



Compost-mixed Biochar Improves Saline Soil Properties and Enhances *Brassica Oleracea* var. *Capitata* physio-biochemical Responses

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Abstract

The present research aimed to correlate changes in saline soil properties and cabbage agro-physiological attributes under compost-biochar co-application. The treatments used prior to cabbage cultivation were soil applications of compost/biochar mixture (CMB) at rates of 0 (CMB₀), 10 (CMB₁₀), and 20 (CMB₂₀) t ha⁻¹ in a randomized complete block design with three replications. The CMB₂₀ was the effective practice for reducing dry bulk density, saturated hydraulic conductivity, pH, and electrical conductivity, while improving total porosity, water-holding pores, soil moisture at field capacity, organic matter, cation exchange capacity, and nutrient availability. CMB₂₀ also improved plant relative water content, membrane stability index, and chlorophyll *a* and *b* concentrations. Hydrogen peroxide and malondialdehyde decreased by 13.5% each under CMB₂₀ treatment. Cabbage plants grown in saline soil produced greater phenolics content (56.0%) with higher superoxide dismutase (17.2%) activity in CMB₂₀-treated plots than CMB₀. Leaf nitrogen, phosphorus, and potassium contents enhanced by 10.1, 28.1, and 18.4%, respectively, compared with CMB₀. Finally, CMB₂₀ achieved the maximal improvements in leaf number plant⁻¹ (41.8%), leaf area plant⁻¹ (216.2%), above-ground biomass (174.5%), head circumference (38.2%) and marketable yield (101.6%) of cabbage. It could be concluded that amending saline soil with CMB is regarded as a promising treatment for alleviating the salinity hazards on cabbage via modulating soil properties and physiological responses. Hence, CMB application, 20 t ha⁻¹, can be recommended as an agronomic practice for cabbage production to obtain high yield and quality.

Keywords Anti-salt defense · Cabbage physiology · Composting · Pyrolysis · Soil reaction

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1 Introduction

According to the sustainable development goals, ensuring global food and nutrition security remains a critical challenge. Therefore, the exploitation of marginal lands, including saline soils, is considered an adaptive strategy to climate change (Abd El Mageed et al. 2025; Ramadan et al. 2025a; Saady et al. 2025a). Global food demand is projected to increase by more than 45.5% by 2050 due to rapid population growth (UNDESA 2024). Cabbage (*Brassica oleracea* L. var. *capitata*), a widely cultivated leafy vegetable, represents an important crop for human diets (Adeniji et al. 2010). Its heads are the economic part consumed fresh or processed, and the leaves are rich in B-complex vitamins, potassium, and calcium (Singh et al. 2006). Because cabbage leaves have a high moisture content, its cultivation in saline soils often results in considerable yield and quality losses (Deveci and Tuğcu 2017).

Saline soils are characterized by low organic matter (OM) and elevated pH, both of which reduce nutrient availability (Saady et al. 2023, 2025b; Shaaban et al. 2023). Poor soil health, reduced water-holding capacity, and limited nutrient acquisition are major constraints to crop cultivation in saline soils, especially in arid climates (Mekdad et al. 2021; Salem et al. 2021; Shaaban et al. 2025a; Saady et al. 2025b). Consequently, plants grown in saline soils suffer from each of osmotic stress and physiological drought (Mahfouz et al. 2020; Lasheen et al. 2024; Emam et al. 2025; Ramadan et al. 2025b), leading to significant reductions in growth, yield, and quality (El Sherbiny et al. 2022; Desoky et al. 2025). Thus, effective soil amendments are urgently needed to restore productivity (El-Hashash et al. 2022; Ali et al. 2024a).

Recently, converting agricultural wastes into biochar has gained attention as a sustainable soil amendment (El-Bially et al. 2023). One of the promising recycling processes that could be utilized for sustaining soil fertility is the pyrolysis of agricultural wastes to obtain biochar (Zhang et al. 2019). By pyrolysis of wastes at a temperature of 300–600 °C, biochar is produced (Semida et al. 2019). As a stable substance with unique physico-chemical properties, biochar is an effective tool for improving soil fertility, ameliorating stress tolerance, and increasing crop productivity (Saady et al. 2021, 2022). Physically, biochar can stabilize soil aggregates and retain soil water, thus overcoming deficiency of moisture availability that occurs in salt-affected soils (Wang et al. 2023). Chemically, biochar has a high concentration of essential nutrients required to support plant growth (Okebalama and Marschner 2023). Owing to its high capacity for exchanging cations, biochar can substantially enhance nutrient retention in saline soils (Duan et al. 2023). Further, biochar addition to soils promotes the biota activity and nutrient uptake, enhancing soil health and crop productivity (Zhang et al. 2024). However, biochar is commonly alkaline, raising soil pH (Fidel et al. 2017; Mosharrof et al. 2021); this is unfavorable in arid soils that have high pH (Mubarak et al. 2021).

Since organic fertilizers provide stabilized availability of various plant nutrients while enhancing soil biological and physico-chemical characteristics, crop yield and its quality were improved (Abd El-Mageed, et al., 2022; Abd-Elrahman et al. 2022; Sheha et al. 2023). Compost, a microbial decomposed organic material, is another amendment that enhances soil fertility and structure while providing readily available nutrients (Diacono and Montemurro 2011; Siedt et al. 2021). Compost application can modify soil properties via increasing OM content, nutrient status, aeration, and bulk density, leading to better crop yields (Mekdad et al. 2022; Youssef et al. 2023; Shaaban et al. 2024).

Based on their potential features, the integrated use of biochar and compost may overcome the limitations of each amendment when used alone. Herein, the combined application of biochar and organic fertilizers together in arable croplands could provide significant ecological benefits (Saady et al. 2021). Biochar can stimulate the microbial activity and improve the various properties in compost (Khan et al. 2020). Further, incorporating biochar into composting had beneficial effects on carbon (C) sequestration and pesticide absorption (Siedt et al. 2021). Biochar and organic fertilizer applications effectively regulate C, nitrogen (N), potassium (K^+), and phosphorus (P) cycles via enhancing the abundance of beneficial microbes in soil (Hu et al. 2024).

Soil salinization currently threatens more than 20% of global irrigated lands and impairs soil structure, nutrient availability, crop productivity, and challenging sustainable agriculture (FAO 2021). Although compost or biochar alone have been reported to improve saline soil quality by enhancing OM, cation exchange capacity (CEC), and water retention (Bello et al. 2023; Huang et al. 2025), each amendment has intrinsic limitations, biochar may elevate soil pH and release nutrients slowly, whereas compost decomposes rapidly and provides only short-term benefits. The present study addresses this gap by evaluating a CMB applied at three rates, under the hypothesis that CMB would synergistically integrate the rapid nutrient release of compost with the long-term structural and buffering capacity of biochar. This integration is expected to improve saline soil health, enhance cabbage physiological tolerance to salt stress, and ultimately increase marketable cabbage productivity under field conditions.

2 Materials and methods

2.1 Trial Conditions

The field trials were implemented in newly reclaimed soils, for two autumn seasons of 2022 and 2023 in the experimental station of Agriculture College (29° 17' 36.4" N and 30° 55' 1.6" E), Fayoum, Egypt. The experimental area's climate is arid as per Ponce et al. (2000) aridity index. The soil at the study site had sandy loam texture, with a saturated electrical conductivity (EC_e) of 6.25 dS m^{-1} measured at a 0–0.3 m depth. As described by Klute (1986), soil physical properties were measured. On average over both cropping seasons, the dry bulk density (DBD in g cm^{-3}), hydraulic conductivity (K_{sat} in cm h^{-1}), total porosity (TP%), and water holding pores (WHP%) of the experimental soil were 1.67, 2.15, 41.20 and 12.01, respectively, in a 0–0.3 m depth. At the same soil depth, the moisture constants (e.g., field capacity and wilting point) averaged 23.75% and 13.68%,

respectively. The soil chemical properties were measured following the methods outlined in Page (1982). Specifically, soil pH (1:2.5 soil-to-water (w/v) extract ratio), OM content (Walkley and Black 1934), CEC and CaCO_3 quantified to 7.85, 0.68, 9.88 and 4.20, respectively.

