rich soil additive, produced through pyrolysis of organic materials in non-oxygen conditions (Samaraweera et al., 2023; Zakaria et al., 2023). Soil health improvement via biochar results from elevated organic carbon levels, water retention capacity, porosity, and CEC, coupled with stimulated soil microbial/enzymatic activity (Dayoub et al., 2023; Rashmi et al., 2023). The application of biochar has demonstrated efficacy in improving resilience and yield of grown crops under environmental stress (Pandian et al., 2024; Sharma et al., 2023).

Biochar, while offering numerous advantages for soil health, presents challenges due to its high pH, which can adversely impact soil fertility and nutrient availability, particularly phosphorus levels (Dai et al., 2017; Dayoub et al., 2023), it demonstrated to enhance soil fertility and carbon sequestration (Ali 2018), its inherent high pH value limits its utility in alkaline soils (Zheng et al., 2019). Elevation of soil pH induced by biochar application can intensify microbial nitrification processes, leading to nitrate losses and limited availability of ammonium (Liu et al., 2023b; Neina 2019). Consequently, various physical, chemical, and thermal protocols for biochar modification have have received increasing interest (Sahin et al., 2017). Hence, the high pH of biochar matiarials which may not suitable for direct soil application, can be mitigated by the incorporation of substances like sulfur with biochar. The incorporated sulfur oxidizes to form sulfuric acid, which actively counteracts the inherent alkalinity of conventional biochar (Hafeez et al., 2022). Enriching biochar with inorganic acids has been shown to improve key physicochemical properties, notably reducing its pH and increasing its cation exchange capacity, leading to enhanced availability of soil nutrients (El-Sharkawy et al., 2022; Grafe et al., 2021). Taheri et al., (2024), reported that the addition of sunflower biochar enriched with a 5% elemental sulfur in saline-sodic and calcareous soil, resulted in significant improvement in yield, enhanced soil water and nutrients content (in particular phosphorus), reduced soil salinity, and stimulated soil microbial and enzymatic activity. Howladar et al. (2025), found that, soil incorporation of sulfur-modified biochar with (3:100 (w/w/) sulphur: citrus wood biochar) by 10 ton ha^{-1} enhanced growth, biochemical responses and yield of drought stressed faba bean compared with control control. Hence, BMS application could be used as a promising technique to improve soil health, promote plant development, and advance sustainable agricultural methods.

Licorice root extract (LRE) comprises bioactive constituents such as glycyrrhizin, flavonoids, and polysaccharides that play a pivotal role in stimulating plant growth processes, enhancing seed germination, and improving nutrient uptake efficiency (Desoky et al., 2019a; Rady et al., 2019). The phytohormones and antioxidants involved in licorice extract regulates plant growth and safeguard against stress-induced damage (Desoky et al., 2019a; Elrys et al., 2020). Notably, the utilization of licorice extract has demonstrated enhancements in water uptake efficiency, photosynthetic activity, biomass production and plant productivity (Desoky et al., 2019b; Shen et al., 2022a), which making licorice extract an important tool for maximizing agricultural output.

While numerous studies have investigated the individual application of biochar-modified sulfur (Taheri et al., 2024; Abuzaid et al., 2025) or plant-based biostimulants such as licorice root extract (Abd El Mageed et al., 2025; Youssef et al., 2025) for mitigating salinity stress, their synergistic potential as a combined soil-plant treatment remains unexplored. We therefore hypothesize that the co-application of biochar-modified sulfur (BMS) and licorice root extract (LRE) will confer greater salinity tolerance in squash plants than any individual treatment. This enhanced tolerance is anticipated to result from the concurrent improvement of soil physicochemical properties by BMS and the direct priming of the plant's antioxidant defense systems by LRE. To test this hypothesis, the present study aims to: (1) evaluate the individual and combined effects of BMS and LRE on squash growth and physiology under saline conditions; (2) assess their impact on key soil parameters and plant nutrient uptake; and (3) quantify key biomarkers of stress tolerance, including total phenolics, proline, free amino acids, total soluble sugars, and protein content.

2 Materials and Methods

2.1 Experimental Layout and Agronomic Details

A trial was established in open field at the experimental station of Faculty of Agriculture, Fayoum University, Fayoum governorate, Egypt (29°17'38" N 30°54'55" E) for

two summer seasons of 2023 and 2024. The experimental site was characterized by a typical Mediterranean climate, with a distinct seasonal precipitation pattern of wet winters and dry summers, as defined by the aridity index (Ponce et al., 2000). The summer period, from May to October, typically experiences negligible precipitation. Relevant meteorological data for both growing seasons are summarized in (Table S3). Healthy seeds of squash (*Cucurbita pepo* L.) cv. Fadwa were sown in summer seasons (15–20 May 2023 and 2024). The experimental setup consisted of plots, each containing three beds. Each bed measured 10 m² (10 m in length × 1 m in width). Seeds were sown at a spacing of 0.5 m between plants, resulting in a density of 20 plants per bed. Consequently, the total plant population for each experimental plot was 60 plants (20 plants/bed × 3 beds). The trials were performed in a split-plot arrangement in (RCBD design), evaluating two factors at three replications. Biochar modified sulfur (BMS) rates and licorice root extract (LRE) were randomly distributed within main and sub main plots, respectively. BMS (A 100:5 (w/w) mixture of citrus wood biochar and elemental sulfur at different schemes [0 t ha^{-1} (BMS_0 - as control), 5 t ha^{-1} (BMS_5) and 10 t ha^{-1} (BMS_{10}) were applied to the surface soil layer before sowing.

Biochar was produced from dried and ground citrus wood residue via pyrolysis at 400–500 °C under an oxygen-limited atmosphere. Sulfur-modified biochar (BMS) was synthesized by homogenizing the base citrus wood biochar (B) with granular elemental sulfur at a 5% (w/w) ratio. This modification lowered the pH of the material from 7.80 (B) to 7.02 (BMS). The applied BMS amendment and soil of experimental site were analyzed. Soil samples were collected before planting and after harvest from the top-soil layer (0–0.6 m). Soil physical analysis (Table S1) was done as described by (Klute and Dirksen 1986), However, the chemical analyses of soil and used BMS (Table S2) were conducted as documented by (Page 1982). The soil ECe value (8.55 ds m^{-1}) indicates that, the soil is highly saline soil (Table S2). Notably, all fertilization, cultural operations, disease and pest control practices were done according to the regional commercial standards of crop production under drip-irrigated system.

2.2 Licorice Root Extract: Preparation and Application Techniques

According to (Rady et al., 2019), Licorice root extract 1% was prepared by soaking10 g of dried licorice roots, in a one liter of hot water (50 °C) for 1 day, then the solution was filtered and adjusted the final volume to one liter by distilled water. Squash plants treated by Licorice root extract (LRE) via foliar application twice during the cultivation period at 25 and 35 days after sowing. Tween 20 at 0.1% (v/v) was used as a surfactant. The spraying was done early in the morning using a backpack sprayer. LRE treatments were performed in two levels [LRE_0 : no addition (control) and LRE_1: licorice root extract 1%]. Chemical characterization of the licorice root extract (Table S4) was performed using standardized analytical procedures. The amino acid profile (comprising lysine, histidine, phenylalanine, methionine, cysteine, glutamic acid, aspartic acid, threonine, arginine, and proline), along with gibberellin, sucrose, and glucose, was analyzed by High-Performance Liquid Chromatography (HPLC) as per (Hodisan et al., 1998). Total nitrogen was determined via the Kjeldahl method, while phosphorus was assessed using the Olsen method (Olsen, 1954). Cationic elements (Na^+, K^+, Ca^{2+}) were measured by flame photometry, and the trace metals (Fe, Zn, Cu, Se) were analyzed by Atomic Absorption Spectroscopy (AAS).

2.3 Leaf Photosynthetic Pigment, Total Phenolics, Proline, Free Amino Acids and Total Soluble Sugars and Protein Content

Fully expanded young leaves of randomly sampled six guarded plants from each sub-plot were used to assess plant physiological and biochemical attributes of squash plants. leaf content of chlorophyll(a), chlorophyll(b) as well as carotenoids (expressed as mg g^{-1} FW) in fresh leaves of squash plants were quantified spectrophotometrically using a Shimadzu (UV-160 A UV–vis) recording spectrometer, however absorbance measurements recorded at 663, 645, and 470 nm respectively, according to (Vernon 1960). Total phenolic content (mgg^{-1} DW) in dry leaf samples was determined spectrophotometrically at 750 nm using a modified Folin-Ciocalteu reagent assay following the (Stratil et al., 2006) method. However, the scheme of aqueous sulfosalicylic acid in combination with acid ninhydrin reagent was implemented to assay the levels of proline (µmol g^{-1} DW) in leaves using a rapid spectrophotometer at 520 nm, as reported by (Bates et al., 1973). Leaf concentration of free amino acids (FAA) in mgg^{-1} DW was determined by the ninhydrin method using a spectrophotometer at 570 nm, as mentioned by (Rosen 1957). Total soluble protein (mgg^{-1} DW) in leaves of squash plants was determined using the method documented by (Bradford 1976), at reading of 595 nm using bovine serum albumin as the standard. Total soluble sugars (mgg^{-1} DW) of squash leaves in a 96% hot ethanol were extracted then spectrophotometrically measured (Shimadzu Corporation, Analytical Instruments Division, Kyoto, Japan) at 625 nm using anthrone reagent and glucose standard according to (Irigoyen et al., 1992).

2.4 Leaf Water Status and Membrane Integrity

Leaf relative water content (RWC%) and membrane stability index (MSI%) were determined from fully expanded fresh leaves. RWC using fresh leaf discs of (2 cm diameter) as introduced by (Barrs 1968).

$$RWC\,(\%) = \frac{\mathrm{FM} - \mathrm{DM}}{\mathrm{TM} - \mathrm{DM}} \times 100$$

Where FM is fresh weight of 20 leaf discs, DM is dry weight of 20 leaf discs and TM is turgid mass of 20 leaf discs.

Membrane stability index (MSI%) was determined in sampled fully expanded fresh leaves tissue, each weighed 0.2 g, as described by (Premachandra 1990), using the formula:

$$\text{Membrane stability index}\ (\%) = \left[1 - \frac{\mathrm{EC1}}{\mathrm{EC2}}\right] \times 100$$

Where EC_1 is the electric conductivity of solution for fresh leaf sample after 30 min in a water bath at 40 °C, and EC_2 is the electrical conductivity of the solution after 10 min at 100 °C.

2.5 Macronutrients and Sodium

To evaluate nutrients levels, 0.2 g of dried leaves of squash plants was pulverized, digested using (H_2SO_4 96%+ H_2O_2 30%), then diluted with distilled water as outlined by (Wolf 1982). then total nitrogen (N) was determined by Kjeldahl method (Ningbo Medical Instruments - Co., Ningbo, China) (Chapman and Pratt 1982). Phosphorus (P) content was measured following (Jackson 1973), using standard reagents of H2MoO7S, molybdenum blue, diluted H_2MoO_7S, and 8% (w/v) $NaHSO_3$-H_2SO_4. Sodium (Na^+) and potassium (K^+) were measured using flame photometry method (Lachica et al., 1973). Calcium was measured using atomic absorption spectrophotometer (Shimadzu AA-660, Shimadzu, Kyoto, Japan).

2.6 Growth and Yield Measurements

To measure growth indices of squash plants, 10 plants from each plot were randomly selected at 50 days from sowing. These measurements included number of leaves plant^{-1} (LN), leaves dry weight (LDW) and stem dry weight (SDW) per plant and plant leaf area (LA). Leaves and stem per plant were dried to a constant weight in an oven (at 75 °C), then the LDW, SDW and the whole plant dry weight were determined. Plant leaf area (dm^2) was measured using a portable Planix 7 digital planimeter (TAMAYA Technics Inc., Shinagawa-ku, Tokyo, Japan). At fruit marketable stage, 10 plants were selected from each treatment to weekly record the fruits number plant^{-1}, fruit weight plant^{-1} (g), average fruit weight (g) and total yield (t ha^{-1}).

