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ORIGINAL ARTICLE

Simulating long-term soil carbon sequestration and wheat productivity under biochar amendments in saline-irrigated sandy soils

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Abstract

Improving carbon sequestration in sandy soils under saline irrigation is essential for sustaining agricultural productivity in marginal environments. This study addressed two key questions: (i) can biochar, alone or combined with organic amendments, enhance soil carbon storage and fertility under saline irrigated? and (ii) What are the long-term impacts of biochar application on soil organic carbon (SOC) dynamics and wheat (*Triticum aestivum* L) productivity? A field experiment was conducted using three treatments: compost-only, biochar at 20 t ha^{-1} (+B), and biochar (20 t ha^{-1}) combined with chicken manure (40 t ha^{-1}) (B+M). The Decision Support System for Agrotechnology Transfer (DSSAT) model was further employed to simulate long-term (20-year) effects. Results showed that biochar amendments significantly enhanced soil carbon storage, with total organic carbon increasing from 9.29 g kg^{-1} (compost-only) to 15.87 g kg^{-1} (+B) and 23.72 g kg^{-1} (B+M). Relative to compost treatment, SOC increased by 117.66% and 208.98%, and inorganic carbon by 126.95% and 368.79% under +B and B+M, respectively. Biochar also significantly increased microbial biomass carbon (by 132.29% in +B and 187.68% in B+M) and improved nutrient availability (N: 77.78%–145.19%, P: 167.14%–354.23%, K: 80.70%–141.10%). In addition, water-use efficiency increased from 4.70 to 6.67 kg mm^{-1} ha^{-1} under B+M, indicating improved soil water retention and plant uptake. Model validation demonstrated high predictive accuracy (R^2 = 0.93) between observed and simulated yields. Long-term DSSAT simulations projected SOC increases of 26.4% (+B) and 30.57% (B+M) over 20 years, along with reduced nutrient leaching and wheat yield improvements of 58.18% and 85.4%, respectively. Although short-term CO_2 fluxes increased following biochar, long-term simulations indicate substantial benefits for carbon sequestration and crop productivity. These findings demonstrate that integrating biochar with organic amendments is an

Abbreviations: CEC, cation exchange capacity; ECe, electrical conductivity; MBC, microbial biomass carbon; SIC, soil inorganic carbon; SOC, soil organic carbon; TOC, total organic carbon; WUE, water-use efficiency.

effective strategy for improving soil carbon storage and sustaining wheat production in saline-irrigated sandy soils.

Plain Language Summary

Sandy soils irrigated with salty water often lose nutrients and water quickly, resulting in poor crop growth and low soil carbon. This study tested whether adding biochar, alone or with chicken manure, could improve soil fertility and carbon storage under these harsh conditions. Field results showed that biochar, especially when mixed with manure, greatly improved soil nutrients, carbon content, and water-use efficiency, leading to higher wheat yields. Computer modeling (Decision Support System for Agrotechnology Transfer) predicted that these benefits would continue for at least 20 years, increasing soil carbon and productivity over time. Although biochar slightly increased short-term carbon dioxide emissions, it strongly enhanced long-term carbon storage. Overall, biochar combined with manure offers a practical and climate-smart solution for restoring saline sandy soils and sustaining crop production.

1 | INTRODUCTION

Marginal environments, characterized by low fertility, high salinity, and arid climates, present significant challenges to soil systems and agricultural productivity (Naorem et al., 2023). These conditions often result in soils with poor physical structure, limited nutrient availability, and reduced microbial activity, key factors for maintaining soil health and crop productivity (Lal, 2016; T. Yang et al., 2020). Globally, >40% of the agricultural land is degraded, severely affecting soil fertility and crop yields (Reynolds et al., 2007). The lack of organic matter further exacerbates nutrient deficiencies, as minimal organic inputs are available for decomposition and nutrient release (Coonan et al., 2020). Salinity is one of the most critical constraints in marginal soils, particularly in arid and semi-arid regions (Gamalero et al., 2020). Excess salts induce osmotic stress, restrict plant water uptake, and may lead to ion toxicity. Saline soils affect approximately 831 million ha worldwide, significantly reducing agricultural productivity (Butcher et al., 2016). Moreover, salinity negatively impacts soil microbial communities and enzymatic activities, thereby impairing soil health and reducing its capacity for carbon sequestration (Muhammad et al., 2024). Consequently, low organic matter inputs and limited vegetation cover further constrain the soil's ability to function as a carbon sink, contributing to increased atmospheric CO_2 levels and accelerating climate change (Luo et al., 2023). Restoring soil carbon in degraded lands could sequester 1.2–3.1 gigatons of CO_2 annually (Jeffery et al., 2017; Meena et al., 2019).

Soil is the largest terrestrial reservoir of organic carbon, containing approximately 1500–2400 petagrams (Pg), and plays a crucial role in achieving carbon neutrality (Amelung et al., 2020; Paustian et al., 2019). Enhancing soil carbon storage while reducing greenhouse gas (GHG) emissions provides a dual pathway for climate mitigation and sustainable agricultural productivity (Paustian et al., 2019). However, approximately 29% of global land is degraded due to processes such as desertification, erosion, salinization, sodification, and acidification, all of which compromise the soil's capacity to sequester carbon (Raza et al., 2021; Shukla et al., 2019). Soil salinization reduces plant biomass, soil organic carbon (SOC), microbial biomass, and GHG fluxes, thereby weakening overall ecosystem functioning (Haj-Amor et al., 2022).

Organic amendments have shown considerable potential in mitigating these constraints. Inputs such as humic substances, vermicompost, and farm manure improve SOC, reduce bulk density, and alleviate salinity stress (Csikós & Tóth, 2023; Luo et al., 2023; Zhang et al., 2020). They also promote microbial activity, improve soil aggregation, and increase crop productivity (Gamalero et al., 2020; Haj-Amor et al., 2022). Among these amendments, biochar has attracted significant attention due to its high carbon stability, porous structure, large surface area, and abundance of functional groups (El-Naggar et al., 2019; El-Tohory et al., 2023; Rady et al., 2025). Biochar is widely applied for soil improvement, carbon sequestration, and sustainable resource management (El-Naggar et al., 2019). Its co-application with nutrient-rich organic materials, such as chicken manure, provides a balanced nutrient supply, enhances nutrient retention, reduces leaching losses, and promotes crop growth, particularly in crops such as radish (*Raphanus sativus* L), maize (*Zea mays* L), wheat (*Triticum aestivum* L), and tobacco (*Nicotiana tabacum* L) (Adekiya et al., 2019; M. A. Khan et al., 2022;

L. Liu et al., 2021; Ming et al., 2025). These synergistic effects improve SOC content, increase cation exchange capacity (CEC), enhance soil buffering capacity, stimulate microbial activity, and promote root development, ultimately leading to improved wheat productivity (Jeffery et al., 2017; Li et al., 2021; Zhang et al., 2020).