2.2 Preparation of Compost Mixed Biochar (CMB)

Compost, as an amendment in this study, is a decomposed organic substance resulting from locally sourced plant-based materials (e.g., cabbage waste, animal dung, and cereal straw) that underwent a controlled three-month aerobic decomposition operation with fortnightly turning to maintain thermophilic conditions and microbial succession. Maturity was confirmed by a stabilized C/N ratio of 20.3:1, thermal balance (ambient $\pm 2^\circ\text{C}$), and key physical indicators (e.g., dark brown coloration, earthy odor, crumbly texture, and lack of phytotoxic effects in seed germination tests), collectively indicating humification and efficient N preservation. The biochar amendment utilized in this study is produced through a slow pyrolysis process, where mixed of woody biomass (e.g., acacia/pruning residues) and plant wastes are pyrolyzed in oxygen-deprived conditions or with very limited oxygen at 600–700 $^\circ\text{C}$ for ~ 2 h. Acacia species are preferred for biochar production because they are abundantly available as by-products of pruning practices, fast-growing, yield high biomass, and provide a low-cost source of lignocellulosic feedstock. Acacia's biochar is characterized by its high surface area, high "C" content, and good CEC, is particularly suitable as a soil amendment for improving its structure, nutrient retention, and crop productivity under saline conditions. The CMB was prepared by combining compost and biochar at a 1:1 weight ratio. This ratio was selected to optimize nutrient availability (via compost) and structural stability (via biochar), following previous recommendations for saline soils (McDonald, et al., 2019; Shaaban et al. 2024). The components were thoroughly blended for 15 min using a mechanical mixer and subsequently kept in sealed containers for a week before application to promote preliminary interaction. Some basic properties of the CMB and their main ingredients (i.e., compost and biochar) used in this experiment are given in Table 1.

2.3 Experimental setup, treatments, and Agronomic Details

The on-farm experiment was designed as a randomized complete block design replicated three times during the 2022 and 2023 cropping seasons. Thirty-day-old white cabbage (*Brassica oleracea* var. capitata cv. O.SS Cross) seedlings, with four true leaves, were provided by the Ministry

Table 1 Characteristics of compost Biochar and their combination (CMB) used in salt-affected soil of cabbage

Characteristic	Unit	Compost	Biochar	CMB
Soil reaction	--	7.75 $\pm$ 1.12	8.20 $\pm$ 1.0	7.85 $\pm$ 0.98
EC_e in paste extract	(dS m^{-1})	2.98 $\pm$ 0.9	4.20 $\pm$ 1.1	3.10 $\pm$ 1.2
CaCO_3	(%)	3.50 $\pm$ 0.7	3.00 $\pm$ 6.0	3.00 $\pm$ 0.8
CEC	(cmole kg^{-1})	22.00 $\pm$ 1.3	23.50 $\pm$ 1.4	22.80 $\pm$ 1.0
Moisture content	(%)	38.50 $\pm$ 2.1	25.10 $\pm$ 1.8	32.80 $\pm$ 2.3
DBD	(g cm^{-3})	0.80 $\pm$ 0.08	0.95 $\pm$ 0.06	0.85 $\pm$ 0.07
Organic matter	(%)	45.76 $\pm$ 3.2	48.50 $\pm$ 3.4	47.10 $\pm$ 3.9
Organic carbon	(%)	32.48 $\pm$ 2.7	28.20 $\pm$ 3.1	29.38 $\pm$ 2.8
Total nitrogen	(%)	1.60 $\pm$ 0.2	1.05 $\pm$ 0.2	1.32 $\pm$ 0.3
Total phosphorus	(g kg^{-1})	5.20 $\pm$ 0.3	10.40 $\pm$ 0.6	7.95 $\pm$ 0.5
Total potassium	(g kg^{-1})	3.82 $\pm$ 0.4	4.65 $\pm$ 0.4	4.25 $\pm$ 0.5

EC_e = electrical conductivity of soil extract, CaCO_3 = calcium carbonate. Means $\pm$ standard error of three replicates of each material are presented. CEC = cation exchange capacity, DBD = dry bulk density

of Agriculture nursery in El-Azab and transplanted at 0.5 m apart in 1 m width and 5 m length-raised beds. Each experimental plot area was 25 m^2 net area (5 m length $\times$ 5 m width) including five planting raised beds. The CMB was manually incorporated into 0–20 cm topsoil layer one week prior to transplanting cabbage seedlings with three rates, i.e., non-amended soil (CMB_0), adding 10 t CMB ha^{-1} (CMB_{10}), and adding 20 t CMB ha^{-1} (CMB_{20}). The drip irrigation system was used with one drip line per raised bed ($\varnothing = 16$ mm) supplied by drippers spaced at 0.25 m with 3.5 L h^{-1} flow rate at 0.15 MPa working pressure with a 0.45 dS m^{-1} irrigation water salinity.

White cabbage seedlings were manually transplanted on September 15, and harvested on December 15, 2022, and September 20, and harvested on December 20, 2023. White cabbage plants received N, P, and K^+ fertilizers as 120 kg N, 50 kg P_2O_5 and 100 kg K_2O by applying 260 kg urea $\text{CO}(\text{NH}_2)_2 \text{ ha}^{-1}$ (46% N), 325 kg single superphosphate $\text{CaP}_2\text{H}_4\text{O}_8 \text{ ha}^{-1}$ (15.5% P_2O_5), and 210 kg potassium sulfate $\text{K}_2\text{SO}_4 \text{ ha}^{-1}$ (48% K_2O), respectively.

2.4 Metrics

2.4.1 Edaphic Properties

Initial samples of soil were collected from the experimental field from 0 to 30 cm surface topsoil layer and repeated after the end of the experiment. Soil physical measurements, i.e., DBD, K_{sat} , TP, WHP and soil moisture at field capacity (θ_{Fc}) were conducted according to Klute (1986) and Jury and Horton (2004) procedures. The measurements and calculations of soil chemical properties, namely pH, EC_e , OM, CEC, soil N, soil P, and soil K^+ were carried out using the Page et al.'s (1982) techniques.

2.4.2 Plant Sample collection, measurements, and Calculations

When cabbage heads reached 20–30% of their expected final size (corresponding to the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) growth stage of 42/43, 5 guarded cabbage plants were sampled randomly per treatment plot to assess key physio-biochemical attributes, leaf nutrient content and growth indices of cabbage.

2.4.2.1 Plant hydro-status and Photosynthetic Pigments The fourth fully expanded cabbage leaf from the apex were collected per plant to measure leaf tissue hydro-status, i.e., leaf tissue relative water content; RWC% (Premachandra et al. 1990) and cellular membrane stability index; MSI% (Hayat et al. 2012). The fresh leaf disc weight (DFW) was immediately weighed. The leaf discs were then soaked for 24 h at 25 °C to in distilled water (D-H₂O) allow them to become fully turgid. The adhered water on the leaf discs was removed by blotting with absorbent paper towels and weighted to obtain turgid leaf disc weight of (DTW). The leaf discs were then air-forced oven dehydrated at 80 °C for 48 h until obtained constant weight (DDW). The RWC% of leaf tissue in three replications was calculated as follows:

$$\text{RWC (\%)} = \frac{(\text{DFW} - \text{DDW})}{(\text{DTW} - \text{DDW})} \times 100$$

Avoiding margins and leaf midribs, 0.2 g young tissue was immersed in a tube containing 10 mL of D-H₂O and heated at 40 °C in Memmert WTB24 water bath (Aeussere Rittersbacher Strasse, Germany) for 10 min and then cooled (~25 °C) for measuring initial electrical conductivity (EC_a). Then the sample tubes were capped, returned to the water bath again, and boiled for 10 min and then cooled to ~25 °C to measure the final electrical conductivity (EC_b). The cellular MSI% in three replications was calculated as follows:

$$\text{MSI (\%)} = 1 - \frac{\text{EC}_a}{\text{EC}_b} \times 100$$

Chlorophyll *a* and chlorophyll *b* concentrations (mg cm⁻²) in fully expanded cabbage leaves were quantified using *N,N*-dimethylformamide (DMF) as dissolver (Lichtenthaler and Buschmann 2001).