2.7 Data Analysis

All data collected over the 2 seasons of experimental work were statistically analyzed in a randomized split-plot arrangement in complete block design. Before performing a combined analysis of variance (ANOVA), each dataset normality was assessed using the Shapiro-Wilk test ($P \leq 0.05$), and the homogeneity of variances across the two growing seasons was confirmed with Bartlett's test. A combined ANOVA was then conducted using the GLM procedure of Info STAT. However, a homogeneity test of error variance, as outlined by(Gomez and Gomez 1984) was performed. the data of both seasons were subjected to combined analysis and differences among the means were compared using Duncan's Multiple Range Test at a significance level of 5%.

3 Results

3.1 Effect of Applied BMS Soil Amendment on Some Soil Properties

Application of biochar-modified sulfur (BMS) significantly improved soil physical properties in a rate-dependent manner (Table 1). Relative to the control (BMS_0), soil bulk density and Ksat decreased by 3.23 and 2.59% under BMS_5 and by 5.16 and 15.54% under BMS_{10}, respectively. Conversely, BMS application enhanced soil pore characteristics, with total porosity increasing by 4.55 and 8.19%, water-holding pores by 11.30 and 24.72%, and useful pores by 10.08 and 21.74% under BMS_5 and BMS_{10}, respectively, compared with BMS_0.

Soil chemical properties were also favorably affected by BMS amendment (Table2). Soil pH declined by 1.84 and 3.74%, while ECe decreased by 27.80 and 40.84% under BMS_5 and BMS_{10}, respectively, relative to the control. In parallel, soil OM increased by 26.15 and 36.92%, and CEC rose by 5.66 and 18.74% under the same treatments. Available N, P and K increased by 25.00, 43.90, and 26.44% under BMS_5, and by 50.00, 85.21,and 37.40% under BMS_{10}, respectively compared with BMS_0.

Table 1 Impact of applied BMS on some soil physical characteristics for S_I (2023) and S_{II} (2024) seasons

Treatment	(ρb) g cm^{-3}	K sat (cm hr^{-1})	T. *P* %	W.H. *P*%	U.*P*%
Season	**	*	NS	NS	**
S_I	1.58 ± 0.033a	2.70 ± 0.062a	41.95 ± 0.678a	15.23 ± 0.550a	25.32 ± 0.68b
S_{II}	1.56 ± 0.030b	2.66 ± 0.064b	41.95 ± 0.678a	15.28 ± 0.550a	26.82 ± 0.686a
BMS (t ha^{-1})	**	**	**	**	**
BMS_0	1.55 ± 0.012a	1.93 ± 0.033a	41.51 ± 0.101c	13.84 ± 0.036c	23.92 ± 0.345c
BMS_5	1.50 ± 0.002b	1.88 ± 0.018b	43.40 ± 0.264b	14.52 ± 0.074b	25.78 ± 0.475b
BMS_{10}	1.46 ± 0.006c	1.63 ± 0.022c	44.91 ± 0.108a	17.42 ± 0.026a	28.51 ± 0.339a

ρb: (dry bulk density); Ksat: (saturated hydraulic conductivity); T.P.: (total porosity); W.H.P: (water holding pores) and U.P.: (useful pores). Data represent means ± standard error (SE). Asterisks denote significant differences: *$p \leq 0.05$, **$p \leq 0.01$; ns, not significant ($p > 0.05$). Within columns, means followed by differing lowercase letters differ significantly according to Duncan's multiple range test ($p \leq 0.05$). SI and SI are the first and second cultivation seasons respectively. BMS_0, BMS_5 and BMS_{10} are applied biochar modified sulfur amendment at rates 0 (control), 5 and 10 ton ha^{-1} respectively. LRE_0 and LRE_1 are foliar application of licorice root extract by rates 0 (control) and 1% respectively

Table 2 Impact of applied BMS on some soil chemical characteristics for S_I (2023) and S_{II} (2024) seasons

Treatment	Soil pH	ECe, (dS m^{-1})	O.M (%)	CEC (cmole kg^1)	Total *N* (%)	Available *P* (mg kg^{-1} soil)	Available K^+ (mg kg^{-1} soil)
Season	**	**	**				
S_I	7.63 ± 0.046a	6.69 ± 0.557a	0.72 ± 0.052b	13.10 ± 0.02a	0.05 ± a0.01	6.05 ± a0.02	62.21 ± a0.01
S_{II}	7.59 ± 0.043a	6.56 ± 0.533a	0.78 ± 0.052a	13.50 ± 0.01a	0.05 ± 0.01a	6.13 ± a0.02	64.84 ± a0.02
BMS (t ha^{-1})	**	**	**	**	**	**	**
BMS_0	7.76 ± 0.011a	8.67 ± 0.061a	0.65 ± 0.015c	11.89 ± 0.01	0.04 ± 0.01	4.26 ± 0.01	53.21 ± 0.01
BMS_5	7.62 ± 0.010b	6.26 ± 0.039b	0.82 ± 0.014b	13.25 ± 0.01	0.05 ± 0.01	6.13 ± 0.02	67.28 ± 0.03
BMS_{10}	7.47 ± 0.006c	4.95 ± 0.009c	0.89 ± 0.014a	14.75 ± 0.01	0.06 ± 0.01	7.88 ± 0.02	73.11 ± 0.02

ECe : electric conductivity, OM: organic matter content, CEC: cation exchangeable capacity, N: nitrogen, P: phosphorus, K: potassium. Data represent means ± standard error (SE). Asterisks denote significant differences: *$p \leq 0.05$, **$p \leq 0.01$; ns, not significant ($p > 0.05$). Within columns, means followed by differing lowercase letters differ significantly according to Duncan's multiple range test ($p \leq 0.05$). S_I and S_{II} are the first and second cultivation seasons. BMS_0, BMS_5 and BMS_{10} are applied biochar modified sulfur amendment at rates 0 (control), 5 and 10 ton ha^{-1} respectively. LRE_0 and LRE_1 are foliar application of licorice root extract by rates 0 (control) and 1% respectively

3.2 Effect of Applied BMS Soil Amendment, Foliar Spraying LRE and Their Interaction On Biochemical Response of Squash Plants

Content of total soluble sugar (TSS), free amino acids (FAA), proline (Pro) and total phenolics (TPh) were significantly infulenced by the applied BMS (Fig. 1a-d). The applied soil amendment BMS_5 and BMS_{10} caused significant reduction in TSS by (29.19 and 54.18%), FAA by (27.78 and 47.15%), Pro by (31.95 and 59.41%) and TPh by (11.05 and 27.53%) compared with BMS_0. In contrast, foliar application of licorice root extract (LRE_1) increased TSS, FAA, Pro and TPh contents by 23.47, 19.65, 21.55 and 7.47% respectively, compared with LRE_0. The highest concentrations of these metabolites were recorded in plants receiving LRE_1 without BMS amendment ($BMS_0 + LRE_1$), whereas the lowest values occurred under the combined treatment of BMS_{10} and LRE_0. Soluble protein content responded positively to both soil and foliar treatments (Fig. 1e). Compared with BMS_0, soluble protein increased by 60.73 and 111.52% under BMS_5 and BMS_{10} respectively, while LRE_1 enhanced soluble protein content by 17.55% relative to LRE_0. In addition, LRE_1 resulted in 17.55% increase in content of soluble protein higher than LRE_0. Notably, the combined treatment ($BMS_{10} + LRE_1$) resulted in the greatest increase in soluble protein, reaching 141.05% above the untreated control (BMS0 + LRE0).

3.3 Effect of Applied BMS Soil Amendment, Foliar Spraying LRE and Their Interaction On Physiological Attributes of Squash Plants

Relative water content (RWC), membrane stability index (MSI), as well as leaf photosynthetic pigment indices (i.e. chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids contents exhibited noticeable increase following to applied soil amendment BMS, licorice root extract (LRE) and their interaction (Fig. 2a-f). In this respect, the applied BMS rates BMS_5 and BMS_{10} increased RWC by (8.50 and 20.08%), MSI by (13.98 and 30.42%), and Cha by (3.13 and 6.64%), Chb by (4.40 and 8.34%), total Ch by (3.58, 7.24%) and carotenoids by (2.07 and 5.91%) compared to BMS_0. Foliar application of (LRE_1) enhanced these physiological attributes increasing RWC, MSI, Cha, Chb, total Ch and carotenoids by 4.28, 7.40, 2.00, 3.09,2.38 and 1.56%, respectively, relative to (LRE_0). Comparable enhancement

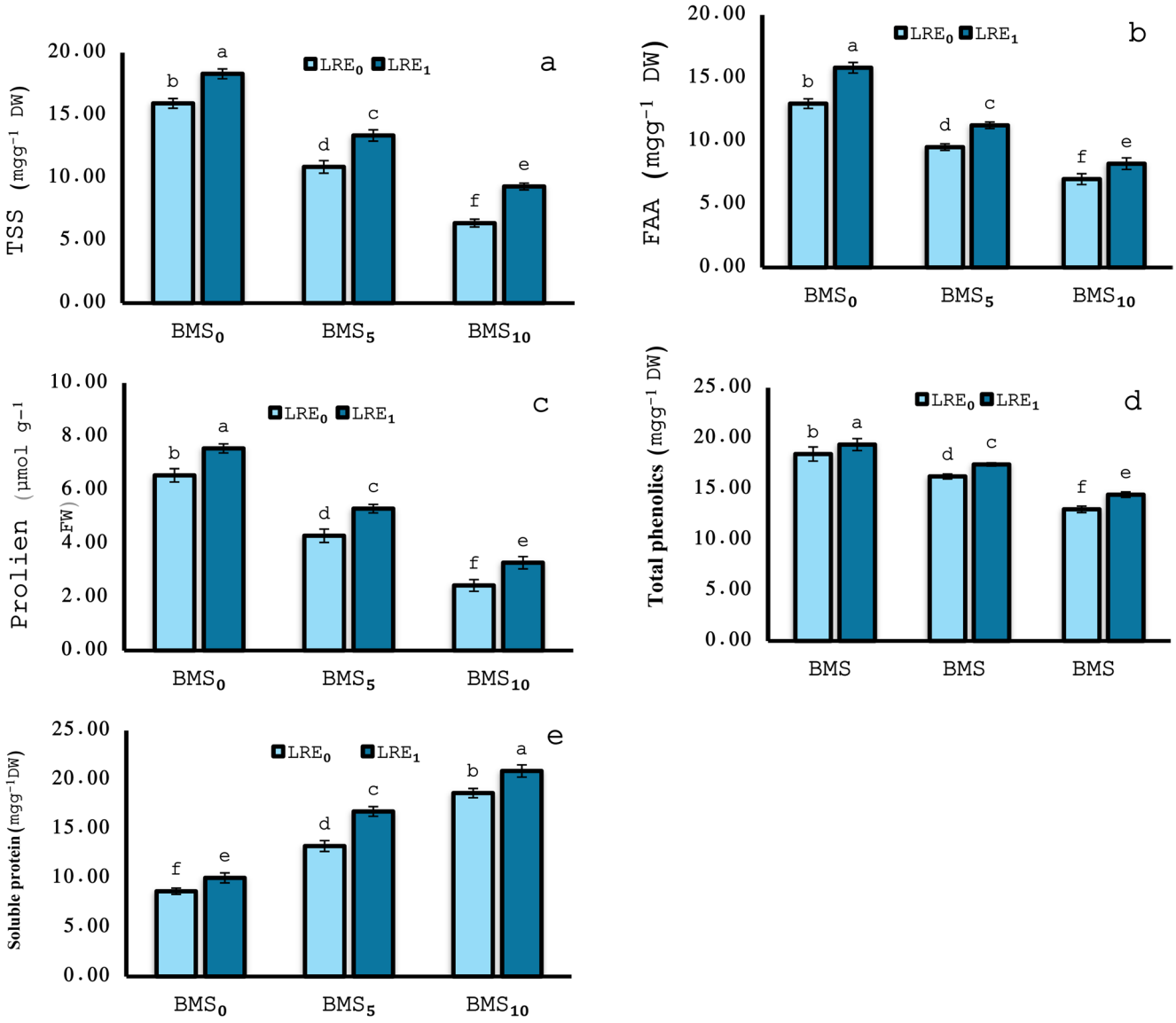


Fig. 1 Influence of BMS and LRE application on content ofosmo-regulatory substances in leaves of squash plants. (**a**)TSS, (**b**)FAA, (**c**) proline, (**d**) total phenolics and (**e**) soluble protein. BMS0,BMS5 and BMS10; are applied biochar modified sulfur amendmentat rates 0 (control), 5 and10 tonha-1 respectively. LRE0 and LRE1,are foliar applied licorice root extract by rates 0 (control) and 1%respectively. TSS: (total soluble sugars); FAA: (free amino acids);DW: (dry weight). Data represent means ± standard error (SE).Columns sharing same small letters are not statistically ($p > 0.05$)different according to Duncan's Multiple Range Test

patterns were also observed following LRE application under all applied BMS amendment levels.