Wheat is a globally important staple crop that plays a central role in food security. However, its cultivation in marginal soils is constrained by salinity, acidity, and nutrient imbalances (Moussa et al., 2022). Approximately 20% of global agricultural land is classified as marginal, with about 10% affected by salinity and 15% by low fertility (Csikós & Tóth, 2023; Soleimani et al., 2016). Improving wheat production in these environment has the potential to transform unproductive lands into viable agricultural systems, reduce pressure on fertile soils, and enhance global food production (Csikós & Tóth, 2023; Shahid et al., 2020). To better understand and optimize soil restoration strategies, crop simulation models provide valuable tools. The Decision Support System for Agrotechnology Transfer (DSSAT) integrates soil, crop, and climate data to evaluate the impacts of agricultural practices on crop performance and environmental sustainability (Hoogenboom et al., 2019). Its CENTURY module simulates soil carbon dynamics by partitioning SOC into active, slow, and passive pools with distinct turnover rates rates (Gijsman et al., 2002; Musinguzi et al., 2014). This makes DSSAT particularly suitable for assessing long-term carbon dynamics in arid sandy soils, where high temperatures and limited moisture accelerate carbon loss. By simulating different scenarios of biochar application, soil management practices, and climatic conditions, DSSAT provides insights into both short-term agronomic responses and long-term carbon sequestration potential (Lehmann et al., 2011). Therefore, this study was designed to address the following research questions: (1) How do biochar amendments, alone or in combination with chicken manure, influence soil carbon sequestration in saline-irrigated sandy soils? (2) What are the long-term effects of biochar application on wheat productivity under marginal conditions? (3) Can DSSAT simulations reliably predict the agronomic and environmental impacts of biochar in arid sandy soils? By addressing these questions, this study aims to evaluate the role of biochar-based amendments in enhancing soil carbon storage and improving wheat production in saline, marginal environments.

Core Ideas

- Biochar amendments enhance soil fertility and promote carbon sequestration in saline sandy soils.
- Biochar improves soil water-use efficiency and alleviates salinity stress by enhancing soil physical properties.
- The DSSAT-CENTURY (where DSSAT is Decision Support System for Agrotechnology Transfer) model effectively simulates wheat yield and long-term soil carbon dynamics.
- Integrating biochar-based amendments supports sustainable crop production and soil restoration in marginal environments.

2 | MATERIALS AND METHODS

2.1 | Site description

A field experiment was conducted at the International Center for Biosaline Agriculture (ICBA) farm, Dubai, United Arab Emirates, during the winter season of 2023 and 2024. The experimental site is located at 25°05′49″ N and 55°23′25″ E. The region receives an average annual rainfall of approximately 118 mm (based on data from 2015 to 2023), with >60% of the precipitation occurring between August and March. The climate is characterized by extremely hot summers and mild winters. July is the hottest month, with an average air temperature of 45°C, while January is the coolest, with an average temperature of 15°C. Soil particle size distribution was determined using the hydrometer method (Kettler et al., 2001), and the soil was classified as sand. Soil electrical conductivity (ECe) and pH were measured in 1:2.5 and 1:5 soil-to-water (w/v) suspensions, respectively, following the method described by Sonmez et al. (2008). Soil organic matter content was determined using wet oxidation method (Mingorance et al., 2007), and CEC was measured using ammonium acetate method at pH 7.0. The physicochemical properties of the experimental soil are presented in Table 1.

2.2 | Biochar preparation and analysis

Biochar was produced from a mixing of teak and mahogany branches. The branches were air-dried to a moisture content of approximately 10% and then cut into pieces measuring. Note that it is 5–10 cm in length. The prepared material was subjected to pyrolysis in a carbonization furnace at 350°C for 2 h to ensure complete carbonization. After pyrolysis, the biochar was allowed to cool to room temperature overnight. The cooled biochar was then ground and sieved to pass through a 5-mm mesh to obtain a uniform particle size. Biochar pH and ECe were determined in a 1:2 biochar-to-water suspension. The suspension was shaken for 1 h, allowed to equilibrate, and subsequently measured using a pH meter and an ECe meter. The physicochemical properties of the biochar are presented in Table 2.

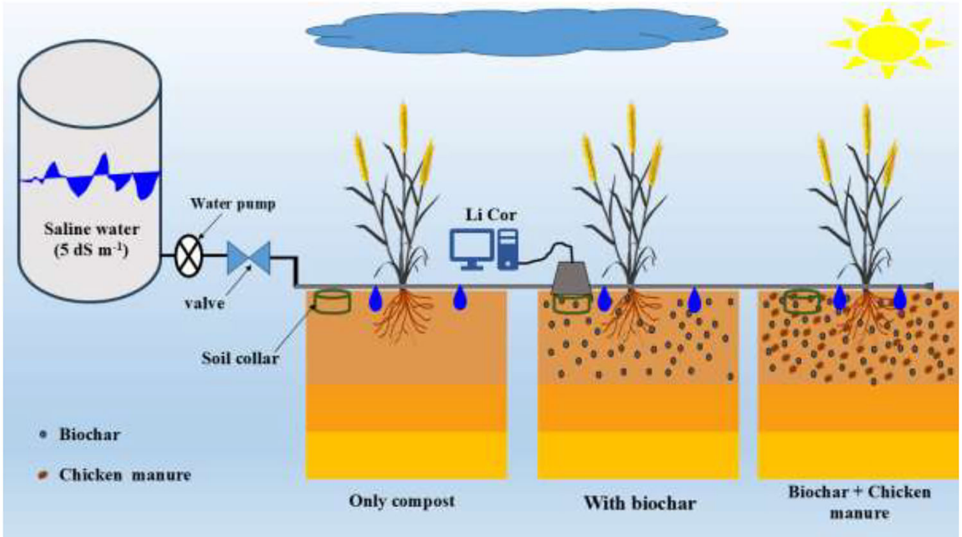

FIGURE 1 Experimental layout under biochar amendment and saline water irrigation.