2.4.2.2 Oxidative Stress Biomarkers The amount of hydrogen peroxide (H₂O₂ in μmol g⁻¹ fresh weight FW) in fully expanded young leaves was quantified per the Velikova et al.

(2000) method. For homogeneity a 0.20 g of fresh leaf was mixed with 1.0 mL of a cold extraction solution that contained 1 mM ethylenediaminetetraacetic acid and 25 mM K₃PO₄ buffer with a pH of 7.0. The supernatant acquired after centrifugation at 15,000×g for ¼ h at 4 °C was used for the H₂O₂ assay. The absorbance was scaled spectrophotometrically at 410 nm and versus a standard curve of H₂O₂ to obtain the H₂O₂ concentration.

To determine the lipid peroxidation extent, the same homogenate as per Dhindsa et al. (1981) technique was used to determine the malondialdehyde (MDA in nmol g⁻¹ FW) content. Briefly, 1 mL of the homogenate was mixed with 4 mL of freshly prepared solution containing 0.5% (w/v) thiobarbituric acid and 20% (w/v) trichloroacetic acid (TCA). The samples were then incubated at 90 °C for ½ h, and the reaction was abruptly halted by freezing the sample. Absorbance at wavelengths of 440 nm and 532 nm was spectrophotometrically measured using a following a further centrifugation round at 4000×g for 15 min, and to correct for non-specific turbidity, the absorbance at 600 nm was subtracted. The equivalent MDA in three replications was calculated:

$$\text{MDA} = \frac{[(\text{Absorbance at } 532 - \text{Absorbance at } 600) - 0.05714 (\text{Absorbance at } 440 - \text{Absorbance at } 600)]}{(0.157 \times \text{sample FW})}$$

The total soluble sugars content (TSSs in mg g⁻¹ on a dried leaf weight basis; DW) was determined using the anthrone-H₂SO₄ colorimetry as described in Fales (1951) method. Total phenolics (TPhCs in mg g⁻¹ dryweight; DW) were quantified following the Kähkönen et al. (1999) method. The activity of superoxide dismutase (SOD in U min⁻¹ mg⁻¹ protein; EC 1.15.1.1) was gauged based on Beyer and Fridovich (1987) method. One unit of SOD activity was defined as the enzyme amount required to achieve a 50% inhibition of NBT reduction at 25 °C.

2.4.2.3 Leaf Mineral Nutrients The cabbage leaf samples, which were dried in a thermostatic oven at 80 °C until a stable weight, were ground. After the completion of wet-digestion in a flask containing 10 mL of (1:3, v/v) HClO₄-H₂SO₄ mixture on a digester block at 300–350 °C until colorless, the 0.2 g digestate mixture was completed to 100 mL using D-H₂O and then filtered. Using the 0.2 g digestate cabbage leaf solution, the total N content was determined using the classical micro-Kjeldahl technique as outlined in AOAC (1990). The P content was colorimetrically assessed as per the molybdenum blue-ascorbic acid technique (Murphy and Riley 1962) at 882 nm. The cations, i.e., sodium (Na⁺) and K⁺ content in cabbage leaves were measured using a PFP7

flame photometer (Jenway, Staffordshire, United Kingdom) as described by Wolf (1982).

2.4.2.4 Agronomic Attributes Concerning the growth indices, the sampled cabbage plants were immediately transported to the laboratory for counting the leaves number/plant. Plant leaf area (dm^2) was measured using the relationship of leaf area leaf weight as demonstrated by Wallace and Munger (1966) with some modifications. The outer surface of fully expanded leaf was thoroughly washed in running tap water, thereafter 10–20 circle leaf disks measuring 10–20 cm^2 in area were taken and dried in a forced-air oven at 80 °C until a stable weight to get disks dry weight (DDW in g). The total plant leaf area was calculated as follows:

$$\text{Plant leaf area (dm}^2\text{)} = \frac{(\text{LDW/DDW}) \times \text{DA}}{100}$$

where LDW is the total leaf dry weight (g) and DA is the discs area in cm^2 . The cabbage plants were divided into leaves and stems to determine their dry weights (leaves DW and stem DW in g) using an electronic balance after drying at 80 °C in a forced-air oven until a constant weight was reached, which took approximately 7 days. The above-ground biomass dry weight (AGB-DW in g) of the plant was calculated by totalizing the dry weights of leaves and stems.

At the harvesting (80–100% of the expected head size reached, BBCH 48/49) date, 10 cabbage heads per plot, randomly sampled, were cut early in the morning and instantly transported to the laboratory to measure the head circumference (cm) using a meter scale. All the compacted cabbage heads (marketable yield) in each plot were cut in addition to the weight of the 10 previously sampled heads, excluding unfolded leaves, to determine the marketable yield per plot, which was then converted into kg per hectare (kg ha^{-1}).

2.5 Economic Evaluation

Following the approach of Cimmyt (1988), the economic analysis was carried out by estimating the cultivation expenses associated with various agricultural inputs,

including labor, fertilizers, irrigation, insect control, harvesting, and other fundamental experimental necessities. The gross returns of each tested treatment were then calculated ($\text{\$ ha}^{-1}$) according to the average local market value ($\text{\$120}$ per ton of marketable cabbage yield) across the 2022 and 2023 growing seasons, as follows:

$$\begin{aligned} \text{Gross returns} &= \text{Marketable yield (t ha}^{-1}\text{)} \times \text{Price per ton of (}\text{\$ ha}^{-1}\text{)} \\ &\text{marketable yield (\$)} \\ \text{Net return} &= \text{Gross returns} - \text{Total cost} \quad (\text{\$ ha}^{-1}) \\ \text{Benefit/Cost ratio} &= \frac{\text{Gross return}}{\text{Total cost}} \end{aligned}$$

2.6 Statistical Analysis

The collected data during the two experimental seasons were analyzed according to analysis of variance (ANOVA) procedures using version 2020 INFOSTAT statistical package. Each data set at significance level ≤ 0.05 was subjected to the Shapiro-Wilk's (Shapiro and Wilk 1965) test before ANOVA to determine if the data exhibited a normal distribution. Moreover, the homoscedasticity assumption for both seasons was verified by Levene (1960) test (Supplementary Tables S1). Once these assumptions were statistically validated, a cross-season ANOVA was employed (Gomez and Gomez 1984) to analyze CMB's effect, considering CMB as a fixed effect, while replications and experimental seasons had random effects (Supplementary Tables S2-S4). The treatment means were then separated using the Duncan's test with a 5% significance level. For the Principle component analysis (PCA) and Pearson's correlation (r) among the measured attributes, R software (version 4.0.2) was used.

3 Results

3.1 Alterations in Soil Features

3.1.1 Physical Traits

Significant effect of compost mixed biochar (CMB) on soil physical properties after cabbage harvesting was observed (Table 2). The DBD and K_{sat} were decreased

Table 2 Effect of compost mixed Biochar (CMB) on some soil physical properties at the end of experiment

CMB rate (t ha^{-1})	DBD (g cm^{-3})	K_{sat} (cm h^{-1})	TP (%)	WHP	θ_{Fc}
0 (CMB ₀)	1.66 ± 0.01a	2.90 ± 0.02a	42.6 ± 0.19c	12.1 ± 0.08c	26.0 ± 0.06c
10 (CMB ₁₀)	1.56 ± 0.01b	2.49 ± 0.03b	45.5 ± 0.20b	13.8 ± 0.03b	27.9 ± 0.10b
20 (CMB ₂₀)	1.43 ± 0.01c	1.78 ± 0.06c	48.2 ± 0.20a	14.5 ± 0.09a	29.3 ± 0.13a

DBD=dry bulk density, K_{sat} =saturated hydraulic conductivity, TP=total porosity, WHP=water holding pores, and θ_{Fc} =soil moisture at field capacity. Means ± standard error of three replicates of each treatment are presented. According to Duncan's test, the averages in each column followed by the same letters indicate non-significantly at $p \leq 5\%$