3.4 Effect of Applied BMS Soil Amendment, Foliar Spraying LRE and Their Interaction On Leaf Nutrient Status of Squash Plants

Leaf nutrient status and ionic balance of squash plants were significantly affected by biochar-modified sulfur (BMS) and licorice root extract (LRE) under salinity stress (Fig. 3a-f). Relative to control (BMS_0), BMS_5 and BMS_{10} increased leaf N by (12.65 and 23.46%), P by (8.74 and 15.63%), K by (18.80 and 32.32%), Ca by (0.94 and 1.64%), while LRE_1 application increased N, P, K, and Ca by 5.57, 3.57, 7.45 and 0.46% respectively, compared with LRE_0. In contrast, leaf Na^+ content decreased by 9.10% and 21.76% under BMS_5 and BMS_{10}, respectively, and by 7.10% with LRE application relative to LRE_0. The applied (BMS_{10}+LRE_1) produced the greatest nutrient enrichment, increasing N, P, K, and Ca by 31.15, 20.08, 41.88 and 52.66%, respectively, while reducing Na^+ accumulation by 29.05% compared with (BMS_0+LRE_0). Both treatments improved ionic balance, as reflected by increases in K/Na by 30.75% under BMS_5,

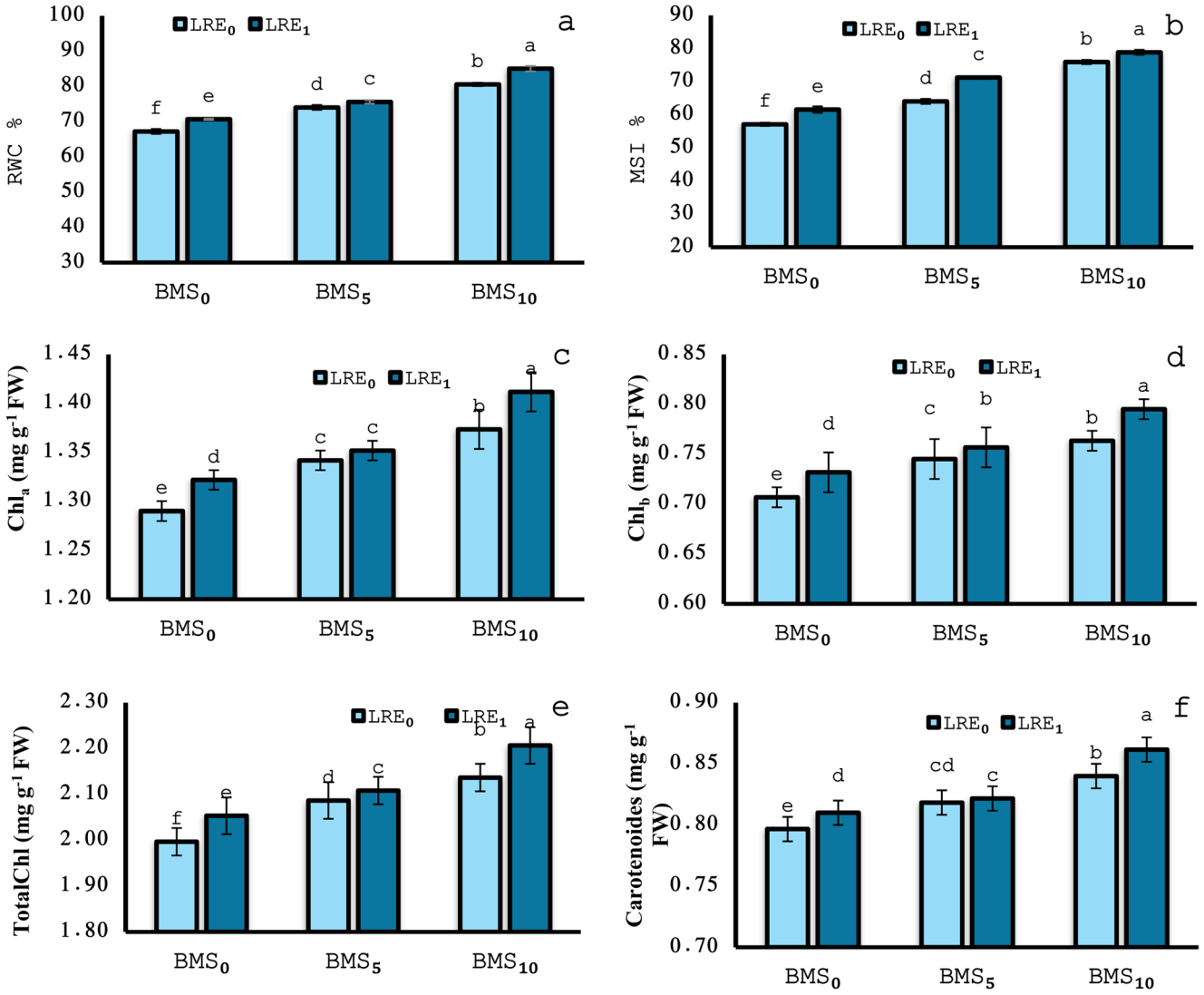


Fig. 2 Effect of BMS and LRE application on water status, membrane integrity and photosynthetic pigment content (**a**) RWC, (**b**) MSI, (**c**) Chl_a, (**d**) Chl_b (**e**) total Chl and (**f**) carotenoids content (mgg^{-1}) in leaves of squash plants. BMS_0, BMS_5 and BMS_{10}; are applied biochar modified sulfur amendment at rates 0 (control), 5 and10 $tonha^{-1}$ respectively. LRE_0 and LRE_1, are foliar applied licorice root extract by rates 0 (control) and 1% respectively. RWC, relative water content, MSI, membrane stability index, Chl_a, chlorophyll a, Chl_b, chlorophyll b, total Chl, total chlorophyll. FW, fresh weight. Data represent means ± standard error (SE). Columns sharing same small letters are not statistically ($p > 0.05$) different according to Duncan's Multiple Range Test

21.76% under BMS_{10}, and 17.59% with LRE application, with the highest ratio recorded under (BMS_{10} + LRE_1).

3.5 Effect of Applied BMS Soil Amendment, Foliar Spraying LRE and Their Interaction On Growth Attributes of Squash Plants

Growth attributes of squash plants were significantly influenced by applied BMS, LRE, and their interaction (Table 3). Compared to BMS_0, BMS_5 increased leaves number (LN), leaves dry weight (LDW) and leaf area (LA) by 16.50, 45.72 and 36.06% respectively, however BMS_{10} induced greater increases of 30.58, 87.58 and 105.75% for the same traits. Similary, the application of BMS_5 and BMS_{10} increased stem dry weight by (34.54 and 61.70%) and plant dry weight (PDW) by (42.07 and 79.12%) respectively in relation to control. Foliar application of LRE (LRE1) also significantly enhanced plant growth, increasing LN, LDW, LA, SDW and PDW by 9.68, 17.27, 16.84, 12.71 and 15.84% respectively compared to control (LRE_0). A significant BMS × LRE interaction was evident, with the combined treatment (BMS_{10} + LRE_1) producing the highest vegetative growth across all measured parameters.

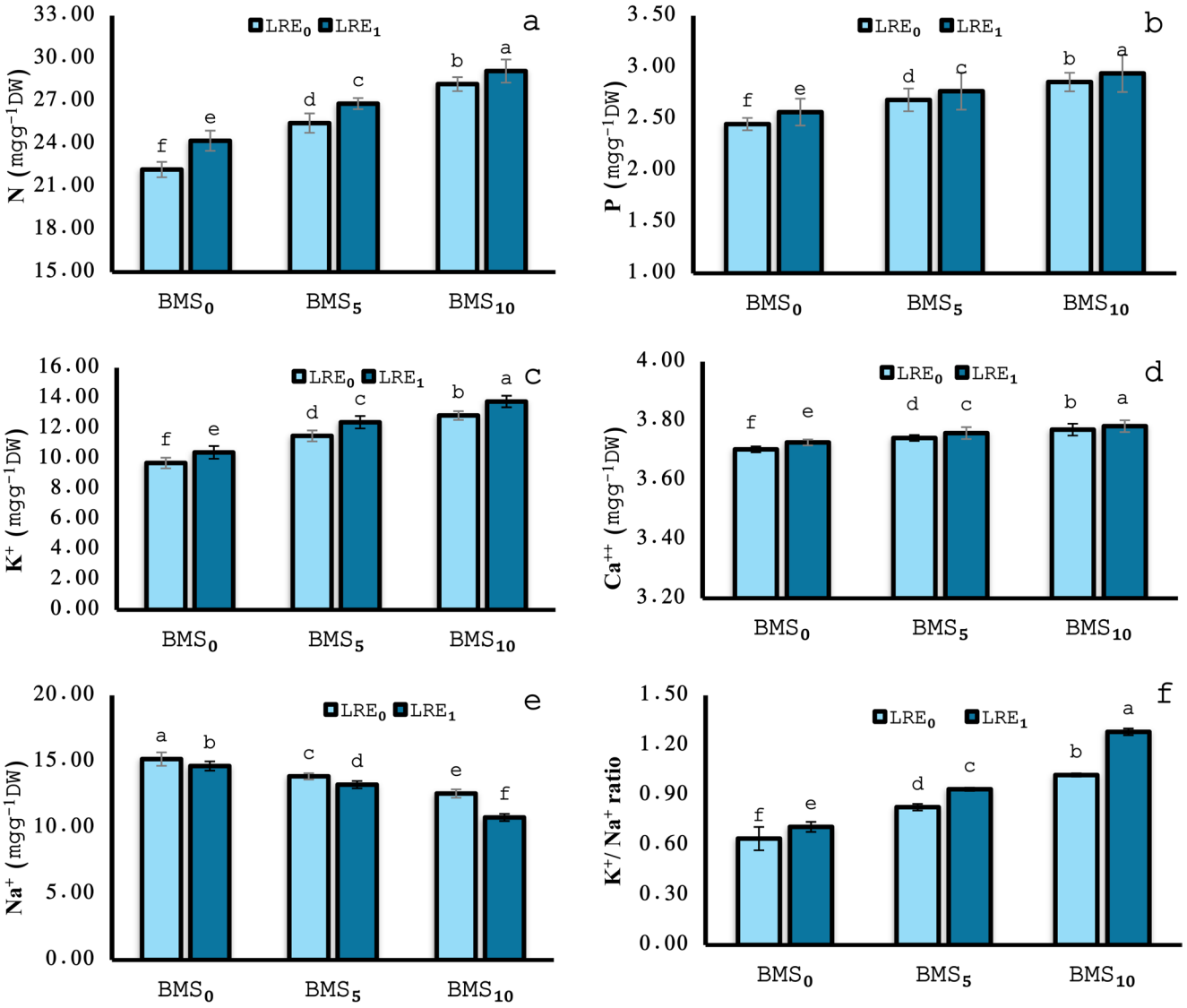


Fig. 3 Effect of BMS and LRE application on nutrient content (**A**) N, (**B**) P, (**C**) K^+, (**D**) Ca^{++} (**E**) Na^+ (**F**) K^+/Na^+ ratio (mgg^{-1}) in leaves of squash plants. BMS_0, BMS_5 and BMS_{10}; are applied biochar modified sulfur amendment at rates 0 (control), 5 and10 $tonha^{-1}$ respectively. LRE_0 and LRE_1, are foliar applied licorice root extract by rates 0 (control) and 1% respectively. Data represent means ± standard error (SE). Columns sharing same small letters are not statistically ($p > 0.05$) different according to Duncan's Multiple Range Test. N, nitrogen; P, phosphorus; K, potassium, Na, sodium; Ca; calcium. DW, dry weight