TABLE 1 Soil physicochemical properties.

Sand	97.21%
Silt	1.96%
Clay	0.83%
Texture	Sand
$CaCO_3$ (%)	34
pH (1:5)	7.67
ECe (dS m^{-1})	0.36
CEC (cmol kg^{-1} soil)	2.39
TN (g kg^{-1})	0.25
TC (g kg^{-1})	0.52
C/N ratio	10.04
Exchangeable sodium percent (%)	1.2
Organic matter (g kg^{-1})	0.64
Available N (mg kg^{-1})	43.8
Available P (Olsen) (mg kg^{-1})	4.35
Available K (mg kg^{-1})	52.67

Abbreviations: C/N, carbon to nitrogen ratio; CEC, cation exchange capacity; ECe, electrical conductivity; TC, total carbon content; TN, total nitrogen.

2.3 | Experimental design and treatments

The experiment was conducted using a randomized complete design with three replications. The treatments consisted of: (1) compost-only, (2) with biochar (+B), and (3) biochar combined with chicken manure (B+M). Prior to treatment application, the entire experimental area was uniformly amended with compost to improve the fertility of the initially nutrient-poor (virgin) sandy soil. Compost was applied at a rate of 4 kg m^{-2} (40 t ha^{-1}) and incorporated into the soil to a depth of 0–50 cm using a small tractor. Following compost incorporation, the field was divided into nine plots, each measuring 4.0 × 5.0 m (Figure 1). Biochar and chicken manure were then manually applied and incorporated into the top 0–30 cm. Chicken manure was applied at a rate of 4 kg m^{-2} (40 t ha^{-1}), while biochar was applied at 2 kg m^{-2} (20 t ha^{-1}). The physicochemical properties of the compost, chicken manure, and biochar are presented in Table 2.

Wheat planted on December 25, 2023, and harvested on April 20, 2024. Seeds were sown manually at a spacing of 30 cm between plants and 35 cm between rows, resulting in a total 180 plants per plot. During the first 2 weeks after sowing, all plots were irrigated with freshwater (approximately 0.6 dS m^{-1}) using a drip irrigation system to ensure successful germination. Following germination, irrigation was switched to saline water with an ECe of 5 dS m^{-1}. The saline irrigation water was obtained from an ICBA groundwater well and diluted with freshwater to achieve the desired salinity level. Fertilization was applied according to recommended rates for wheat, with nitrogen (N) at 150 kg ha^{-1}, phosphorus (P) at 60 kg ha^{-1} (as P_2O_5), and potassium (K) at 90 kg ha^{-1} (as K_2O). Superphosphate (15% P_2O_5) and potassium sulfate (50% K_2O) were applied as basal fertilizers prior to planting. Nitrogen, in the form of ammonium sulfate (21% N), was divided and applied in four equal splits: at the first irrigation and subsequently at 5, 7, and 9 weeks after planting.

2.4 | Weather data and irrigation

Meteorological data, including air temperature, wind speed, relative humidity, rainfall, and solar radiation, were recorded using a weather station installed at the ICBA experimental farm (Figure 2). The station was equipped with (i) a GMX500 Compact Weather Station for measuring air temperature, humidity, and wind speed; (ii) a CS320 Digital

TABLE 2 Physicochemical properties of soil amendments.

	Chicken manure	Compost	Biochar
pH (1:2)	7.65	6.83	7.84
ECe (dS m^{-1})	6.23	4.36	3.56
CEC (cmol kg^{-1} soil)	–	–	16.85
TN (g kg^{-1})	27.31	12.98	18.7
TC (g kg^{-1})	367	260	762.3
C/N ratio	13.44	20	40.7
Organic matter (g kg^{-1})	686.5	400.5	–
Boron (g kg^{-1})	0.04	0.01	–
Calcium (g kg^{-1})	4.72	2.53	–
Iron (g kg^{-1})	0.39	0.13	–
Mg (g kg^{-1})	0.52	0.2	–
Mn (g kg^{-1})	0.12	0.06	–

Abbreviations: C/N, carbon to nitrogen ratio; CEC, cation exchange capacity; ECe, electrical conductivity; TC, total carbon content; TN, total nitrogen.