Table 3 Effect of compost mixed Biochar (CMB) on some soil chemical properties at the end of experiment

CMB rate (t ha ⁻¹)	pH	EC _e (dS m ⁻¹)	OM (%)	CEC (cmol kg ⁻¹)	Available element (mg kg ⁻¹)		
					N	P	K ⁺
0 (CMB ₀)	7.76±0.02a	4.13±0.03a	1.17±0.17b	10.1±1.03c	19.8±0.17c	4.33±0.04c	52.0±0.21c
10 (CMB ₁₀)	7.63±0.02b	3.81±0.03a	1.46±0.13b	13.6±0.74b	22.0±0.12b	4.70±0.01b	54.4±0.24b
20 (CMB ₂₀)	7.47±0.03c	2.10±0.04c	1.93±0.10a	15.7±0.45a	24.7±0.48a	5.76±0.19a	58.2±0.23a

pH=soil reaction, EC_e = electrical conductivity of soil extract, OM=organic matter, CEC=cation exchange capacity, N=nitrogen, P=phosphorus, K⁺= potassium. Means±standard error of three replicates of each treatment are presented. According to Duncan's test, the averages in each column followed by the same letters indicate non-significantly at $p \leq 5\%$

while the TP, WHP, and soil moisture at field capacity increased with application of CMB. In this respect, CMB₂₀ treatment significantly reduced DBD by 13.9% and K_{sat} by 38.6% while increasing TP, WHP, and soil moisture at field capacity by 13.1, 19.8, and 12.7%, respectively relative to CMB₀.

3.1.2 Chemical Traits

All assessed soil chemical properties after cabbage harvesting significantly influenced by CMB application (Table 3). Un-amended soil (CMB₀) exhibited the highest pH (7.76) and EC_e (4.13 dS m⁻¹), whereas CMB₂₀ reduced these properties by 3.7% and 49.2%, respectively (Table 3). There was no significant variation in EC_e between CMB₁₀ and CMB₀ treatments. On the other hand, the maximal values of OM, CEC, soil N, soil P, and soil K⁺ contents were recorded with application of CMB₂₀ outperformed CMB₀ by about 65.0, 55.5, 24.7, 33.0, and 11.9%, respectively. CMB₁₀ ranked second, surpassing CMB₀ by approximately 24.8, 34.7, 11.1, 8.5, and 4.6%, respectively.

3.2 Changes in Cabbage Physiological Performance

3.2.1 Water status, Membrane Stability and Chlorophylls of Leaves

The water status, as indicated by RWC and MSI (Fig. 1A and B), and chlorophylls in terms of chlorophyll *a* and chlorophyll *b* (Fig. 2A and B) of cabbage leaf substantially responded to CMB application. CMB supply maintained leaf water content, stability of membrane and chlorophylls of cabbage grown in saline soil. In this context, CMB₂₀ treatment exhibited the best improvements in RWC, MSI, chlorophyll *a* and chlorophyll *b* which amounted to 11.9, 17.7, 34.8 and 23.6% increases, respectively, higher than the control treatment (CMB₀).

3.2.2 Hydrogen peroxide, Malondialdehyde and Total Soluble Sugars Accumulation

As depicted in Fig. 3A-C, hydrogen peroxide (H₂O₂) and malondialdehyde (MDA) decreased and total soluble sugars

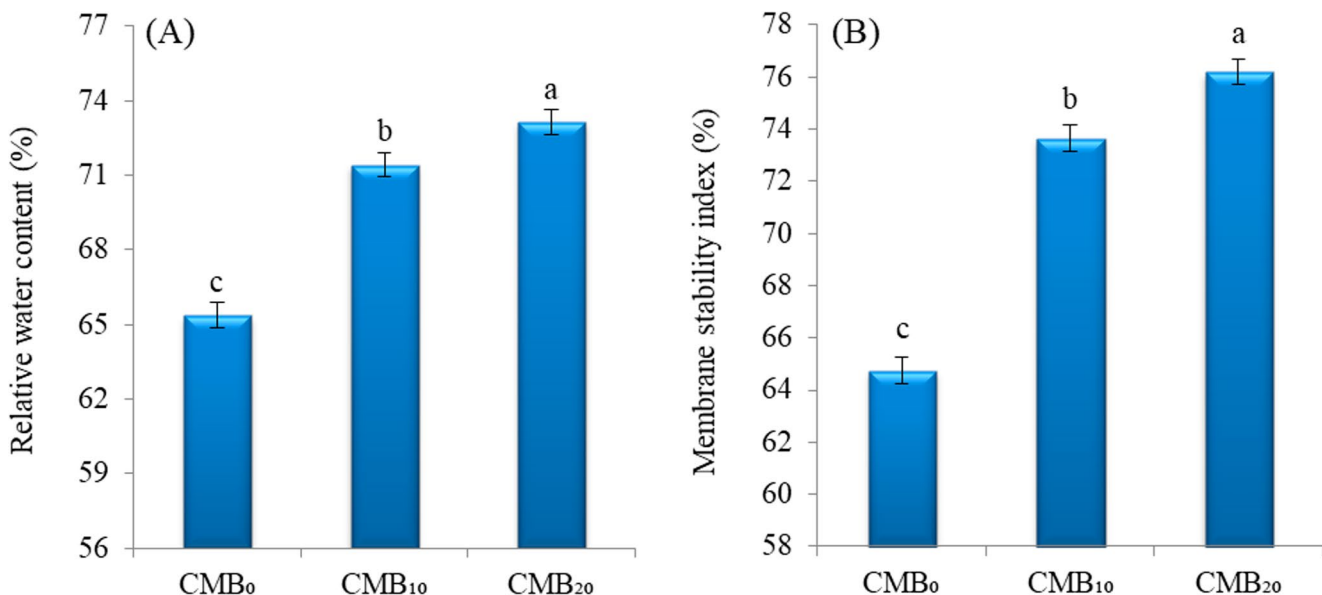


Fig. 1 Effect of compost mixed biochar (CMB) rate on relative water content (A) and membrane stability index (B) of white cabbage plant grown under saline soil conditions. CMB₀, CMB₁₀ and CMB₂₀=0, 10 and 20 t ha⁻¹ compost/biochar mixture, respectively. Means±standard

error of three replicates of each treatment are presented. According to Duncan's test, the means in each bars followed by different lower-case letters differ significantly at $p \leq 5\%$

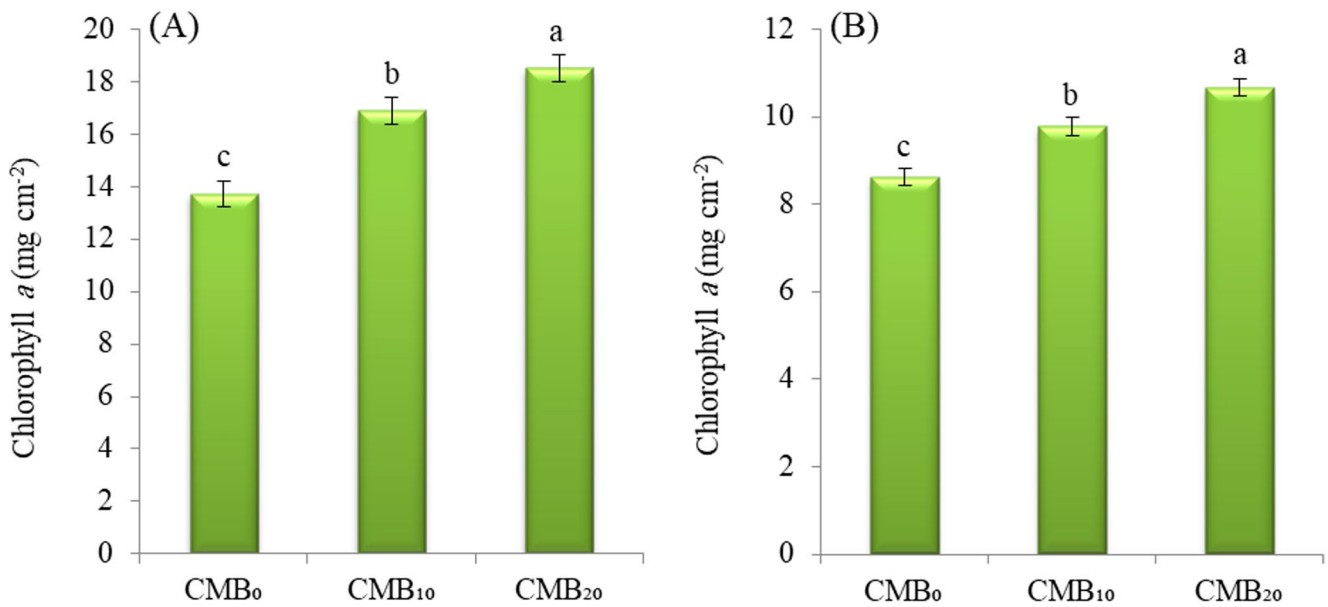


Fig. 2 Effect of compost mixed biochar (CMB) rate on chlorophyll *a* (A) and chlorophyll *b* (B) of white cabbage plant grown under saline soil conditions. CMB₀, CMB₁₀ and CMB₂₀=0, 10 and 20 t ha⁻¹ compost/biochar mixture, respectively. Means±standard error of three rep-