3.6 Effect Applied BMS Soil Amendment, Foliar Spraying LRE and Their Interaction On Yield and Yield Related Indices of Squash Plant

Yield and its yield- related traits of squash plants including fruit weight (FW) fruits number $plant^{-1}$ (FNP), fruit weight $plant^{-1}$ (FWP) and fruit yield (FY) were significantly by implemented BMS, LRE and their interaction (Table 4). In this regard, compared with control, increasing the application level of BMS at levels 5 and 10 t ha^{-1} increased FW by (22.11 and 45.44%), FNP by (25.95 and 45.41%), FWP by (31.14 and 69.18%) and FY by (30.52and 69.18%). Exogenously application of LRE_1 treatment further enhanced these traits by 11.09, 10.74, 17.39 and 17.79% respectively, higher than (LRE_0). The use of (BMS_{10}+LRE_1) producing the highest yield response, increasing FW, FNP, FWP and FY by 60.39, 65.48, 99.78 and 99.78% respectively, relative to the untreated control (BMS_0+LRE_0).

4 Discussion

Soil salinization is a major abiotic stress that inhibits plant growth by inducing osmotic stress and hyper-ionic toxicity, thereby threatening global food security (Balasubramaniam et al., 2023; Zhou et al., 2024). A proposed sustainable

Table 3 Influence of BMS, LRE and their interaction on growth traits of squash plants for S_I (2023) and S_{II} (2024) seasons

Treatment	No of leaves	leaves DW(g)	Stem DW(g)	Plant DW(g)	Leaf Area m^2
Season	**	NS	NS	NS	NS
S_I	19.78 ± 0.59a	40.78 ± 1.775a	18.11±0.0.37a	59.16 ± 1.07a	2.38 ± 0.17a
S_{II}	19.94±.86a	41.05 ± 1.792a	18.25 ± 0.36a	59.03 ± 1.12a	2.39 ± 0.18a
BMS	NS	**	**	**	**
BMS_0	17.17 ± 0.44a	28.33 ± 1.18c	13.77 ± 0.35c	42.09 ± 1.45c	1.62 ± 0.04c
BMS_5	20.00±0.0.64a	41.28 ± 1.29b	18.52 ± 0.32b	59.80 ± 1.46b	2.20 ± 0.05b
BMS_{10}	22.42 ± 0.32a	53.14 ± 0.630a	22.26 ± 0.52a	75.58 ± 1.09a	3.33 ± 0.08a
LRE	**	**	**	**	**
LRE_0	18.94±0.0.56b	37.66 ± 1.44b	17.10 ± 0.75b	54.76 ± 1.12b	2.20 ± 0.16b
LRE_1	20.78±0.0.53a	44.17±0.1.55a	19.27 ± 0.876a	63.43 ± 1.33a	2.57 ± 0.15a
BMS × LRE	NS	**	**	**	**
$BMS_0 \times LRE_0$	15.83 ± 0.30f	24.54 ± 1.03f	12.54 ± 0.35f	37.08 ± 1.39f	1.48 ± 0.75f
$BMS_0 \times LRE_1$	18.50 ± 0.22e	32.11 ± 1.89e	14.99 ± 0.34e	47.11 ± 1.56e	1.76 ± 0.37e
$BMS_5 \times LRE_0$	19.50 ± 0.51d	37.87 ± 0.74d	17.75 ± 0.57d	55.62 ± 1.21d	2.08 ± 0.03d
$BMS_5 \times LRE_1$	20.50 ± 0.22c	44.69 ± 0.27c	19.29 ± 0.26c	63.98 ± 1.55c	2.33 ± 0.01c
$BMS_{10} \times LRE_0$	21.50 ± 0.34b	50.58 ± 0.32b	21.00 ± 0.45b	71.58 ± 1.74b	3.04 ± 0.05b
$BMS_{10} \times LRE_1$	23.33 ± 0.61a	55.69 ± 0.84a	23.52 ± 0.22a	79.21 ± 1.99a	3.62 ± 0.09a

Data represent means ± standard error (SE). Asterisks denote significant differences: *$p \leq 0.05$, **$p \leq 0.01$; ns, not significant ($p > 0.05$). Within columns, means followed by differing lowercase letters differ significantly according to Duncan's multiple range test ($p \leq 0.05$). S_I and S_{II} are the first and second cultivation seasons. BMS_0, BMS_5 and BMS_{10} are applied biochar modified sulfur amendment at rates 0 (control), 5 and 10 ton ha^{-1} respectively. LRE_0 and LRE_1 are foliar application of licorice root extract by rates 0 (control) and 1% respectively. DW: dry weight

Table 4 Effect of BMS, LRE and their interaction on yield and yield components of squash plants for S_I (2023) and S_{II} (2024) seasons

Treatment	Number of fruits $Plant^{-1}$	fruit weight $Plant^{-1}$ (g)	Average fruit weight (g)	Fruit yield)t ha^{-1})
Season	NS	NS	NS	NS
S_I	19.17 ± 0.65a	811.66 ± 15.77a	41.80 ± 1.17a	16.23 ± 0.89a
S_{II}	19.00 ± 0.70a	806.75 ± 16.03a	41.57 ± 1.03a	16.08 ± 0.94a
BMS	**	**	**	**
BMS_0	15.42 ± 0.46c	606.42 ± 14.89c	34.02 ± 0.58c	12.13 ± 0.32c
BMS_5	19.42 ± 0.27b	795.27 ± 12.93b	41.55 ± 1.17b	15.83 ± 0.86b
BMS_{10}	22.42 ± 0.38a	1025.92 ± 13.14a	49.48 ± 1.19a	20.52 ± 0.58a
LRE	**	**	**	**
LRE_0	18.11 ± 0.86b	744.46 ± 15.63b	39.49 ± 0.69b	14.84 ± 0.89b
LRE_1	20.06 ± 0.53a	873.94 ± 14.78a	43.87 ± 1.25a	17.48 ± 0.843a
BMS × LRE	**	**	**	**
$BMS_0 \times LRE_0$	14.00 ± 0.28d	554.58 ± 6.18f	32.22 ± 1.06f	11.09 ± 0.11f
$BMS_0 \times LRE_1$	16.83 ± 0.30c	658.25 ± 5.15e	35.83 ± 0.59e	13.17 ± 0.17e
$BMS_5 \times LRE_0$	18.67 ± 0.25b	734.92 ± 9.75d	38.98 ± 0.43d	14.55 ± 0.19d
$BMS_5 \times LRE_1$	20.17 ± 0.47b	855.63 ± 5.89c	44.12 ± 1.25c	17.11 ± 0.12c
$BMS_{10} \times LRE_0$	21.67 ± 0.26a	943.88 ± 8.54b	47.29 ± 0.50b	18.88 ± 0.17b
$BMS_{10} \times LRE_1$	23.17 ± 0.69a	1107.96 ± 4.88a	51.68 ± 1.44a	22.16 ± 0.08a

Data represent means ± standard error (SE). Asterisks denote significant differences: *$p \leq 0.05$, **$p \leq 0.01$; ns, not significant ($p > 0.05$). Within columns, means followed by differing lowercase letters differ significantly according to Duncan's multiple range test ($p \leq 0.05$). S_I and S_{II} are the first and second cultivation seasons. BMS_0, BMS_5 and BMS_{10} are applied biochar modified sulfur amendment at rates 0 (control), 5 and 10 ton ha^{-1} respectively. LRE_0 and LRE_1 are foliar application of licorice root extract by rates 0 (control) and 1% respectively

solution is the synergistic use of soil amendments like biochar-modified sulfur combined with foliar applications of licorice root extract. This approach aims to enhance the physiological resilience of squash plants under saline conditions.

The current study showed that the addition of biochar modified sulfur (BMS) had direct and indirect favorable effects on saline-stressed squash plants. The direct effects included enhancement in growth (Table 3) and yield (Table 4) of grown plant, while the indirect effects were observed

in improved soil physicochemical properties (Tables 1 and 2). Notably, due to applied BMS, soil bulk density and Ksat showed significant decrease, while, T.P., W.H.P. and U.P. were increased. Biochar is characterized by its porous nature, low density, and high specific surface area, acts as a moisture-absorbent material (Li and Tasnady 2023). Hence, the applied BMS tratments by 5 and 10 ton ha^{-1} increased soil porosity and declined bulk density, which was in agreement with (Abdou et al., 2024; Singh et al., 2022a). Incorporation of biochar amendment with the soil enhances the filling and clogging of soil macro pores with tiny biochar particles, leading to an increase in micro-pores rather than macro-pores (Edeh and Mašek 2022), resulting in a notable increase in water-holding pores, indicating an increase of capillary potential, decrease in water movement (Table 1) and enhancement in soil's water retention capacity (Chen et al., 2023). This indicates of enhanced water availability to stressful plants, which in turn promoting growth (Table 3), physiological attributes (Figs. 2a-f), biochemical reaction (Fig. 1a-e) and yield (Table 4) of BMS amended squash plants in saline conditions. Using of BMS amendments resulted in notable improvements in soil chemical properties (Table 2), characterized by a reduction in soil pH and salinity, as well as an increase in soil CEC, organic matter content, and the concentrations of N, P, and K^+ also have been increased. Improved soil chemical properties in biochar amended soil was reported by several studies) EL-Samnoudi et al., 2021; Sun et al., 2022). The activation of sulfur-oxidizing microorganisms following applied BMS could be responsible of reduced soil pH (Taheri et al., 2024). Moreover, the release of active organic acids resulted from decomposed organic materials also contributes to decrease in soil pH (Alharbi et al., 2021; Jien et al., 2015). Furthermore, treating soil with biochar-sulfur mixture enhances the formation of acidic ions produced from the reaction of sulfur ions with water, which is responsible of decreased soil pH (El-Sharkawy et al., 2022; Taheri et al., 2024). Decreased soil salinity following BMS might be attributed to the lower salt concentrations of applied soil amendment (Table S2) compared to salinity levels observed in soil initial analysis (Table S1), indicating that BMS may has dilution effect on soil salinity. Also, this decrease in soil ECe values induced by BMS could be attributed to the involvement of charged sites, such as COO^-, which exhibit the ability of BMS to retain cations, hence keeping them in inactive forms (Irshad et al., 2022; Sadegh-Zadeh et al., 2018). Moreover, incorporation of BMS amendment in soil could be resulted in better leaching processes of salts from the soil profile, which efficiently reducing soil salinity (Wang et al., 2024). Interestingly, biochar particles are distinguished by their high surface area, which significantly contributes to an enhancement in soil CEC (Adhikari et al., 2024; Zhang et al., 2017). In addition, the applied biochar mixed with sulfur might be provided a stable habitat for soil microorganisms, resulting in better microbial diversity, that enhances the decomposition of organic materials leading to higher amounts of accumulated of soil organic matter (Feng et al., 2021; Liu et al., 2022). Furthermore, the decomposition of BMS, increases the release of macro and micronutrients, particularly with a higher BMS concentration, which improves soil fertility (Singh et al., 2023; Tang et al., 2023), which in turn enhances crop resilience under stressful conditions (Boudjabi et al., 2023; Hasnain et al., 2023). The observed increase in phosphorus availability might be linked to the presence of chelating agents, organic acids and enzymes, that stimulate the microbial activity crucial for phosphorus mineralization in BMS amendment as evidenced by studies conducted by (Abd El-Mageed et al., 2021). Moreover, owing to high surface area and existence of functional groups on biochar substances, that leads to significant increase in soil CEC and enhances its capacity to retain nutrients, by limiting their leaching, consequently increasing their availability to plants (Adhikari et al., 2024; Tomczyk et al., 2020). Hence, sulfur modification of biochar introduces sulfate ions through oxidation, directly acidifying the biochar and subsequently lowering soil pH. This acidity enhances nutrient solubility. Concurrently, the modification increases the density of oxygen-containing functional groups (e.g., carboxyl and hydroxyl) on the biochar's surface, which boosts its cation exchange capacity (CEC) for improved nutrient retention. Furthermore, the porous structure of biochar provides a favorable habitat for sulfur-oxidizing and other beneficial microorganisms, whose activity drives nutrient cycling and availability (Zhang and Shen 2022). Thus, sulfur-modified biochar serves as a multi-functional amendment that improves soil fertility through coupled chemical and biological mechanisms. Also, the present investigation examined the diverse impacts of biochar-modified sulfur (BMS) and licorice root extract (LRE) on morphological (Table 3), biochemical reactions (Fig.1 a-e) and physiological (Fig. 2a-f) of saline affected squash plants. Utilization of BMS and LRE resulted in improvement in plant resilience to salt stress. Squash plants subjected to salinity stress in BMS_0 amended plots exhibited a notable rise of accumulated osmoregulatory substances including total soluble sugars, free amino acids, proline and total phenolics. Salinity stress induces numerous harmful impacts on plant physiological and biochemical functions (Arif et al., 2020; Chourasia et al., 2021). Under these unfavorable conditions, plants tend to enhance their osmotic adaptation, integrates several substances (Abdelkhalik et al., 2025; Hosseinifard et al., 2022; Nawaz et al., 2022; Salim, et al., 2021). Consequently, osmotic adjustment is vital for supporting cell turgor and ensuring higher growth and yield of stressed plants (Zhou et