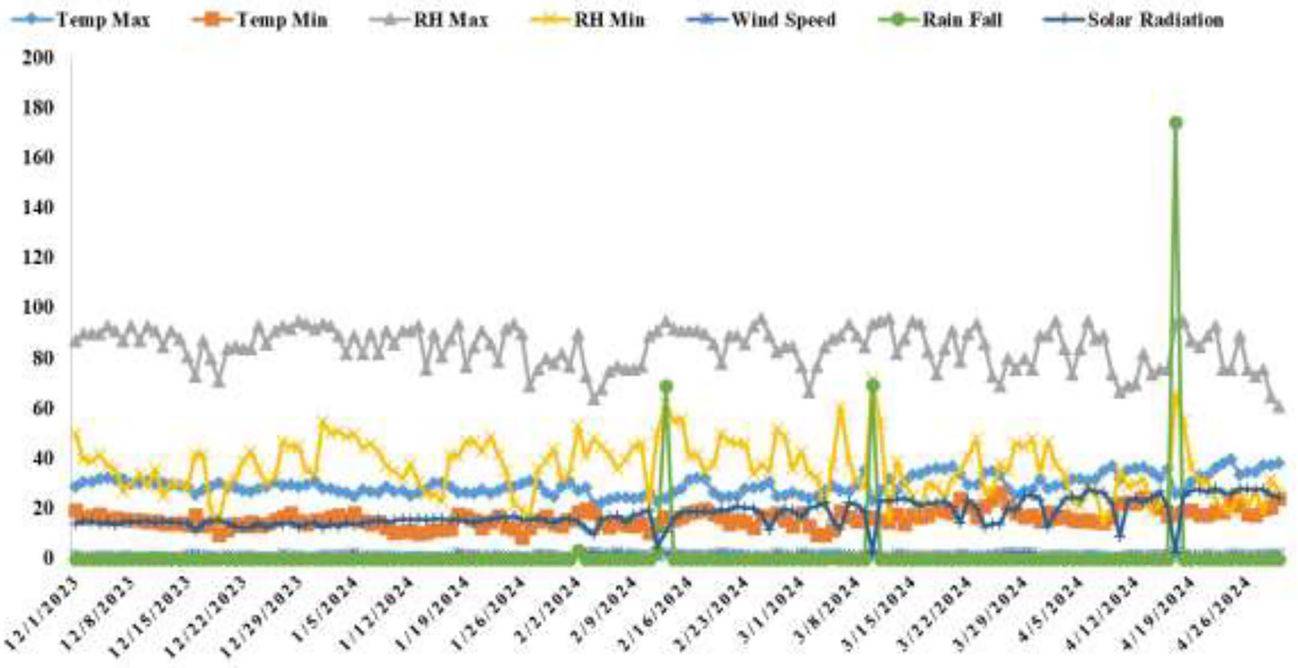

FIGURE 2 Daily air temperature, solar radiation, wind speed, relative humidity, and precipitation from December 2023 to April 2024 during the wheat growing season.

Thermopile Pyranometer for monitoring solar radiation; (iii) a KALYX-RG Aerodynamic Rain Gauge for accurate rainfall measurement; and (iv) a Campbell Scientific CR1000 data logger for data acquisition and storage. These measurements were used to calculate reference evapotranspiration (ET_0) using the Penman-Monteith equation (Allen, 1998). Irrigation was applied automatically twice daily (morning and evening) through a drip irrigation system, with scheduling controlled by timers and solenoid valves. Crop water requirements were determined using crop coefficient (Kc) values obtained from FAO 56 guidelines (Allen, 1998), set at 0.3 for the initial stage, 1.15 for the mid-season stage, and 0.4 for the late-growth stage. The collected climatic data were also used as inputs for the DSSAT model to simulate environmental conditions influencing wheat growth and soil carbon dynamics (Hoogenboom et al., 2019).

2.5 | Water use efficiency

Water use efficiency (WUE) was calculated to evaluate the effectiveness of irrigation during the wheat growing season. WUE was determined following the methodology described by Ren et al. (2017) and was calculated using the following equation:

$$\mathrm{WUE} = \frac{\mathrm{GY}}{\mathrm{ETc}} \tag{1}$$

where GY is the wheat grain yield (kg ha^{-1}), and ETc is the actual the crop evapotranspiration (mm), representing the total water consumed by the crop during the growth season. The ETc values were derived from daily meteorological data recorded by the on-site weather station as described above.

2.6 | Measurement of soil gases

Polyvinyl chloride collars (20 cm in diameter and 11.4 cm in height) were installed in the center row of each treatment replicate after the application of soil amendments. The collars were inserted into the soil, leaving approximately 2 cm above the surface. No wheat plants were growing within the collars, which remained in place throughout the growing season. Soil CO_2 flux measurements were conducted at 5-day intervals. Soil CO_2 flux was measured using a semi-automated chamber (Model 8200–01, LI-COR Inc.) placed securely on the pre-installed collars. The chamber was connected to an infrared gas analyzer (LI-8100A soil CO_2 flux system, Model 7810-01, LI-COR Inc.), which recorded CO_2 concentration inside the chamber every second over a 90 s measurement period. Prior to each measurement, the chamber was purged with air for 5 s, followed by a post-purge of 30 s between measurements to prevent cross-contamination among subplots. The chamber operation, including closing/opening, purging, and measurement cycles, was controlled via Wi-Fi-connected software provided by LICOR. Soil CO_2 fluxes were calculated using SoilFluxPro software (LI-COR Inc.) based on the exponential increase in CO_2 concentration, following the method described by Ads et al. (2026). All measurements were conducted between 8:30 a.m. and 11:00 a.m. to minimize diurnal variability in soil CO_2 flux.

2.7 | Soil analysis

Soil samples were collected after wheat was harvested from the 0- to 30-cm depth. The samples were air-dried, crushed, and passed through a 2-mm sieve prior to analysis to evaluate the effects of biochar and chicken manure amendments on soil characteristics. To assess the influence of biochar on soil salinity dynamics during the growing season, ceramic suction cups were installed in the center of each treatment plot, and soil solution samples were collected at 10-day intervals. Soil salinity was determined using saturated soil extracts, with ECe measured using an ECe meter (Mettler-Toledo, AG, 8603). Available soil N was extracted with 2 M KCl and determined using the micro-Kjeldahl method (BÜCHI Labortechnik AG, Distillation Unit K-355). Available P was extracted using 0.5 M $NaHCO_3$ at pH 8.5 and determined by spectrophotometer (SPECTRO UV-2510TS). Available K was extracted with ammonium acetate method and determined using flame photometry (JENWAY-PFP7). Soil carbon fractions, including SOC, total organic carbon (TOC), soil inorganic carbon (SIC), and microbial biomass carbon (MBC), were quantified to assess soil carbon dynamics under different treatments. TOC and SIC were measured using a Shimadzu TOC analyzer with a solid sample module (SSM-5000A), using approximately 1.0 g of soil per analysis. TOC was determined by high-temperature combustion at 900°C, converting carbon to CO_2, which was subsequently quantified by the analyzer. The TOC analyzer then quantified the total CO_2 output. IC was measured by acidification with HCl to release CO_2 from carbonates, following Gao et al. (2017). SOC was determined using the Walkley and Black method. Briefly, 2 g of soil was treated with 10 mL of 1N $K_2Cr_2O_7$ and 20 mL of concentrated H_2SO_4. After oxidation of organic matter, the remaining dichromate was titrated with 0.5 N $FeSO_4$ as detailed by Lettens et al. (2007). MBC was determined using the chloroform fumigation-extraction method (Joergensen, 1996). Soil samples were fumigated with chloroform, and microbial carbon was extracted using a K_2SO_4 solution. The extracted organic carbon was measured using the TOC analyzer, and MBC was calculated as the difference between fumigated and non-fumigated samples.