licates of each treatment are presented. According to Duncan's test, the means in each bars followed by different lower-case letters differ significantly at $p \leq 5\%$

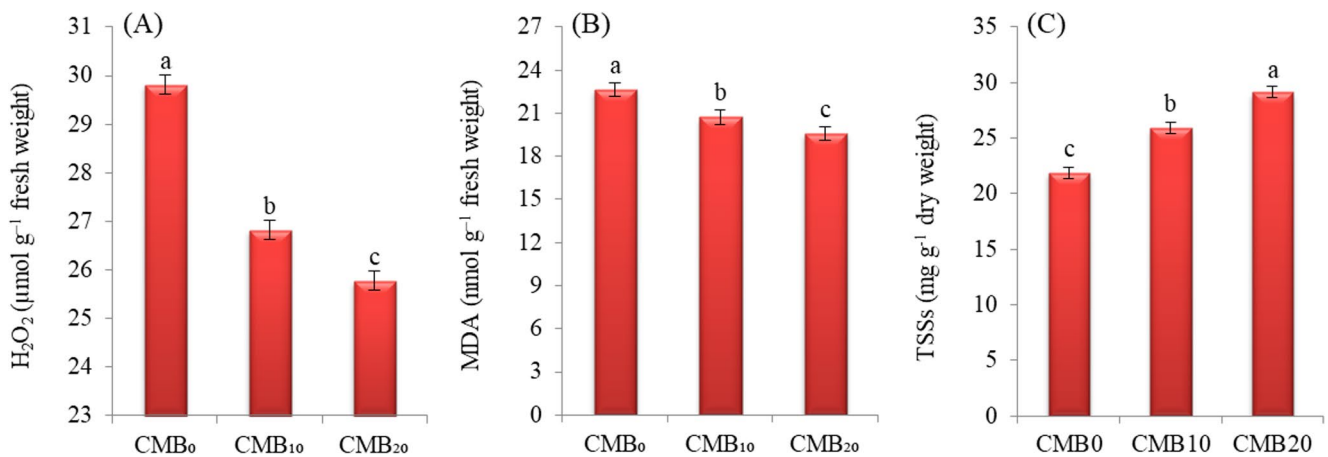


Fig. 3 Effect of compost mixed biochar (CMB) rate on hydrogen peroxide, H₂O₂ (A), malondialdehyde MDA, (B) and total soluble sugars, TSSs (C) of white cabbage plant grown under saline soil conditions. CMB₀, CMB₁₀ and CMB₂₀=0, 10 and 20 t ha⁻¹ compost/biochar mix-

ture, respectively. Means±standard error of three replicates of each treatment are presented. According to Duncan's test, the means in each bars followed by different lower-case letters differ significantly at $p \leq 5\%$

(TSSs) increased as CMB rate increased. The H₂O₂ and MDA levels in CMB-untreated cabbage soil were 29.81 and 22.65 μmol g⁻¹ FW which decreased to be 26.82 and 20.74 μmol g⁻¹ FW with application of CMB₁₀ and 25.78 and 19.59 μmol g⁻¹ FW with application of CMB₂₀ by reduction percentages of 10.0% and 8.4% (for CMB₁₀) and 13.5% and 13.5% (for CMB₂₀), respectively. On the contrary, the increases in TSSs reached 18.1 and 33.0% with application of CMB₁₀ and CMB₂₀, respectively, compared to CMB₀.

3.2.3 Total Phenolics and Superoxide Dismutase (SOD)

As a defense mechanism, cabbage plants grown in saline soil produced greater phenolics content with higher activity of SOD in CMB-treated soil plots than untreated plots (Fig. 4A and B). Herein, phenolics content increased by approximately 29.0% (CMB₁₀) and 56.0% (CMB₂₀), while SOD activity increased by 9.1% (CMB₁₀) and 17.2% (CMB₂₀) compared to CMB₀.

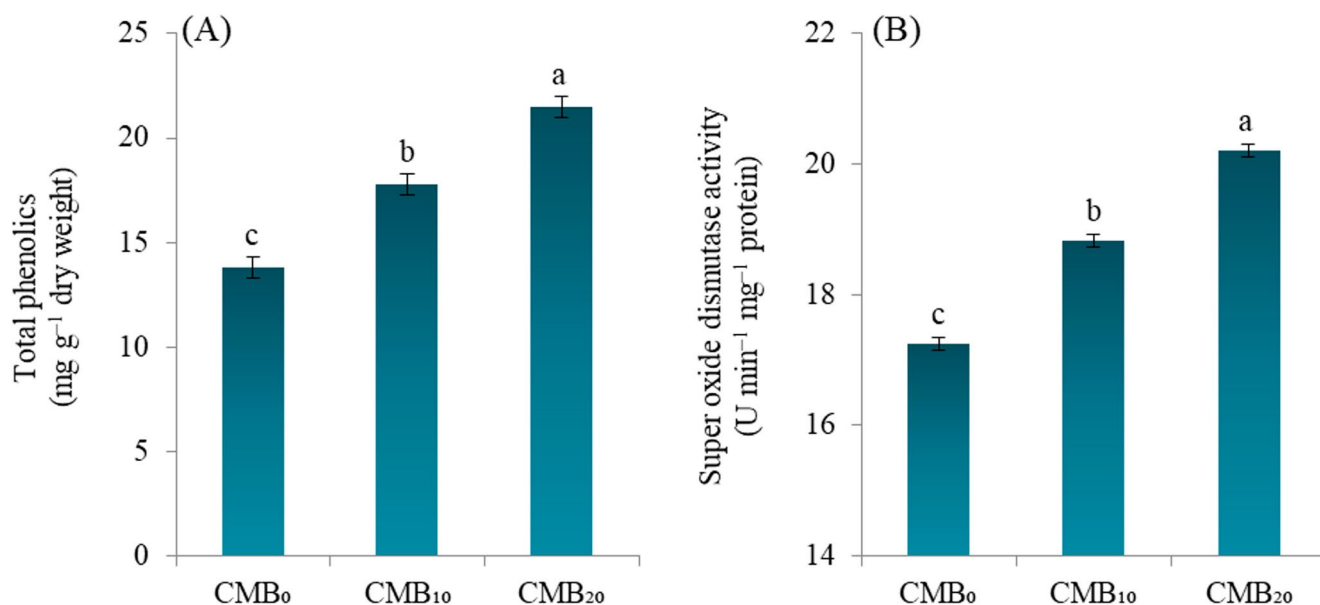


Fig. 4 Effect of compost mixed biochar (CMB) rate on total phenolics (A) and super oxide dismutase activity (B) of white cabbage plant grown under saline soil conditions. CMB₀, CMB₁₀ and CMB₂₀=0, 10 and 20 t ha⁻¹ compost/biochar mixture, respectively. Means±standard

error of three replicates of each treatment are presented. According to Duncan's test, the means in each bars followed by different lower-case letters differ significantly at $p \leq 5\%$