al., 2024). Proline is an osmo-protectant and a phyto-signaling compound, that concentrates in plant cytosol (Dawood et al., 2021). It plays a pivotal role in maintaining and safeguarding membranes, protein-aceous enzymes, and various proteins (Hosseinifard et al., 2022). It helps in regulating plant metabolism by boosting the expression of membrane proteins, reactive oxygen species (ROS) scavengers, and ensuring cell solute homeostasis (Chourasia et al., 2021). Numerous studies have been highlighted that, under salinity, proline improves the absorption of water and antioxidant machinery (El Moukhtari et al., 2020; Ibrahim et al., 2022). Additionally, it lowers the accumulation of toxic ions (Atta et al., 2024). Under harsh conditions, sugars also contribute in retaining cell osmotic stability. Researchers have shown that, plants experiencing salinity synthesis various reduced sugars including glucose, fructose, and sucrose, which provide further ability to tolerate with salinity (Naseem et al., 2023; Saddhe et al., 2021). Thus, they act as vital osmolyte stabilizing membrane integrity and protects from protein denaturation. Phenolic compounds, being antioxidants, their synthesis increases under salinity stress to mitigate the oxidative damage induced by ROS molecules (Pungin et al., 2023). Notably, the accumulation of these osmo-protectants being increased with the addition of LRE indicating better salt tolerance of saline stressed squash plants (Figs.1 a-e). Enriching plants with bioactive components including amino acids, vitamins, nutrients, phytohormones and sugars involved in LRE foliar application (Table S4) could be responsible of promoted the antioxidative defenses for saline stressed squash plants (Merwad 2020; Rady et al., 2019). Proline is one of the non-enzymatic antioxidant components involved in LRE (Table S4) acts an essential role in osmotic regulation, that improves the tolerance of squash to salt stress. Desoky et al. (2018) indicated that the endogenous antioxidant system is often insufficient to protect plants under saline stress. However, licorice root extract (LRE), which is rich in bioactive compounds such as glycyrrhizin and flavonoids, can supplement this defense. These compounds function as direct antioxidants, detoxifying ROS and thereby mitigating oxidative damage (Agati et al., 2012). In contrast, reduced osmolytes production in correspondence of applied soil amendment BMS might be associated with the improved soil water holding capacity, nutrient availability, indicating less stress on grown plants. Furthermore, the applied BMS soil amendment played a beneficial role in protecting membrane stability (Fig. 2b), adjusting cell osmotic pressure (Abd El-Mageed et al., 2020), and enhancing relative water content (Fig. 2a), that reducing oxidative stress. These results are in line with the results of (Elrys et al., 2020; Holatko et al., 2023; Taheri et al., 2024). These results indicate a synergistic effect between the biochar-modified sulfur (BMS) amendment and licorice root extract (LRE) in enhancing salinity stress resilience. The BMS likely improved the soil environment, while the LRE directly fortified the plant through osmoprotective and antioxidant activities. Nevertheless, the precise mechanisms of this synergy require further deconstruction through multi-omics studies. Employing transcriptomic and metabolomic profiling under salinity stress will elucidate the key regulatory genes and metabolic pathways primed by this combination.

Protein content was adversely influenced by salt stress, which could mainly attributed to diminished uptake and assimilation of nitrogen (Sajjad et al., 2021). In addition, salinity stress triggers the hydrolysis of protein into amino acids such as proline, which in turn limits protein synthesis. In contrast, treating salt affected squash plants with (BMS + LRE) improved leaf protein content (Fig. 2e). This finding could be attributed to effective role of LRE, that contains several bioactive compounds (Table S4), essential for enhancing plant growth and thus improving biomass production. These results are in line with (Desoky et al., 2019a; Merwad 2020). However, increased protein content in saline stressed squash plants following BMS soil addition could be a result of enhanced nutrient availability in particular, nitrogen, which is acritical component of amino acids, hence protein synthesis. Furthermore, enhanced nutrient uptake and water availability in BMS amended plots could resulted in better metabolic processes including protein production.

Salinity stress induced significant decrease in leaf RWC (Fig. 2a) and leaf MSI (Fig. 2b). This decrease in both RWC and MSI limits the potential of water uptake by roots (Choudhary et al., 2023). Reduced water uptake and stomatal closure under salinity induces dehydration in plant cell, causing a decrease in RWC (Somaddar et al., 2023; Zhao et al., 2020). Moreover, salinity stress stimulates ROS production, that damage proteins and lipids, which decreasing MSI (Liu et al., 2023a; Shunkao et al., 2022). Photosynthesis—a critical physiological and biochemical process in plants, is highly susceptible to salinity. Salinity reduces chlorophyll fluorescence, and chlorophyll content (Fig. 2c-e). It also triggers damage in chloroplast and stomata structure (Hameed et al., 2021). In addition, salt stress inhibits CO_2 fixation that decreases photosynthetic processes (Zhou et al., 2024). Conversely, due to proline and sugars substances involved in LRE, that play a significant role in regulating water imbalances in plant cells, resulting in improved MSI and RWC and photosynthetic pigment compared to non-LRE sprayed squash plants (Figs. 2a-f). Also, presence of Mg in LRE, which considered a key element in Chl biosynthesis (Younes et al., 2021). In addition, increased soluble sugar content in squash plants treated with LRE (Fig.1 a), might have a beneficial function in energy supply and osmotic regulation to sustain leaf water potential (Mohammadi Alagoz

et al., 2023). The beneficial role of LRE of plant physiological indices was confirmed by several studies (Rady et al., 2019; Younes et al., 2021). Similar finding was observed due to applied BMS amendment on measured photosynthetic pigments (carotenoid, and chlorophyll) in leaves of squash plants under salinity stress. These results agreed with several studies which verified that biochar enhanced the release and uptake of nutrients, essential for chlorophyll synthesis (EL-Samnoudi et al., 2021; Holatko et al., 2022; Rashmi et al., 2023). Moreover, enhanced water avaiability due to BMS application alleviates salinity stress and maintaining optimal photosynthetic activity (Taheri et al., 2024). Furthermore, amending soil with biochar may help in maintaining ion balance and limiting the excessive accumulation of toxic ions, that enhances the production of photosynthetic pigments (Huang et al., 2023).

The content of essential nutrients (i.e. nitrogen, phosphorus, and potassium) in leaves of squash plants was negatively affected by salt stress (Figs. 3a-c). Salinity stress may has an antagonistic effect on plant nutrition (Bidalia et al. 2019). Salinity exhibits numerous influences on nutrient uptake in soil: (i) it disrupts root nutrient absorption owing to ionic imbalances (Arif et al., 2020); (ii) it triggers water stress, impairing nutrient use efficiency and metabolic processes in plant tissues (Arif et al., 2020; Shahid et al., 2020); and (iii) it contributes to excessive production of toxic ions (Na^+ and Cl^-) resulting in leaf edge burns (Balasubramaniam et al., 2023). Elevated salinity levels inhibit the functioning and integrity of cell membranes (Liu et al., 2021). Plant nutrition efficiency is highly correlated with the activity level of membrane transporters, which facilitate the movement of ions to plant from soil, controlling their distribution within and between cells (Ameen et al., 2022). In addition, increased Na^+ content in plant leaves, may be a reason of decreased K^+ content (Fig. 3c), and disrupting potassium balance in cytosol (Hniličková et al., 2019; Shen et al., 2022b). Consequently, maintaining optimal levels of K^+ ions and balanced K^+/Na^+ ratio is known as a critical strategy helping in mitigating negative effects of salinity stress on plants (Assaha et al., 2017; Peña Calzada et al., 2023). However, the individual use of BMS or in combination with LRE resulted in improved contents of nitrogen (N), phosphorus (P) and potassium (K) in leaves of squash plants affected by salinity stress. The application of BMS amendment enhanced soil nutrient content, soil nutrient retention capacity, which improves the availability and uptake of nutrients. This finding was parallel with those reported by (Holatko et al., 2022; Taheri et al., 2024). Interestingly, the measured nitrogen concentrations in leaves of squash plants under stress conditions were consistent with the values reported by (Doklega et al., 2022; El-Masry et al., 2014; Ibrahim and Selim 2007; Jasim et al., 2015). However, the use of LRE via foliar application improved plant nutritional status, indicating enhancement in plant resilience to cope with stressful condition (Fig. 3a-d). These outcomes are consistent with those highlighted by (Elrys and Merwad 2017; Merwad 2020; Zulfiqar et al., 2020). This beneficial effect of LRE, likely stems from its rich phytochemical profile of various bioactive components that promote nutrient uptake. In this regard, squash plants treated with LRE showed a remarkable decrease in their leaves Na^+ content and increase in K^+ levels, hence an improvement in the K^+/Na^+ ratio (Fig. 3f).

Salinity stress induced a notable reduction in growth traits of squash plants, including leaves number, leaves dry weight, and leaf area, stem dry weight and plant dry weight (Table 3) as well as yield metrics such as fruit weight, fruits number $plant^{-1}$, fruit weight $plant^{-1}$ and fruit yield (Table 4). This decrease could be a result of increased concentrations of toxic-ions (Na^+) in saline stressed squash plants, nutrient imbalances, reduced photosynthesis (Fig. 2 a and f). Moreover, increased energy demand to maintain ion homeostasis (Ma et al., 2022), caused by salinity may decreases the activity meristematic organs, cell division, elongation processes and biomass accumulation (Urano et al., 2014; Yu et al., 2022), which disrupting growth and productivity of saline-stressed squash plants. However, the application of LRE separately or in integration with BMS resulted in enhanced plant growth (Table 3) and increased yield production in salt-stressed squash plants (Table 4). BMS has beneficial effects on soil properties (Tables 1 and 2), which play a critical role in alleviate the deleterious consequences on squash plants caused by salt stress, consequently improving plant growth. Increasing growth and yield of saline stressed plants due to BMS application was previously confirmed by several studies (Abd El-Mageed et al., 2020; Holatko et al., 2022; Huang et al., 2023). Similar results were observed in growth and yield of squash plants caused by LRE. This finding possibly attributed to improved metabolic activities in plant cells which activated by dissolved substances involved in LRE (Table S4) such as nutrients, sugars, antioxidants, vitamins and phytohormones and gibberellins, resulting in increase in cell division and elongation (El-Morsy et al., 2017). Moreover, increased growth characteristics and biomass production of saline affected squash plant could be attributed to phytohormones, especially gibberellin in LRE.