2.8 | Plant analysis

At physiological maturity (approximately 120 days after sowing), wheat plants were harvested and separated into roots, shoots, and grains. The roots were carefully washed with distilled water to remove adhering soil particles. All plant components were oven-dried at 75°C for 48 h until a content weight was achieved. The dried samples were finely ground to pass through a 0.2-mm sieve for subsequent chemical analysis. Subsamples (approximately 0.25 g) were digested using concentrated sulfuric acid (H_2SO_4) at 180°C for 60 min in a fume hood. Hydrogen peroxide (H_2O_2) was then added gradually until the digest became clear, indicating complete oxidation. The digested samples were cooled and diluted to a final volume of 50 mL with deionized water, followed by filtration. Total N was determined using the Kjeldahl method. P concentration was determined colorimetrically using ammonium molybdate and potassium antimonyl tartrate with ascorbic acid as a reduction agent ($\lambda = 700$ nm), using a Jenway 6405 UV-vis spectrophotometer. K concentration was determined using a flame photometer.

2.9 | DSSAT model setup, calibration, and parameterization

The DSSAT model (Version 4.8.2) was used to simulate the long-term effects of biochar and manure amendments on SOC and wheat productivity under saline irrigation in sandy soils. The CENTURY soil organic matter (SOM) module within DSSAT was employed to simulate carbon dynamics by partitioning SOC into active, slow, and passive pools with distinct turnover rates. The model was initialized using site-specific field data collected during the 2023–2024 wheat-growing season at the ICBA, Dubai, UAE. Input parameters included soil physicochemical properties, climatic data, and crop growth observations, as summarized in Tables 1 and 2 and Figure 2. Crop-specific variables, including phenological stages, leaf area index (measured weekly), and biomass accumulation, were recorded at key growth stages and used for model calibration. SOC was determined using the Walkley–Black wet oxidation method, which quantifies the oxidizable fraction of organic carbon. TOC was measured using a dry combustion method with an elemental analyzer (FLASHSMART CHNS/O analyzer). The use of both methods followed standard soil analysis protocols and enabled cross-validation between chemical oxidation and combustion-based determinations. SOC values were used for model initialization, while TOC served as an independent dataset for comparison and validation.

2.10 | Statistical analysis

Statistical analyses were performed using SPSS version 20.0 (SPSS Inc.). Data are presented as mean ± standard deviation (SD) based on three replicates per treatment. Differences among treatments were evaluated using one way analysis of variance, and statistical significance was determined at $p < 0.05$. Graphs were generated using Origin Pro 2018.

3 | RESULTS

3.1 | Effect of biochar on soil physicochemical properties and carbon fractions

The results showed that biochar amendments, either applied alone (+B) or in combination with chicken manure (B+M), induced significant changes in the physicochemical properties of saline-irrigated sandy soil (Table 3). ECe increased significantly ($p < 0.05$) by 39.25% under the B+M treatment compared with the compost treatment. Similarly, CEC was significantly enhanced ($p < 0.05$) under both +B and B+M treatments, suggesting an improved capacity of the soil to retain and exchange cations. In contrast, soil pH was not significantly affected by the treatments ($p > 0.05$). Moreover, biochar application significantly increased ($p < 0.05$) the availability of essential nutrients. Compared with the compost-only treatment, available N, P, and K increased by 77.78% and 145.19%, 167.14% and 354.23%, and 80.70% and 141.10% under +B and B+M treatments, respectively (Table 3). These findings suggest that biochar as sole or B+M can improve soil fertility and nutrient availability in saline sandy soils.

Biochar amendments significantly influenced soil carbon fractions in saline-irrigated sandy soils ($p < 0.05$, Table 4). TOC increased markedly, with values rising by 70.83% and 155.33% under +B and B+M treatments, respectively, compared with the compost treatment. Similarly, SOC showed significant increases ($p < 0.05$) of 117.66% and 208.98% under +B and B+M, respectively. SIC concentrations ranged from 1.41 to 6.61 g kg^{-1} across treatments (Table 4). Relative to the compost, SIC increased significantly ($p < 0.05$) by 126.95% and 368.79% under +B and B+M treatments, respectively. MBC, an indicator of microbial activity and soil health, also increased significantly ($p < 0.05$) by 132.29% and 187.68% under +B and B+M treatments, respectively, compared with the compost-only treatment. These results indicate that biochar amendments, particularly when combined with chicken manure, improve carbon accumulation and microbial activity, thereby improving carbon sequestration potential in saline sandy soils.

3.2 | Effect of biochar on soil CO_2 flux, total biomass carbon, and water use efficiency

The effects of biochar amendments on soil CO_2 emissions and fluxes were monitored throughout the wheat growing season under saline sandy soil conditions (Figure 3). To ensure accurate measurement of soil-derived CO_2 fluxes, independent of plant respiration, the area within each collar was kept free of vegetation across all treatments. Soil CO_2 emissions increased under the +B and B+M treatments during the active growth period (20–75 days after sowing) compared with the compost treatment. In contrast, CO_2 emissions declined during the harvest stage, suggesting that elevated emissions during earlier stages were primarily associated with increased microbial activity and rhizosphere processes during peak plant growth. Biochar amendments also influenced the temporal

TABLE 3 Effect of biochar amendments on soil physicochemical properties under saline irrigation.

Treatments	pH	ECe (dS m^{-1})	CEC (cmol kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
Compost	7.37 ± 0.08a	1.86 ± 0.14b	2.44 ± 0.04c	63.00 ± 3.70c	4.96 ± 2.47c	90.19 ± 18.13c
+B	7.49 ± 0.09a	2.09 ± 0.13b	2.68 ± 0.09b	112.00 ± 7.00b	13.25 ± 1.36b	162.97 ± 22.82b
B+M	7.52 ± 0.04a	2.59 ± 0.34a	3.11 ± 0.18a	154.47 ± 4.50a	22.53 ± 3.38a	217.45 ± 8.47a

Note: Vertical bars indicate the standard deviation of the mean ($n = 3$), different lowercase letters indicate significant differences by Ducan test ($p < 0.05$, $n = 3$). Abbreviations: AK, available potassium; AN, available nitrogen; AP, available phosphorus; +B, biochar; B+M, biochar combined with chicken manure; CEC, cation exchange capacity; ECe, electrical conductivity.

TABLE 4 Effect of biochar amendments on carbon fraction in saline-irrigated soil.