Table 4 Effect of compost mixed Biochar (CMB) rate on leaf mineral nutrients (mg g⁻¹ DW) of white cabbage plant grown under saline soil conditions

CMB rate (t ha ⁻¹)	N	P	K ⁺	K ⁺ /Na ⁺
0 (CMB ₀)	29.82±0.15c	3.98±0.10c	30.90±0.34c	0.71±0.01c
10 (CMB ₁₀)	31.18±0.12b	4.36±0.09b	33.02±0.09b	0.84±0.01b
20 (CMB ₂₀)	32.84±0.21a	5.10±0.12a	36.58±0.77a	1.08±0.04a

N=nitrogen, P=phosphorus, K⁺= potassium ion, Na⁺= sodium ion. Means±standard error of three replicates of each treatment are presented. According to Duncan's test, the averages in each column followed by the same letters indicate non-significantly at $p \leq 5\%$

3.2.4 Leaf Nutrients Content

Under saline soil medium, cabbage leaf mineral contents changed with application of CMB (Table 4). Increasing CMB rate led to increased nutrient contents, with CMB20 resulting in the highest increases. The N, P and K⁺ contents of cabbage leaf enhanced by about 10.1, 28.1 and 18.4%, respectively, due to adding CMB₂₀ compared with CMB₀. The CMB₂₀ came in the second order in this regard, surpassing CMB₀ by 4.6, 9.5 and 6.9%, respectively. Further, the ratio of K⁺/Na⁺ significantly improved with addition of CMB₁₀ and CMB₂₀ to exceed CMB₀ by approximately 1.18-fold and 1.52-fold, respectively.

3.3 Changes in Cabbage Yield Attributes

All cabbage yield attributes were significantly affected by CMB applied to the saline soil (Table 5). Cabbage exhibited poor growth and yield in the absence of CMB application. Herein, the lowest yield attributes were produced in CMB-untreated plots. While, plots received CMB₁₀ or CMB₂₀ resulted in significant increases in cabbage yield attributes compared to CMB₀. CMB₂₀ treatment achieved the maximal improvements in leaf number plant⁻¹ (41.8%), leaf area plant⁻¹ (216.2%), above-ground biomass (174.5%), head circumference (38.2%) and marketable yield (101.6%). CMB₁₀ treatment ranked second in this regard, demonstrating increases of 22.3, 108.6, 119.6, 21.8, and 72.0%, respectively.

3.4 Economic Evaluation

The economic evaluation in Table 5 demonstrates that although the initial investment for the CMB₂₀ rate is higher, it yields the greatest net return due to the substantial increase in marketable yield. The net return for CMB₂₀ is \$8034 ha⁻¹, which is 21.9% higher than that of CMB₁₀ (\$6338 ha⁻¹) and markedly superior (161.4%) to the control (CMB₀, \$3074 ha⁻¹). Crucially, the benefit/cost ratio for the CMB₂₀ rate (3.30) was highly favorable and comparable to the other CMB treatments.

Table 5 Economic evaluation of marketable yield of the cabbage plant as affected by compost mixed Biochar (CMB) addition rate under saline soil conditions

Table 5. Effect of compost mixed biochar (CMB) rate on marketable yield and its attributes of white cabbage plant grown under saline soil conditions

CMB rate (t ha ⁻¹)	Leaves plant ⁻¹		AGB-DW (g)	Head circumference (cm)	Marketable yield (t ha ⁻¹)
	Number	Area (dm ²)			
0 (CMB ₀)	21.33 ± 0.61c	91.1 ± 6.2c	120.53 ± 6.77c	80.75 ± 2.40c	46.45 ± 3.48c
10 (CMB ₁₀)	26.08 ± 0.27b	190.0 ± 6.6b	264.73 ± 3.66b	98.33 ± 1.16b	79.90 ± 1.13b
20 (CMB ₂₀)	30.25 ± 0.48a	288.1 ± 14.6a	330.85 ± 7.59a	111.58 ± 1.26a	93.62 ± 1.98a

AGB-DW=above-ground biomass dry weight. Means ± standard error of three replicates of each treatment are presented. According to Duncan's test, the averages in each column followed by the same letters indicate non-significantly at $p \leq 5\%$

3.5 Principal Component Analysis (PCA) and Correlation Matrix

Based on the morphological, physiological, and biochemical responses of cabbage, as well as its marketable yield, PCA illustrated that the first two PCs combined account for 100% of the variability among the CMB treatments (97.7 and 2.3% for PC-1 and PC-2, respectively; Fig. 5). The adjacent vectors of the measured properties exhibited positive associations with each other. According to the PCA, Leaf N, P, K⁺, and K⁺/Na⁺, chlorophyll *b*, TSSs, TPhCs,

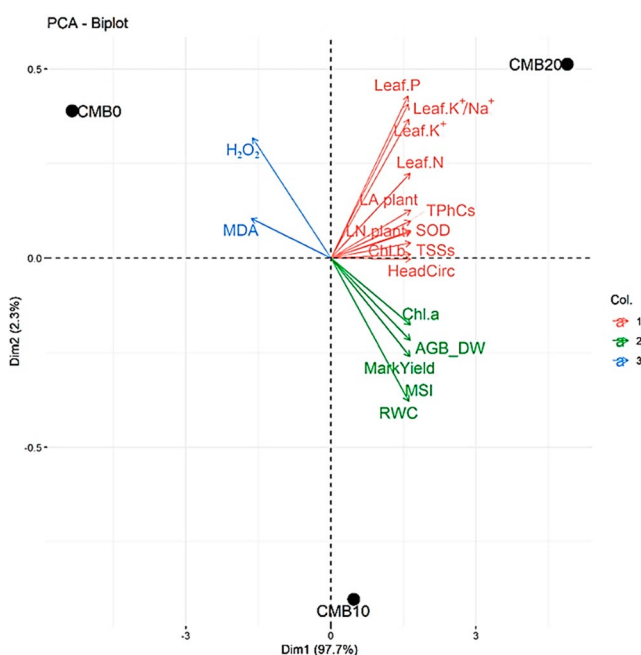


Fig. 5 Principal component analysis (PCA) for applied compost mixed biochar (CMB) rate and studied attributes. CMB₀, CMB₁₀ and CMB₂₀=0, 10 and 20 t ha⁻¹ compost/biochar mixture, respectively. N: nitrogen, P: phosphorus, K⁺: potassium, Na⁺: sodium, RWC: relative water content, MSI: membrane stability index, Chl *a*: chlorophyll *a*, Chl *b*: chlorophyll *b*, H₂O₂: hydrogen peroxide, MDA: malondialdehyde, TSSs: total soluble sugars, TPhCs: total phenolics, SOD: super oxide dismutase activity. LN plant: leaf number plant⁻¹, LA plant: and leaf area plant⁻¹, AGB-DW: above-ground biomass dry weight, HeadCirc: head circumference, and MarkYield: marketable yield; Dim1 and Dim2: dimension 1 and dimension 2, respectively

SOD, leaves number/plant, plant leaf area, and head circumference belong to the same category. Additionally, chlorophyll *a*, RWC, MSI, AGB-DW, and marketable yield were in a separate group, while H₂O₂ and MDA were grouped together in a third group. The PC-1 divided the applied CMB treatments into two groups; CMB₁₀ and CMB₂₀ were located on the positive side while CMB₀ was situated on the negative side. However, PC-2 seems to classify the tested CMB treatments into two groups: CMB₁₀ was positioned at the bottom, while the CMB₀ and CMB₂₀ were at the top. The CMB₂₀ treatment was associated with the best performance for Leaf N, P, K⁺, and K⁺/Na⁺, chlorophyll *b*, TSSs, TPhCs, SOD, leaves number/plant, plant leaf area, and head circumference, followed by CMB₁₀ for chlorophyll *a*, RWC, MSI, AGB-DW, and marketable yield. Cabbage marketable yield was significantly (Fig. 6) positively correlated with TP (0.930), WHP (0.981), θ_{Fc} (0.950), OM (0.723), CEC (0.977), soil N (0.874), soil P (0.753), and soil K⁺ (0.878), while was significantly and negatively correlated with DBD (-0.902), pH (-0.840), EC (-0.863), and K_{sat} (-0.815).