This field study confirms the synergistic efficacy of biochar-modified sulfur (BMS) and licorice root extract (LRE) in enhancing salinity tolerance in squash. However, broader adoption necessitates validation across diverse agro-climatic zones and a formal cost-benefit analysis. Although the slow-release nature of the applied BMS (5:100 w/w S: biochar) is predicted to minimize sulfur leaching compared to

conventional fertilizers, its environmental impact requires direct field quantification. To transition from physiological correlation to causal mechanism, future research should employ integrated multi-omics approaches. Transcriptomic and metabolomic profiling would elucidate the specific gene regulatory networks and metabolic reprogramming—such as the upregulation of ion transporters and antioxidant biosynthesis pathways—underlying this synergistic resilience.

5 Conclusion

This study confirms that the synergistic application of sulfur-enriched biochar and licorice root extract effectively mitigates salinity stress in squash through complementary mechanisms. Soil amendment with biochar-modified sulfur (BMS) enhanced key soil properties, including cation exchange capacity, organic matter, and water retention, thereby improving the availability and uptake of nitrogen, phosphorus, and potassium. Concurrently, foliar application of licorice root extract (LRE) activated the plant's biochemical defenses, significantly increasing osmoprotectants and antioxidants such as proline and phenolics. The integration of biochar-modified sulfur at 10 ton ha^{-1} with foliar licorice root extract significantly enhanced squash performance under salinity stress, surpassing all individual treatments. These findings validate a novel and sustainable strategy to enhance crop resilience and optimize nutrient management in salt-affected agroecosystems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-026-03206-8.

Acknowledgements The authors express gratitude to the agriculture experimental center (Faculty of Agriculture, Fayoum University) for conducting the field experiments.

Author Contributions "Conceptualization, N.M.A., M.A.G., and A.RA.; methodology, N.M.A., M.A.G., B.R.A., and A.RA.; validation, N.M.A., M.A.G., B.R.A., and A.RA.; formal analysis, N.M.A., M.A.G., B.R.A., and A.RA.; investigation, N.M.A., M.A.G., B.R.A., and A.RA.; resources, N.M.A., M.A.G., B.R.A., and A.RA.; data curation, N.M.A., M.A.G., and A.RA.; writing—original draft preparation N.M.A., M.A.G., B.R.A., and A.RA.; writing—review and editing, N.M.A., M.A.G., B.R.A., and A.RA.; visualization, N.M.A., M.A.G., B.R.A., and A.RA.; supervision, N.M.A., M.A.G., and A.RA. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Data Availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abd El Mageed SA, Sayed AA, Shaaban A, Hemida KA, Abdelkhalik A, Semida WM, Abd El Mageed TA (2025) Integrative application of licorice root extract and melatonin improves faba bean growth and production in Cd-contaminated saline soil. BMC Plant Biol 25:26. https://doi.org/10.1186/s12870-024-05954-0

Abd El-Mageed TA, Rady MM, Taha RS, Abd El Azeam S, Simpson CR, Semida WM (2020) Effects of integrated use of residual sulfur-enhanced biochar with effective microorganisms on soil properties, plant growth and short-term productivity of *Capsicum annuum* under salt stress. Sci Hortic 108930. https://doi.org/10.1016/j.scienta.2019.108930

Abd El-Mageed TA, Belal EE, Rady MOA, Abd El-Mageed SA, Mansour E, Awad FM, Semida WM (2021) Acidified biochar as a soil amendment to drought stressed (*Vicia faba* l.) plants: influences on growth and productivity, nutrient status, and water use efficiency. Agronomy 1290. https://doi.org/10.3390/agronomy11071290

Abdelkhalik A, Gyushi MAH, Howladar SM, Kutby AM, Asiri NA, Baeshen AA, Nahari AM, Alsamadany H, Semida WM (2025) Synergistic effects of zinc oxide nanoparticles and moringa leaf extracts on drought tolerance and productivity of *Cucurbita pepo* L. under saline conditions. Plants 14:544. https://doi.org/10.3390/plants14040544

Abdou NM, EL-Samnoudi IM, Ibrahim AEAM, EL-Tawwab ARA (2024) Biochar Amendment Alleviates the Combined Effects of Salinity and Drought Stress on Water Productivity, Yield and Quality Traits of Sugar Beet (*Beta vulgaris* L.). J Soil Sci Plant Nutr 24:2091–2110. https://doi.org/10.1007/s42729-024-01754-5

Abuzaid AS, Abdel-Salam M, Abbas MH, Khalil F, Abdelhafez AA (2025) Effectiveness of biochar and elemental sulfur for sustaining maize productin in arid soils. Egypt J Soil Sci 65:163–177

Adhikari S, Moon E, Timms W (2024) Identifying biochar production variables to maximise exchangeable cations and increase nutrient availability in soils. J Clean Prod 446:141454. https://doi.org/10.1016/j.jclepro.2024.141454

Agati G, Azzarello E, Pollastri S, Tattini M (2012) Flavonoids as antioxidants in plants: location and functional significance. Plant Sci 196:67–76. https://doi.org/10.1016/j.plantsci.2012.07.014

Alharbi S, Majrashi A, Ghoneim AM, Ali EF, Modahish AS, Hassan FAS, Eissa MA (2021) A new method to recycle dairy waste for the nutrition of wheat plants. Agronomy 11:840. https://doi.org/10.3390/agronomy11050840

Ali MM (2018) Effect of plant residues derived biochar on fertility of a new reclaimed sandy soil and growth of wheat (*Triticum aestivum* L.). Egypt J Soil Sci 58:93–103. https://doi.org/10.21608/ejss.2018.5615

Ameen M, Akhtar J, Anwar-Ul-Haq M, Abbasi GH, Jamil M, Ali M, Athar T (2022) Nutrient acquisition, transport and metabolism within the plant cells. In: Sustainable Plant Nutrition. Academic Press: 51–70. https://doi.org/10.1016/B978-0-443-18675-2.00005-5

Arif Y, Singh P, Siddiqui H, Bajguz A, Hayat S (2020) Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. Plant Physiol Biochem 156:64–77. https://doi.org/10.1016/j.plaphy.2020.08.042

Assaha DVM, Ueda A, Saneoka H, Al-Yahyai R, Yaish MW (2017) The role of Na^+ and K^+ transporters in salt stress adaptation in glycophytes. Front Physiol 8:509. https://doi.org/10.3389/fphys.2017.00509

Atta N, Shahbaz M, Farhat F, Maqsood MF, Zulfiqar U, Naz N, Ahmed MM, Hassan NU, Mujahid N, Mustafa AEZMA, Elshikh MS, Chaudhary T (2024) Proline-mediated redox regulation in wheat for mitigating nickel-induced stress and soil decontamination. Sci Rep 14:456. https://doi.org/10.1038/s41598-023-50576-5

Balasubramaniam T, Shen G, Esmaeili N, Zhang H (2023) Plants' Response Mechanisms to Salinity Stress. Plants 12:2253. https://doi.org/10.3390/plants12122253

Barrs (1968) Determination of water deficit in plant tissues. In: Kozlowski TT (ed) Water deficit and plant growth. Academic, New York, pp 235–368

Bates LS, Waldren RP, Teare ID (1973) Rapid determination of free proline for water-stress studies. Plant Soil 39:205–207. https://doi.org/10.1007/BF00018060

Bidalia A, Vikram K, Yamal G, Rao KS (2019) Effect of salinity on soil nutrients and plant health. In: Salt Stress, Microbes, and Plant Interactions: Causes and Solution. In: Akhtar, M. (eds)1: 273–297. https://doi.org/10.1007/978-981-13-8801-9_1

Boudjabi S, Ababsa N, Chenchouni H (2023) Enhancing soil resilience and crop physiology with biochar application for mitigating drought stress in durum wheat (*Triticum durum*). Heliyon 9:12. https://doi.org/10.1016/j.heliyon.2023.e22909

Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal Biochem 248–254. https://doi.org/10.1016/0003-2697(76)90527-3

Chapman HD, Pratt PF (1982) Determination of minerals by titration method: methods of analysis for soils, plants and water. Calif Univ Agric Div USA 169–170. https://doi.org/10.1097/00010694-196201000-00015

Chen X, Li L, Li X, Kang J, Xiang X, Shi H, Ren X (2023) Effect of biochar on soil-water characteristics of soils: a pore-scale study. Water 15:1909. https://doi.org/10.3390/w15101909

Choudhary S, Wani KI, Naeem M, Khan MMA, Aftab T (2023) Cellular responses, osmotic adjustments, and role of osmolytes in providing salt stress resilience in higher plants: polyamines and nitric oxide crosstalk. J Plant Growth Regul 42:539–553. https://doi.org/10.1007/s00344-022-10584-7

Chourasia KN, Lal MK, Tiwari RK et al (2021) Salinity stress in potato: understanding physiological, biochemical and molecular responses. Life 11:545. https://doi.org/10.3390/life11060545

Dai Z, Zhang X, Tang C, Muhammad N, Wu J, Brookes PC, Xu J (2017) Potential role of biochars in decreasing soil acidification - a critical review. Sci Total Environ 581:601–611. https://doi.org/10.1016/j.scitotenv.2016.12.169

Dawood MG, Khater MA, El-Awadi ME (2021) Physiological role of osmoregulators proline and glycinebetaine in increasing salinity tolerance of chickpea. Egypt J Chem 64:7637–7648. https://doi.org/10.21608/EJCHEM.2021.85725.4233

Dayoub EB, Tóth Z, Anda A (2023) Biochar and its effects on soil properties and evapotranspiration: a sustainable solution for plant growth. Cogent Food Agric 9:2256136. https://doi.org/10.1080/23311932.2023.2256136

Desoky EM, Merwad AMA, Rady MM (2018) Natural biostimulants improve saline soil characteristics and salt stressed-sorghum performance. Commun Soil Sci Plant Anal 49:967–983. https://doi.org/10.1080/00103624.2018.1448861

Desoky ESM, Elrys AS, Rady MM (2019a) Integrative moringa and licorice extracts application improves *Capsicum annuum* fruit yield and declines its contaminant contents on a heavy metals-contaminated saline soil. Ecotoxicol Environ Saf 169:50–60. https://doi.org/10.1016/j.ecoenv.2018.10.117

Desoky ESM, ElSayed AI, Merwad ARMA, Rady MM (2019b) Stimulating antioxidant defenses, antioxidant gene expression, and salt tolerance in *Pisum sativum* seedling by pretreatment using licorice root extract (LRE) as an organic biostimulant. Plant Physiol Biochem 142:292–302. https://doi.org/10.1016/j.plaphy.2019.07.020

Doklega SMA, El-Afify STM, Ibrahim EA (2022) Effect of glycine betaine and chitosan on water stress tolerance of summer squash plants. J Plant Prod 13:675–681

Edeh IG, Mašek O (2022) The role of biochar particle size and hydrophobicity in improving soil hydraulic properties. Eur J Soil Sci 73:13138. https://doi.org/10.1111/ejss.13138

El Moukhtari A, Cabassa-Hourton C, Farissi M, Savouré A (2020) How does proline treatment promote salt stress tolerance during crop plant development? Front Plant Sci 11:1127. https://doi.org/10.3389/fpls.2020.01127

El-Masry TA, Osman AS, Tolba MS, Abd El-Mohsen YH (2014) Increasing nitrogen efficiency by humic acid soil application to squash plants (*Cucurbita pepo* L.) grown in newly reclaimed saline soil. Egypt J Hortic 41:17–38