Treatments	TOC (g kg^{-1})	SOC (g kg^{-1})	SIC (g kg^{-1})	MBC (mg kg^{-1})
Compost	9.29 ± 2.30c	3.34 ± 0.16c	1.41 ± 0.35c	48.15 ± 3.39c
+B	15.87 ± 0.24b	7.27 ± 0.71b	3.20 ± 0.34b	111.85 ± 5.59b
B+M	23.72 ± 3.94a	10.32 ± 1.76a	6.61 ± 0.58a	138.52 ± 4.63a

Note: Vertical bars indicate the standard deviation of the mean ($n = 3$), different lowercase letters indicate significant differences by Ducan test ($p < 0.05$, $n = 3$). Abbreviations: +B, biochar; B+M, biochar combined with chicken manure; MBS, microbial biomass carbon; SIC, soil inorganic carbon; SOC, soil organic carbon; TOC, total organic carbon.

dynamics of CO_2 flux. Fluxes were consistently higher in the +B and B+M treatments than in the compost-only treatment, particularly from approximately 40 days after sowing onward. This increase in CO_2 flux in biochar-amended soils suggests enhanced carbon turnover and microbial activity, which may contribute to improving nutrient availability and crop performance under saline conditions.

Biochar amendments significantly increased the total biomass carbon of wheat, encompassing both aboveground and belowground biomass ($p < 0.05$, Figure 4A). Specifically, total biomass carbon increased by 28.38% and 55.82% under the +B and B+M treatments, respectively, compared with the compost treatment. Biochar application, either alone +B or B+M, also resulted in significantly higher cumulative CO_2 emissions ($p < 0.05$), increasing by 24.35% and 48.19%, respectively, relative to the compost treatment. The elevated cumulative CO_2 flux under +B and B+M indicates enhanced microbial activity and accelerated carbon turnover in response to increased organic inputs.

Water-use efficiency (WUE) was highest under the B+M treatment, reaching 6.67 kg mm^{-1} ha^{-1}, with a corresponding grain yield of 3013.87 kg ha^{-1}. The +B treatment achieved a WUE of 5.77 kg mm^{-1} ha^{-1} and a grain yield of 2608.57 kg ha^{-1}, whereas the compost treatment recorded the lowest WUE (4.70 kg mm^{-1} ha^{-1}) and grain yield (2126.53 kg ha^{-1}) (Figure 4C). These findings suggest that biochar, particularly B+M enhanced soil water retention and availability, thereby improving WUE and crop productivity. At the same time, the increased biomass production and organic inputs likely stimulate microbial activity, contributing to higher CO_2 fluxes and more active carbon cycling in saline sandy soils.

3.3 | Effect of biochar amendments on wheat growth and nutrient uptake

Biochar amendments significantly affected wheat growth parameters ($p < 0.05$), as shown in Figure 5. The application of biochar alone (+B) or B+M significantly increased plant height at both the initial and maturity stages compared with the compost treatment. The SPAD index, a unitless indirect measure of leaf chlorophyll content and plant nitrogen status obtained using a Soil Plant Analysis Development chlorophyll meter, also increased significantly ($p < 0.05$) at all growth stages under +B and B+M relative to the compost treatment. Our findings suggest that biochar amendments, particularly B+M, improve wheat growth in saline sandy soils by improving plant physiological status.

Biochar amendments significantly increased ($p < 0.05$) wheat biomass and grain yield under saline-irrigated sandy soil conditions (Figure 6). Compared with the compost treatment, both +B and B+M treatments resulted in substantial increases in root and shoot dry biomass. Root biomass increased by 81.6% and 165.5%, while shoot biomass increased by 41.9% and 93.2% under the +B and B+M treatments, respectively. Grain yield was also significantly improved ($p < 0.05$), increasing by 50.9% under +B and 90.3% under B+M relative to compost treatment. These results demonstrate that integrating biochar and chicken manure is particularly effective in improving crop growth and productivity in saline sandy soils. Biochar amendments also significantly increased ($p < 0.05$) macronutrient uptake (N, P, and K) across all wheat organs (Figure 6B–D). N uptake increased by 54.8% and 114.4% in roots, 50.6% and 72.7% in shoots, and 48.7% and 69.5% in grains under +B and B+M,