4 Discussion

In vegetables cultivation, the intensive use of fertilizers is a common practice to achieve high productivity (Wu et al. 2019). Application of high fertilizer quantities leads to soil problems such as excessive accumulation of P, nitrate, and salt (Xiao et al. 2020). Accordingly, to enhance soil health and quality, it is of great significance to utilize efficient soil amendments that provide effective and sustainable solutions against salinity (Helal et al. 2024; Ansabayeva et al. 2025; Ataya et al. 2025; Saady et al. 2025c). The CMB₂₀ treatment drove profound alterations in soil hydro-physical structure (Ibraheem et al. 2024), reducing dry DBD by 13.9% and K_{sat} by 38.6%. These changes directly enhanced pore connectivity, enhancing TP by 13.1% and WHP by 19.8%. Chemically, biochar's porous architecture and oxygenated surface groups (e.g., carboxyl and phenolic) provide high CEC (23.50 cmol kg⁻¹, facilitating Na⁺ adsorption via electrostatic binding and ion exchange mechanisms (Kamal

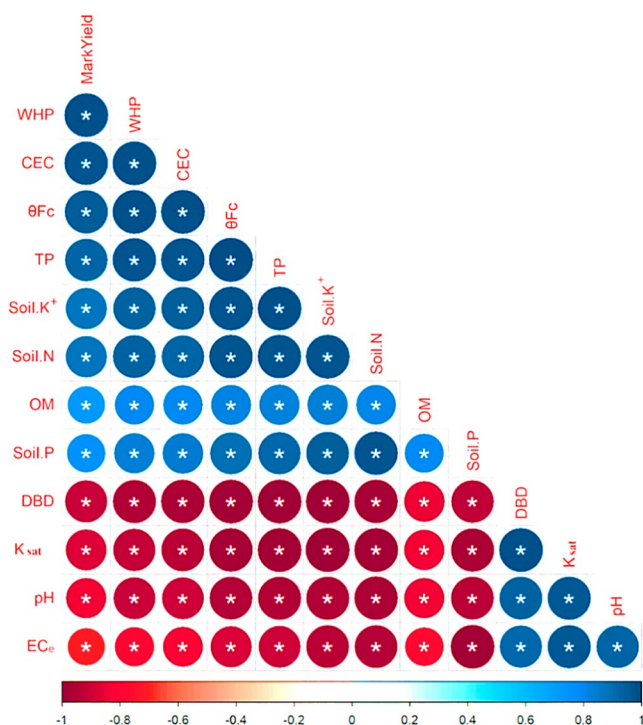


Fig. 6 Pearson's correlation coefficients among the hydro-physio-biochemical soil attributes and yield and white cabbage marketable yield. *:significant ($p \leq 0.05$) correlation; WHP: water holding pores CEC: cation exchange capacity θ_{Fc} : soil moisture at field capacity, TP: total porosity, Soil.K⁺: soil potassium content, Soil.N: soil nitrogen content, OM organic matter, Soil.P: soil phosphorus content, DBD dry bulk density, K_{sat} saturated hydraulic conductivity, pH soil reaction, and EC_e, electrical conductivity of soil extract

et al. 2024), thereby reducing soluble salts expressed in EC_e by 49.2% at CMB₂₀ vs. CMB₀. Simultaneously, a 55.5% increase in CEC highlights biochar-compost synergy in increasing cation retention sites, thereby promoting Na⁺ substitution by Ca²⁺ and K⁺ cations (Duan et al. 2023). Concurrently, CMB-liberated humic/fulvic acids protons (H⁺ release) during microbial degradation, neutralizing soil carbonates (initial CaCO₃=4.2%) and counteracting biochar's ingrained alkalinity (pH=8.20) Howell et al. 2024). This organic acid-liberated protons result in a reduction of soil pH by 0.29 units at CMB₂₀ vs. CMB₀ (Makhlouf et al. 2022; Shaaban et al. 2024; Fikry et al. 2025). Adjusting the growth medium to match the plant's needs is crucial for sustaining crop productivity and quality especially in stressed ecosystems. Improving the hydro-chemo-physical properties of soil is of paramount importance. The current study demonstrated the synergistic mechanisms of biochar and compost in ameliorating saline soil properties and mitigating salt-induced stress on cabbage. Biochar and compost have distinctive features and advantages that modify the soil environment to become suitable for plant growth. Soil analysis after cabbage harvesting revealed that CMB,

particularly at the high rate (20 t ha⁻¹), significantly modified the physicochemical properties of the saline soil.

The combination of CMB was strategically designed to leverage their complementary mechanisms in ameliorating saline soils, as neither amendment alone optimally addresses the multifaceted salinity's challenges (Ibraheem et al. 2024). While biochar supplies long-term structural improvements (e.g., TP enhancement, reduced DBD and CEC elevation), it often exhibits limited prompt nutrient availability and can elevate soil pH (pH 8.20 for biochar). Conversely, compost promptly supplies OM and nutrients (N=1.60%, P=5.20 g kg⁻¹, and K⁺=3.82 g kg⁻¹ for compost) but decomposes quickly, offering transitory benefits (Leogrande et al. 2024). Their integration in CMB synergistically balances short-term nutrient release for compost with long-term soil structural resilience for biochar, while alleviating the alkalinity risk of pure biochar through compost's buffering capacity (pH=7.47 for CMB₂₀ vs. 8.20 for biochar). This approach is validated by our data, as CMB₂₀ outperformed either amendment alone in enhancing soil health (e.g., EC_e reduction by 49.2%), plant stress tolerance (e.g., H₂O₂ and MDA both by 13.5%), and increased marketable yield by 101.6%, aligning with previous studies that demonstrating superior outcomes of integrated organo-mineral strategies in saline ecosystems (El-Sharkawy et al. 2022; Howell et al. 2024).

Biochar effectively reduces soil tensile strength and bulk density (Blanco-Canqui 2017), while enhancing moisture retention (Razzaghi et al. 2020) owing to its spacious pores and high specific surface area. Incorporation of biochar into soil increased macro-aggregates, improved soil structure, and thus mitigated the effects of salt stress (Chen et al. 2022; Ibraheem et al. 2024). The DBD, as a physical trait, represents a key factor influencing soil compacting and productivity (Blanco-Canqui 2021), hence affecting plant roots growth and tolerance to salt stress (Ali et al. 2021). As per Haque et al. (2021), biochar has a substantial role in modulating bulk density, water holding and availability of moisture and nutrients and microbial activity in soils. Macro-aggregates and porosity were increased and DBD was reduced by addition of biochar in sandy soil under drought conditions (Chen et al. 2022; Tran et al. 2022). Biochar, being a porous material with a high concentration of chemo functional groups have hydrophilic features (Amoakwah et al. 2017; Alessandrino et al. 2023), can remarkably increase moisture retention of soil, thereby alleviating the salinity effects (Ali and Elshaikh 2022). Also, the soil storage potentiality for water enhanced with application of biochar due to its spacious voids (Zong and Lu 2020). The proper biochar addition rate enhanced the pore structure of soil via improving porosity and porous conductance (Zhou et al. 2021), thus