El-Morsy F, Mohamed M, Bedrech S (2017) Effect of Foliar Application and Soil Addition of Licorice and Yeast Extract: B- Vegetative Growth and Fruiting of Red Globe Grafted Grapevines. J Plant Prod 8:59–63. https://doi.org/10.21608/jpp.2017.37814

EL-Samnoudi IM, El-Aty Ibrahim AM, Abd EL-Tawwaband AR, Abdou NM (2021) Addition biochar to enhanced soil quality and sugar beet crop grown under water stress treatments in salt-affected soils. FJARD: 478–494

El-Sharkawy M, El-Naggar AH, AL-Huqail AA, Ghoneim AM (2022) Acid-modified biochar impacts on soil properties and biochemical characteristics of crops grown in saline-sodic soils. Sustainability 14:8190. https://doi.org/10.3390/su14138190

Elrys A, Merwad AR (2017) Effect of alternative spraying with silicate and licorice root extract on yield and nutrients uptake by pea plants. Egypt J Agron 39:279–292. https://doi.org/10.21608/agro.2017.1429.1071

Elrys AS, Abdo AIE, Abdel-Hamed EMW, Desoky ESM (2020) Integrative application of licorice root extract or lipoic acid with fulvic acid improves wheat production and defenses under salt stress conditions. Ecotoxicol Environ Saf 190:110144. https://doi.org/10.1016/j.ecoenv.2019.110144

Enneb S, Drine S, Bagues M, Triki T, Boussora F, Guasmi F, Nagaz K, Ferchichi A (2020) Phytochemical profiles and nutritional composition of squash (*Cucurbita moschata* D.) from Tunisia. S Afr J Bot 130:165–171. https://doi.org/10.1016/j.sajb.2019.12.011

Farrag D, Darwesh R, Moursi E (2015) The combined effect between irrigation and K-fertilizer forms on squash productivity in the north Nile delta region. Egypt J Agric Sci 66:180–195. https://doi.org/10.21608/ejarc.2015.213342

Feng Z, Fan Z, Song H, Li K, Lu H, Liu Y, Cheng F (2021) Biochar induced changes of soil dissolved organic matter: the release and adsorption of dissolved organic matter by biochar and soil. Sci

Total Environ 783:147091. https://doi.org/10.1016/j.scitotenv.2021.147091
Ghanbari F, Bag-Nazari M, Azizi A (2023) Exogenous application of selenium and nano-selenium alleviates salt stress and improves secondary metabolites in lemon verbena under salinity stress. Sci Rep 13:5352. https://doi.org/10.1038/s41598-023-32436-4
Gomez KA, Gomez AA (1984) procedures for agricultural research, vol 680, 2nd edn. John Willy and Sons, inc, New York
Grafe M, Kurth JK, Panten K et al (2021) Effects of different innovative bone char based P fertilizers on bacteria catalyzing P turnover in agricultural soils. Agric Ecosyst Environ 314:107419. https://doi.org/10.1016/j.agee.2021.107419
Hafeez A, Pan T, Tian J, Cai K (2022) Modified biochars and their effects on soil quality: a review. Environments 9(5):60. https://doi.org/10.3390/environments9050060
Hameed A, Ahmed MZ, Hussain T, Aziz I, Ahmad N, Gul B, Nielsen BL (2021) Effects of salinity stress on chloroplast structure and function. Cells 10:2023. https://doi.org/10.3390/cells10082023
Hashash Maher M, Mohammed El-Sayed M, Ahmed Abdel-Hady A, Abdel Hady H, Abdallah Morsi E (2017) Nutritional potential, mineral composition and antioxidant activity squash (*Cucurbita pepo* L.) fruits grown in Egypt. Eur J Biomed Pharm Sci 4:11–12
Hasnain M, Munir N, Abideen Z, Zulfiqar F, Koyro HW, El-Naggar A, Caçador I, Duarte B, Rinklebe J, Yong JWH (2023) Biochar-plant interaction and detoxification strategies under abiotic stresses for achieving agricultural resilience: a critical review. Ecotoxicol Environ Saf 249:114408. https://doi.org/10.1016/j.ecoenv.2022.114408
Hniličková H, Hnilička F, Orsák M, Hejnák V (2019) Effect of salt stress on growth, electrolyte leakage, Na^+ and k^+ content in selected plant species. Plant Soil Environ 65:90–96. https://doi.org/10.17221/620/2018-PSE
Hodisan T, Culea M, Cimpoiu C, Cot A (1998) Separation, identification and quantitative determination of free amino acids from plant extracts. J Pharm Biomed Anal 18(3):319–323. https://doi.org/10.1016/S0731-7085(98)00094-6
Holatko J, Hammerschmiedt T, Kintl A, Mustafa A, Naveed M, Baltazar T, Latal O, Skarpa P, Ryant P, Brtnicky M (2022) Co-composting of cattle manure with biochar and elemental sulphur and its effects on manure quality, plant biomass and microbiological characteristics of post-harvest soil. Front Plant Sci 13:1004879. https://doi.org/10.3389/fpls.2022.1004879
Holatko J, Hammerschmiedt T, Mustafa A, Kintl A, Skarpa P, Ryant P, Baltazar T, Malicek O, Latal O, Brtnicky M (2023) Time-dependent impact of co-matured manure with elemental sulfur and biochar on the soil agro-ecological properties and plant biomass. Sci Rep 13:4327. https://doi.org/10.1038/s41598-023-31348-7
Hosseinifard M, Stefaniak S, Javid MG, Soltani E, Wojtyla Ł, Garnczarska M (2022) Contribution of exogenous proline to abiotic stresses tolerance in plants: a review. Int J Mol Sci 23:5186. https://doi.org/10.3390/ijms23095186
Howladar SM, Semida W, Abd ElMageed TA, Kutby A, Howladar M (2025) Sulfur-enriched biochar soil amendment enhances tolerance to drought stress in faba bean (*Vicia faba* L.) under saline soil conditions. Egypt. J. Soil Sci. 65(1):275–290. https://doi.org/10.21608/ejss.2024.324682.1868
Huang K, Li M, Li R, Rasul F, Shahzad S, Wu C, Shao J, Huang G, Li R, Almari S, Hashem M, Aamer M (2023) Soil acidification and salinity: the importance of biochar application to agricultural soils. Front Plant Sci 14:1206820. https://doi.org/10.3389/fpls.2023.1206820
Hussaan M, Javed MT, Akram MS, Saleem MH, Chaudhary HJ (2022) Abiotic Stress in Plants and Metabolic Responses. Improvement of Plant Production in the Era of Climate Change. CRC, pp 123–151
Ibrahim E, Selim EM (2007) Effect of irrigation intervals and nitrogen fertilization rates on summer squash (*Cucurbita pepo* L.) growth, yield, nitrogen nutritional status and water use efficiency. J Plant Prod 32:10333–10346
Ibrahim AEA, Abd El Mageed T, Abohamid Y, Abdallah H, El-Saadony M, AbuQamar S, El-Tarabily K, Abdou NM (2022) Exogenously applied proline enhances morph-physiological responses and yield of drought-stressed maize plants grown under different irrigation systems. Front Plant Sci 13:1–11. https://doi.org/10.3389/fpls.2022.897027
Irigoyen JJ, Einerich DW, Sánchez-Díaz M (1992) Water stress induced changes in concentrations of proline and total soluble sugars in nodulated alfalfa (*Medicago sativa*) plants.Physiologia plantarum, 84 :55-60. https://doi.org/10.1111/j.1399-3054.1992.tb08764.x
Irshad I, Anwar-Ul-Haq M, Akhtar J, Maqsood M (2022) Effects of Different Organic Amendments on Maize (*Zea Mays* L.) Growth in Salt Affected Soil. J Glob Innov Agric Sci 10:121–130. https://doi.org/10.22194/JGIAS/10.998
Jackson ML Soil chemical analysis. Verlag: Prentice Hall, Inc., Cliffs E (1973) NJ. 1958, 498 S. DM 39.40
Jasim AH, Alryahii I, Abed HM, Badry AN (2015) Effect of some treatments on alleviating environmental stress on growth and yield of squash (*Cucurbita pepo* L). Mesop Environ J 1:67–74
Jien SH, Wang CC, Lee CH, Lee TY (2015) Stabilization of organic matter by biochar application in compost-amended soils with contrasting pH values and textures. Sustain 7:13317–13333. https://doi.org/10.3390/su71013317
Jin F, Ran C, Anwari Q, Geng Y, Guo L, Li J, Han D, Zhang X, Liu X, Shao X (2018) Effects of biochar on sodium ion accumulation, yield and quality of rice in saline-sodic soil of the west of songnen plain, Northeast China. Plant Soil Environ 64:612–618. https://doi.org/10.17221/359/2018-PSE
Klute A, Dirksen C (1986) Hydraulic conductivity and diffusivity: Laboratory methods. En: Methods of soil analysis: part 1; physical and mineralogical methods: 687–734
Lachica M, Aguilar A, Yanez J (1973) Plant analysis, 2: analytical methods used in the Estacion Experimental del Zaidin. Edafol y Agrobiol 32:1033–1047
Li S, Tasnady D (2023) Biochar for soil carbon sequestration: current knowledge, mechanisms, and future perspectives. C 9:67. https://doi.org/10.3390/c9030067
Liu H, Xiao C, Qiu T, Deng J, Cheng H, Cong X, Cheng S, Rao S, Zhang Y (2023a) Selenium Regulates Antioxidant, Photosynthesis, and Cell Permeability in Plants under Various Abiotic Stresses: A Review. Plants 12:44. https://doi.org/10.3390/plants12010044
Liu J, Zhang W, Long S, Zhao C (2021) Maintenance of cell wall integrity under high salinity. Int J Mol Sci 22:3260. https://doi.org/10.3390/ijms22063260
Liu M, Tan X, Zheng M, Yu D, Lin A, Liu J, Wang C, Gao Z, Cui J (2023b) Modified biochar/humic substance/fertiliser compound soil conditioner for highly efficient improvement of soil fertility and heavy metals remediation in acidic soils. J Environ Manage 325:116614. https://doi.org/10.1016/j.jenvman.2022.116614
Liu M, Zhu J, Yang X, Fu Q, Hu H, Huang Q (2022) Biochar produced from the straw of common crops simultaneously stabilizes soil organic matter and heavy metals. Sci Total Environ 828:1544954. https://doi.org/10.1016/j.scitotenv.2022.154494
Ma L, Liu X, Lv W, Yang Y (2022) Molecular mechanisms of plant responses to salt stress. Front Plant Sci 13:934877. https://doi.org/10.3389/fpls.2022.934877
Merwad ARMA (2020) Mitigation of salinity stress effects on growth, yield and nutrient uptake of wheat by application of organic extracts. Commun Soil Sci Plant Anal 51:1150–1160. https://doi.org/10.1080/00103624.2020.1751188

Mohammadi Alagoz S, Hadi H, Toorchi M, Pawłowski TA, Asgari Lajayer B, Price GW, Farooq M, Astatkie T (2023) Morpho-physiological responses and growth indices of triticale to drought and salt stresses. Sci Rep 13:8896. https://doi.org/10.1038/s41598-023-36119-y

Munir N, Hanif M, Abideen Z, Sohail M, El-Keblawy A, Radicetti E, Mancinelli R, Haider G (2022) Mechanisms and strategies of plant microbiome interactions to mitigate abiotic stresses. Agronomy 12:2069. https://doi.org/10.3390/agronomy12092069

Naseem A, Iqbal S, Jabeen K, Umar A, Alharbi K, Antar M, Grądecka-Jakubowska K, Gancarz M, Ali I (2023) Organic amendments improve salinity-induced osmotic and oxidative stress tolerance in Okra (*Abelmoschus esculentus* (L.)Moench). BMC Plant Biol 23:522