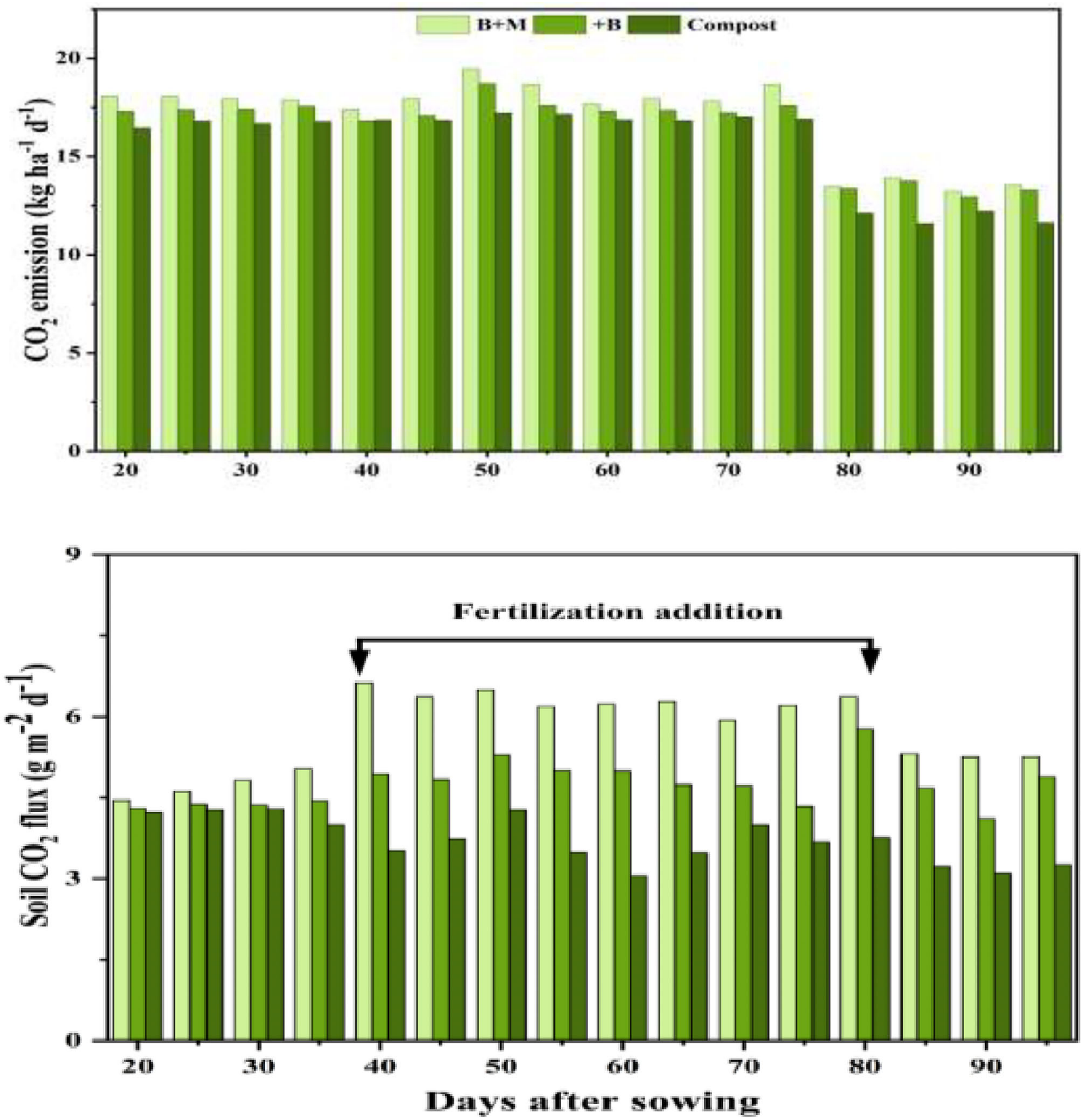

FIGURE 3 Effect of biochar amendments on soil CO_2 emission, weekly CO_2 flux in wheat cultivated under compost, (+B) biochar, and biochar combined with chicken manure (B+M) in saline-irrigated sandy soil (5 dS m^{-1}).

respectively, compared with the compost treatment. P uptake also increased significantly ($p < 0.05$) by 50.1% and 76.7% in roots, 18.9% and 27.4% in shoots, and 49.4% and 66.3% in grains under +B and B+M, respectively. Similarly, K uptake increased by 53.9% and 69.2% in roots, 45.2% and 69.9% in shoots, and 42.4% and 54.0% in grains relative to the compost treatment. Overall, biochar amendments, particularly B+M, improved wheat biomass production, grain yield, and nutrient uptake, highlighting their potential to improve soil fertility and crop performance in marginal saline soil.

3.4 | DSSAT model validation and performance

3.4.1 | Model validation: observed versus simulated wheat yields

As shown in Figure 7, a strong linear relationship was observed between measured and simulated wheat yields, with a coefficient of determination (R^2) of 0.93. The regression slope (0.9151) was slightly below unity, indicating a tendency

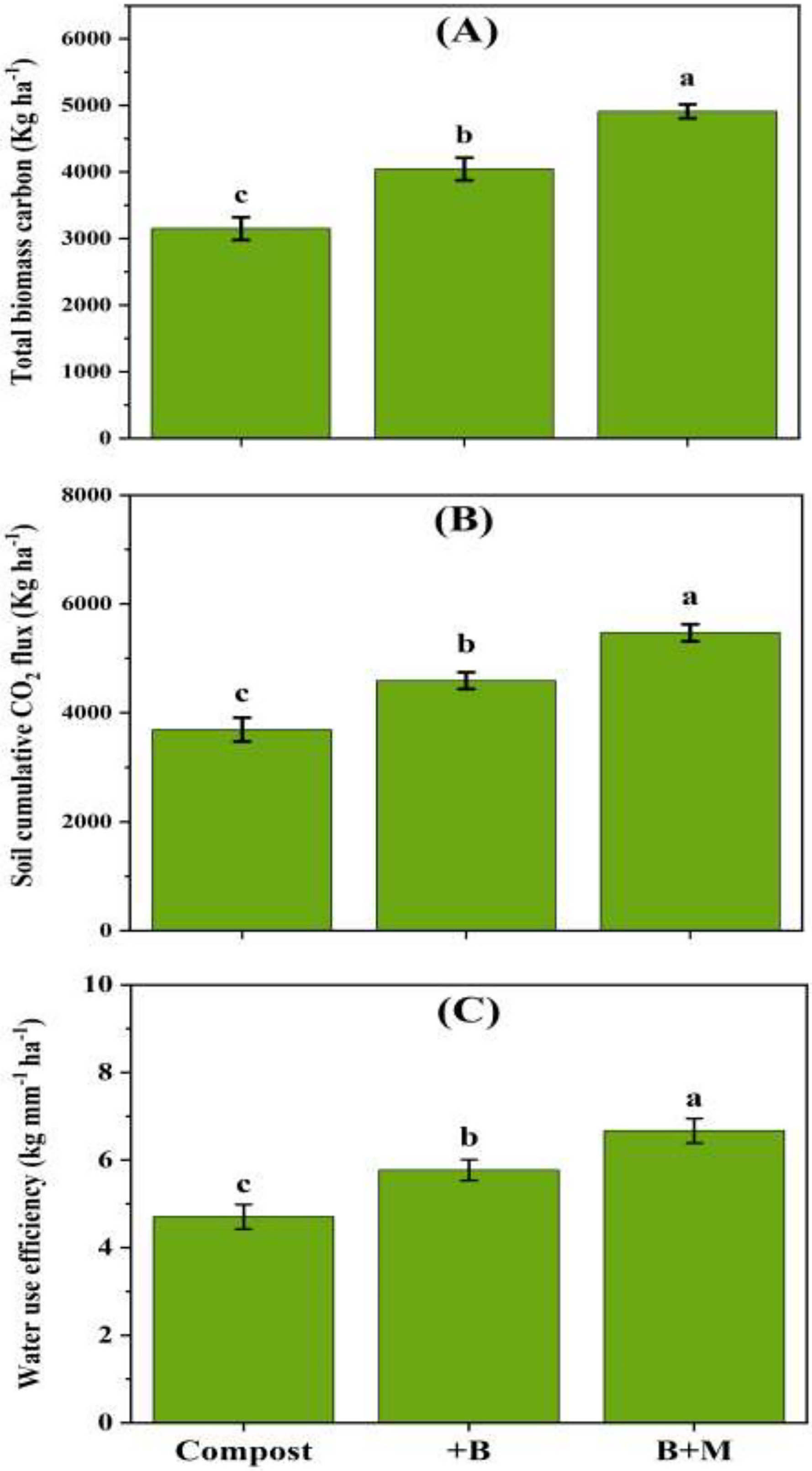

FIGURE 4 Effect of biochar amendments on total biomass carbon (A), accumulative soil carbon (B), and water use efficiency (C) of wheat grown under compost, biochar (+B), and biochar combined with chicken manure (B+M) in saline-irrigated sandy soil (5 dS m^{-1}). Vertical bars indicate the standard deviation of the mean ($n = 3$); different lowercase letters indicate significant differences by Ducan test ($p < 0.05$, $n = 3$).