promoting root growth under salinity (Saifullah et al. 2018). Further, exploiting biochar in saline soil boosted the stability of aggregates, which enhanced crop performance (Ali et al. 2021; Zong et al. 2023). Additionally, augmenting the soil aggregates stability enhanced the leaching of salts downwardly, reducing the salinity effects while stimulating the activity of microbes (Alghamdi 2018; Alghamdi et al. 2023; Luo et al. 2018). Organic “C” obtained from biochar can increase soil aggregation stability via binding the individual soil granules (Yang and Lu 2021). Biochar constitutes a “C”-rich particulate material and has emerged as a promising soil modifier owing to its resistance to decomposition and useful actions for soil (Joseph et al. 2009). Biochar as a soil amendment can improve soil biological features by affording biodegradable organic “C” and fitting the appropriate medium for microbial activities (Rahaman et al. 2023). Further, biochar is considered a low-cost alternative to soil conditioners, correcting the depletion of soil fertility while improving the crop productivity (Atkinson et al. 2010). Being biochar can generate a suitable rhizosphere medium, plant roots grow and develop well (Bruun et al. 2014). Remarkable improvements in root development and acquisition of nutrients were recorded with biochar application (Kabir et al. 2024). Commonly, biochar raises soil pH level, improving the microbial processes and nutrient content (Cusack et al. 2009). Due to its “C”-rich structure, biochar affords the soil biota their “C” requirements, thus increasing microbial secretions, which promote soil aggregates formation (Palansooriya et al. 2019). Since it is characterized by high ash content and various minerals such as N, P and K⁺, biochar application is considered a promising agronomic practice for alleviating the impacts of nutrient deficiency while enhancing nutrients uptake by plant under various other environmental stressors (Bagues et al. 2024; Shaaban et al. 2025b). Accordingly, in saline soils that suffer from imbalance and deficiency in nutrients (Rady et al. 2025), biochar addition can positively influence soil health and plant growth (Baijukya et al. 2021). Biochar not only increases nutrient availability, but also ameliorates plant nutrient uptake and utilization (Zhao et al. 2020). Briefly, having unique features such as porosity and retention capacity of water and nutrient (McDonald et al. 2019), biochar provides optimal edaphic conditions for cabbage growth.

On the other hand, compost is known for its potential to nourish soil, sustain its health with good retaining the moisture and nutrients, thus enhancing crop productivity (Youssef et al. 2023). To be highly effective for rebuilding physico-chemical traits of soil and reestablishing the beneficial biota biomass and activities, compost must be repeatedly applied (Leogrande et al. 2024). The improvements in soil traits via compost addition are mainly attributed to raising the levels of OM and C/N ratio while reduction of

DBD (El-Sharkawy et al. 2022; Ibraheem et al. 2024). Plant wastes exploited in compost production are rich in nutrients, growth stimulators and vitamins (Oyetunji et al. 2022). Therefore, compost incorporation in saline soils modulated the various features of soil via affording organic substances and nutrients (Singh 2023). Also, the application of organic materials as soil amendment could adjust the soil reaction and raise temperature by enhancing the potential of moisture and mineral supply, hence reinforcing the growth of plants grown in saline soils (Oyetunji et al. 2022). Moreover, available “C” and useful salt-tolerant microbes increased while the electrical conductivity and Na⁺ and Cl[−] ions decreased due to organic material additions (Mao et al. 2022; Irin and Hasanuzzaman 2024a).

The CMB's functional integration results from the readily degradable “C” in compost, which stimulates soil microbial proliferation, while the stable “C” in biochar provides a persistent pore structure (Hu et al. 2024). Notably, the CMB's near-neutral pH (7.85) buffered the biochar's alkaline nature, preventing over-alkalinization in soil pH, resulting in a 0.38-unit reduction in soil pH compared to biochar alone under saline conditions. This balance improved nutrient accessibility, as reflected by a 65.0% increase in OM and 33.0% higher in soil P. Moreover, compost-derived organics fortified the biochar's nutrient-retentive efficiency (Zhang et al. 2024). Undoubtedly, improving the properties of saline soil will positively influence crop growth and potentiality. In this situation, the growth and yield as well as the quality of economic marketable product of cabbage grown in saline soil improved substantially with providing CMB. Photosynthetic pattern is a pivotal biological action for “C” assimilation and plant growth, influencing synthesis of carbohydrates and dry matter accumulation (Abdelkhalik et al. 2024). However, photosynthesis is detrimentally affected by soil salinity (Kamran et al. 2021). The noticeable increased level of MDA in the salt-stressed cabbage leaves could be ascribed to excess formation of toxic Na⁺ and Cl[−] and poor water availability, which may stimulate reactive oxygen species (ROS) production, suppressing photosynthesis and protein synthesis (Kumari et al. 2022). Under salt impacts, plants activate antioxidant systems to quench the hazards of generated ROS, hence minimizing oxidative damages (Abd El-Mageed et al., 2023; Abdelkhalik et al. 2023). A 13.5% reduction in H₂O₂ and MDA levels under CMB₂₀ reflects effective biochar-mediated ROS neutralization via phenolic adsorption (Siedt et al. 2021). Concurrently, SOD activity increased by 17.2%, indicating catalysis of the O₂^{•−} detoxification cascade. This enzymatic resilience, reinforced by a 56.0% elevation in phenolic accumulation, directly protected membrane functionality (MSI improved by 17.7%, reducing ion leakage and photosynthetic functionality (Irin

and Hasanuzzaman 2024b). Thus, beside the high content of MDA, elevated levels of total soluble sugars, total phenolics, and SOD were observed, particularly with application of CMB, thus encountering the oxidative stress (Liu et al. 2021; Kamal et al. 2024). Similar findings related to the biostimulatory effects of organic amendments on the growth of salt-stressed plants were recorded (Ud Din et al. 2023). Yield enhancement (by 101.6%) was attributed to CMB₂₀-stimulated K⁺/Na⁺ homeostasis (by 52.1%), which boosted stomatal regulation and CO₂ assimilation efficiency, as indicated by an 11.9% increase in RWC. A 216.2% increase in foliage area further amplified CO₂ fixation, contributing to a 174.5% increase in AGB-DW. These attributes were closely associated with soil porosity ($r=0.930$) and CEC ($r=0.977$), confirming soil structural improvements as the key factors influencing yield (El-Kafrawy et al. 2024).

A benefit/cost ratio > 1 indicates profitability, while a higher ratio reflects greater efficiency per dollar invested. These results confirm that the substantial yield gain achieved with the CMB₂₀ rate more than offsets its additional cost, making it an agronomically sound and economically superior recommendation for maximizing farmer profitability under saline conditions. Biochar benefits plants under normal or stressful environments by enhancing productivity (Chen et al. 2022). In saline media, the growth and yield of various crops were improved with biochar input (Mikajlo et al. 2024). Mitigations of the negative effects of salinity, manifested in significant enhancements of nutrient uptake and chlorophyll synthesis, were associated with increased water and nutrient retention capacity of biochar (Shashi et al. 2018; Abd El-Mageed et al. 2021). Biochar can also enhance crop quality, for instance, in tomatoes, where quality indicators such as fructose-ascorbic acid, glucose, lycopene, and vitamin C in fruit were significantly enhanced when biochar was incorporated into the soil (Suthar et al. 2018; Almaroai and Eissa 2020).

As an organic fertilizer, compost enriches the soil fertility, nutrient availability and nutrient absorption, the formation of chlorophyll of leaves is effectively stimulated (Iqbal et al. 2021; Sharma et al. 2022). Further, the chlorophyllase enzyme activity may be inhibited by humic substances released from applied compost, delaying the senescence of chlorophyll (Ali et al. 2024b; Kamal et al. 2024). Since compost increased leaf nutrients reinforced the translocation of photosynthesis assimilates to form numerous cabbage leaves, the marketable yield increased (Ud Din et al. 2023; Ali et al. 2024c). Future studies are warranted to assess variable salinity severities and salt redistribution across soil profiles under organic amendment applications, as upright salt movement may affect long-term soil health and sustainability and support the uniformity and resilience of the ameliorative effects.

5 Conclusions

This study demonstrated that integrating compost and biochar as a mixture is an effective strategy for improving the functionality of salt-affected soils and enhancing cabbage growth and productivity. The combined amendment improved soil structure, increased organic matter content, enhanced nutrient availability, and strengthened soil water retention capacity, collectively contributing to a more favorable root-zone environment under salinity stress. These improvements were accompanied by enhanced physiological status, including better water relations, membrane stability, pigment accumulation, and antioxidant activity, along with reduced oxidative damage, ultimately translating into higher marketable yield. Our findings validate the hypothesis that compost-biochar integration provides synergistic benefits that surpass the use of either amendment alone. This approach offers a scalable and environmentally sound solution for rehabilitating saline soils and sustaining vegetable production in marginal lands. Future work should optimize mixture ratios, explore individual amendment contributions, and investigate the underlying molecular and biochemical mechanisms governing plant responses to integrated organic amendments under salt stress.

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Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

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