Nawaz M, Hassan MU, Chattha MU, Mahmood A, Shah AN, Hashem M, Alamri S, Batool M, Rasheed A, Thabit MA, Alhaithloul HAS, Qari SH (2022) Trehalose: a promising osmo-protectant against salinity stress—physiological and molecular mechanisms and future prospective. Mol Biol Rep 49:11255–11271. ttps://doi.org/10.1007/s11033-022-07681-x

Neina D (2019) The role of soil pH in plant nutrition and soil remediation. Appl Environ Soil Sci 2019:5794869. https://doi.org/10.1155/2019/5794869

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with NaHCO3. USDA Cir.939. U.S., Washington

Page AL (1982) Methods of soil analysis-Part 2: Chemical and Microbiological properties, vol 9, 2nd edition. Am Soc Agron Inc PublMadison, USA, p 1159

Pandian K, Vijayakumar S, Mustaffa MRAF, Subramanian P, Chitraputhirapillai S (2024) Biochar – a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: a review. Front Soil Sci 4:1–17. https://doi.org/10.3389/fsoil.2024.1376159

Peña Calzada K, Calero Hurtado A, Olivera Viciedo D, Habermann E, de Mello Prado R, de Oliveira R, Ajila G, Tenesaca LFL, Rodríguez JC, Gratão PL (2023) Regulatory role of silicon on growth, potassium uptake, ionic homeostasis, proline accumulation, and antioxidant capacity of soybean plants under salt stress. J Plant Growth Regul 42:4528–4540. https://doi.org/10.1007/s00344-023-10921-4

Ponce VM, Pandey RP, Ercan S (2000) Characterization of drought across climatic spectrum. J Hydrol Eng 5:222–224. ttps://doi.org/10.1061/(asce)1084-0699

Premachandra GS, Saneoka H, Ogata S (1990) Cell membrane stability, an indicator of drought tolerance, as affected by applied nitrogen in soyabean. J Agric Sci 115:63–66. https://doi.org/10.1017/S0021859600073925

Pungin A, Lartseva L, Loskutnikova V, Shakhov V, Popova E, Skrypnik L, Krol O (2023) Effect of salinity stress on phenolic compounds and antioxidant activity in halophytes *Spergularia marina* (L.) Griseb. and *Glaux maritima* L. cultured in vitro. Plants 12:1905. https://doi.org/10.3390/plants12091905

Rady MM, Desoky ES, Elrys AS, Boghdady MS (2019) Can licorice root extract be used as an effective natural biostimulant for salt-stressed common bean plants? S Afr J Bot 121:294–305. https://doi.org/10.1016/j.sajb.2018.11.019

Rashmi I, Kumawat A, Munawery A, Sreekumar Karthika K, Kumar Sharma G, Kala S, Pal R (2023) Soil Amendments: An Eco-friendly Approach for Soil Health Improvement and Sustainable Oilseed Production. In: Oilseed Crops - Uses, Biology and Production. IntechOpen. https://doi.org/10.5772/intechopen.106606

Rosen H (1957) A modified ninhydrin colorimetric analysis for amino acids. Arch Biochem Biophys 67:10–15. https://doi.org/10.1016/0003-9861(57)90241-2

Saddhe AA, Manuka R, Penna S (2021) Plant sugars: homeostasis and transport under abiotic stress in plants. Physiol Plant 171:739–755. https://doi.org/10.1111/ppl.13283

Sadegh-Zadeh F, Parichehreh M, Jalili B, Bahmanyar MA (2018) Rehabilitation of calcareous saline-sodic soil by means of biochars and acidified biochars. Land Degrad Dev 29(10):3262–3271. https://doi.org/10.1002/ldr.3079

Sahin O, Taskin MB, Kaya EC, Atakol O, Emir E, Inal A, Gunes A (2017) Effect of acid modification of biochar on nutrient availability and maize growth in a calcareous soil. Soil Use Manage 33:447–456. https://doi.org/10.1111/sum.12360

Sajjad N, Bhat EA, Shah D, Manzoor I, Noor W, Shah S, Hassan S, Ali R (2021) Nitrogen uptake, assimilation, and mobilization in plants under abiotic stress. Transporters Plant Osmotic Stress 215–233. https://doi.org/10.1016/B978-0-12-817958-1.00015-3

Salim BBM, Abou El-Yazied A, Salama YAM, Raza A, Osman HS (2021) Impact of silicon foliar application in enhancing antioxidants, growth, flowering and yield of squash plants under deficit irrigation conditions. Ann Agric Sci 66:176–18

Samaraweera H, Palansooriya KN, Dissanayaka PD, Khan AH, Sillanpää M, Mlsna T (2023) Sustainable phosphate removal using Mg/Ca-modified biochar hybrids: current trends and future outlooks. Case Stud Chem Environ Eng 8:100528. https://doi.org/10.1016/j.cscee.2023.100528

Shahid MA, Sarkhosh A, Khan N, Balal RM, Ali S, Rossi L, Gómez C, Mattson N, Nasim W, Garcia-Sanchez F (2020) Insights into the physiological and biochemical impacts of salt stress on plant growth and development. Agronomy 10:938. https://doi.org/10.3390/agronomy10070938

Sharma AK, Ghodke PK, Goyal N, Bobde P, Kwon EE, Lin KYA, Chen WH (2023) A critical review on biochar production from pine wastes, upgradation techniques, environmental sustainability, and challenges. Bioresour Technol 387:129632. https://doi.org/10.1016/j.biortech.2023.129632

Shen Z, Cheng X, Li X, Deng X, Dong X, Wang S, Pu X (2022a) Effects of silicon application on leaf structure and physiological characteristics of *Glycyrrhiza uralensis* Fisch. and *Glycyrrhiza inflata* Bat. under salt treatment. BMC Plant Biol 22:390

Shen Z, Pu X, Wang S, Dong X, Cheng X, Cheng M (2022b) Silicon improves ion homeostasis and growth of liquorice under salt stress by reducing plant Na^+ uptake. Sci Rep 12:5089. https://doi.org/10.1038/s41598-022-09061-8

Shunkao S, Thitisaksakul M, Pongdontri P, Theerakulpisut P (2022) Additive effects of combined heat and salt stress is manifested in an enhanced sodium ions accumulation and increased membrane damage in wheat seedlings. Chil J Agric Res 82:5089. https://doi.org/10.4067/S0718-58392022000400552

Singh H, Northup BK, Rice CW, Prasad PVV (2022a) Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar 4:8. ttps://doi.org/10.1007/s42773-022-00138-1

Singh P, Choudhary KK, Chaudhary N, Gupta S, Sahu M, Tejaswini B, Sarkar S (2022b) Salt stress resilience in plants mediated through osmolyte accumulation and its crosstalk mechanism with phytohormones. Front Plant Sci 13:1006617. ttps://doi.org/10.3389/fpls.2022.1006617

Singh Yadav SP, Bhandari S, Bhatta D, Poudel A, Bhattarai S, Yadav P, Ghimire N, Paudel P, Paudel P, Shrestha J, Oli B (2023) Biochar application: a sustainable approach to improve soil health. J Agric Food Res 11:100498. https://doi.org/10.1016/j.jafr.2023.100498

Somaddar U, Mim SK, Dey HC, Biswas A, Sarker UK, Uddin R, Saha G (2023) Assessment of seedling salinity tolerance of Bangladeshi coastal rice landraces using morpho-physiological stress indices. Emirates J Food Agric 35:153–161. https://doi.org/10.9755/ejfa.2023.v35.i2.3010

Stratil P, Klejdus B, Kubáň V (2006) Determination of total content of phenolic compounds and their antioxidant activity in vegetables - evaluation of spectrophotometric methods. J Agric Food Chem 54:607–616. https://doi.org/10.1021/jf052334j

Sun Z, Hu Y, Shi L, Li G, Pang Z, Liu S, Chen Y, Jia B (2022) Effects of biochar on soil chemical properties: a global meta-analysis of agricultural soil. Plant Soil Environ 68:272–289

Taheri Mal, Astaraei R, Lakzian AR, Emami A H (2024) The role of biochar and sulfur-modified biochar on soil water content, biochemical properties and millet crop under saline-sodic and calcareous soil. Plant Soil 499:221–236. ttps://doi.org/10.1007/s11104-023-05912-z

Tang C, Yang J, Xie W, Yao R, Wang X (2023) Effect of biochar application on soil fertility, nitrogen use efficiency and balance in coastal salt-affected soil under barley–maize rotation. Sustainability 15:2893. https://doi.org/10.3390/su15042893

Tedeschi A, Schillaci M, Balestrini R (2023) Mitigating the impact of soil salinity: recent developments and future strategies. Ital J Agron 18:2173. https://doi.org/10.4081/ija.2023.2173

Tomczyk A, Sokołowska Z, Boguta P (2020) Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Biotechnol 19:191–215. https://doi.org/10.1007/s11157-020-09523-3

Urano D, Colaneri A, Jones AM (2014) Gα modulates salt-induced cellular senescence and cell division in rice and maize. J Exp Bot 65:6553–6561. https://doi.org/10.1093/jxb/eru372

Vernon LP (1960) Spectrophotometric determination of chlorophylls and pheophytins in plant extracts-corrections. Anal Chem 32:1414. https://doi.org/10.1021/ac60167a041

Wang X, Ding J, Han L, Tan J, Ge X, Nan Q (2024) Biochar addition reduces salinity in salt-affected soils with no impact on soil pH: a meta-analysis. Geoderma 443:116845. https://doi.org/10.1016/j.geoderma.2024.116845

Wolf B (1982) A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. Commun Soil Sci Plant Anal 13:1035–1059. https://doi.org/10.1080/00103628209367332

Younes NA, Rahman MM, Wardany AA, Dawood MFA, Mostofa MG, Keya SS, Latef AAHA, Tran LSP (2021) Antioxidants and bioactive compounds in licorice root extract potentially contribute to improving growth, bulb quality and yield of onion (*Allium cepa*). Molecules 26:2633. https://doi.org/10.3390/molecules26092633

Youssef EAE, Abdelbaset MM, El-Shafie AF (2025) Impact of licorice extract foliar application on some growth and yield parameters on wheat grown under water stress conditions. Egypt J Agron 47(1):133–143

Yu Z, Ren Y, Liu J, Zhu JK, Zhao C (2022) A novel mitochondrial protein is required for cell wall integrity, auxin accumulation and root elongation in Arabidopsis under salt stress. Stress Biol 2:13. https://doi.org/10.1007/s44154-022-00036-3

Zakaria MR, Ahmad Farid MA, Andou Y, Ramli I, Hassan MA (2023) Production of biochar and activated carbon from oil palm biomass: current status, prospects, and challenges. Ind Crops Prod 199:16767. https://doi.org/10.1016/j.indcrop.2023.116767

Zhang J, Shen JL (2022) Effects of biochar on soil microbial diversity and community structure in clay soil. Ann Microbiol 72(1):35. https://doi.org/10.1186/s13213-022-01689-1

Zhang H, Voroney RP, Price GW, White AJ (2017) Sulfur-enriched biochar as a potential soil amendment and fertiliser. Soil Res 55(1):93–99. https://doi.org/10.1071/SR15256

Zhao C, Zhang H, Song C, Zhu JK, Shabala S (2020) Mechanisms of plant responses and adaptation to soil salinity. Innovation 1:100017. https://doi.org/10.1016/j.xinn.2020.100017

Zheng Y, Han X, Li Y, Yang J, Li N, An N (2019) Effects of biochar and straw application on the physicochemical and biological properties of paddy soils in Northeast China. Sci Rep 9:16531. ttps://doi.org/10.1038/s41598-019-52978-w

Zhou H, Shi H, Yang Y, Feng X, Chen X, Xiao F, Lin H, Guo Y (2024) Insights into plant salt stress signaling and tolerance. J Genet Genomics 51:16–34. https://doi.org/10.1016/j.jgg.2023.08.007

Zulfiqar F, Casadesús A, Brockman H, Munné-Bosch S (2020) An overview of plant-based natural biostimulants for sustainable horticulture with a particular focus on moringa leaf extracts. Plant Sci 295:110194. https://doi.org/10.1016/j.plantsci.2019.110194

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.