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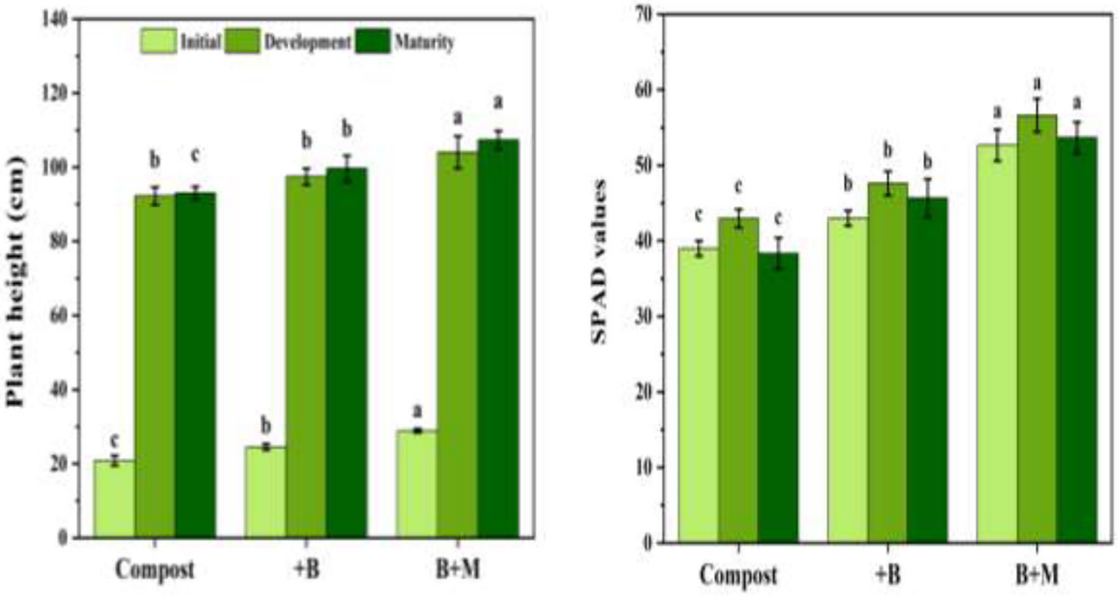

FIGURE 5 Effect of biochar amendments on plant height and SPAD values of wheat at different growth stages under compost, biochar (+B), and biochar combined with chicken manure (B+M) in saline-irrigated sandy soil (5 dS m^{-1}). Vertical bars indicate the standard deviation of the mean ($n = 3$); different lowercase letters indicate significant differences by Duncan test ($p < 0.05$, $n = 3$).

for minor underprediction at lower yield levels and slight overestimation at higher yield levels. The intercept (0.2503) suggests a small positive bias in the simulated values. Across treatments, simulated yields closely matched observed values. The compost treatment produced the lowest yields, averaging 2.38 t ha^{-1} (observed) and 2.50 t ha^{-1} (simulated). The biochar treatment (+B) resulted in intermediate yields of 3.38 t ha^{-1} (observed) and 3.35 t ha^{-1} (simulated), whereas the B+M treatment achieved the highest yields, with 3.88 t ha^{-1} (observed) and 3.90 t ha^{-1} (simulated). Model performance statistics further confirmed high predictive accuracy, with a root mean square error (RMSE) of 0.32 t ha^{-1} and a mean absolute error (MAE) of 0.25 t ha^{-1}. These correspond to relative errors of approximately 10.2% (RMSE) and 8.0% (MAE), based on the observed yield range (2.25–4.0 t ha^{-1}) and mean yield (3.13 t ha^{-1}). Overall, the close agreement between observed and simulated yields indicates that the DSSAT model reliably captured treatment effects and adequately reproduced wheat yield response under saline, sandy soil conditions.

3.4.2 | Long-term simulations of SOC dynamics

The DSSAT-CENTURY model was used to simulate SOC dynamics over a 20-year period under different biochar amendments (Figure 8). The simulations showed a consistent increase in SOC across all treatments, with the B+M treatment exhibiting the greatest accumulation throughout the simulated period. After 20 years, predicted SOC concentrations reached 9.7 g kg^{-1} in the compost treatment, 17.5 g kg^{-1} under +B, and 21 g kg^{-1} under B+M. The rate of SOC increase was most pronounced during the initial 5–10 years, followed by a gradual stabilization with slower rates of accumulation in later years. In terms of annual carbon sequestration rates, the B+M treatment achieved approximately 7.2 Mg C ha^{-1} $year^{-1}$, followed by 6.3 Mg C ha^{-1} $year^{-1}$ under +B, whereas the compost treatment remained below 1.0 Mg C ha^{-1} $year^{-1}$. These results highlight clear treatment-dependent differences in modeled SOC trajectories, with biochar, particularly B+M substantially enhancing long-term carbon sequestration in saline sandy soils.

4 | DISCUSSION

4.1 | Effect of biochar on soil physicochemical properties in marginal soils

Biochar application markedly improved soil physicochemical properties and nutrient availability in saline-irrigated sandy soil. The observed increases in CEC and soil carbon fractions (Tables 3 and 4) indicate that biochar, either applied alone or in combination with chicken manure (B+M), enhanced the soil's capacity to retain nutrients and improve overall fertility. These improvements can be attributed to biochar's high surface area, porous structure, and abundance of oxygen-containing functional groups, which facilitate cation exchange, nutrient adsorption, and improved soil

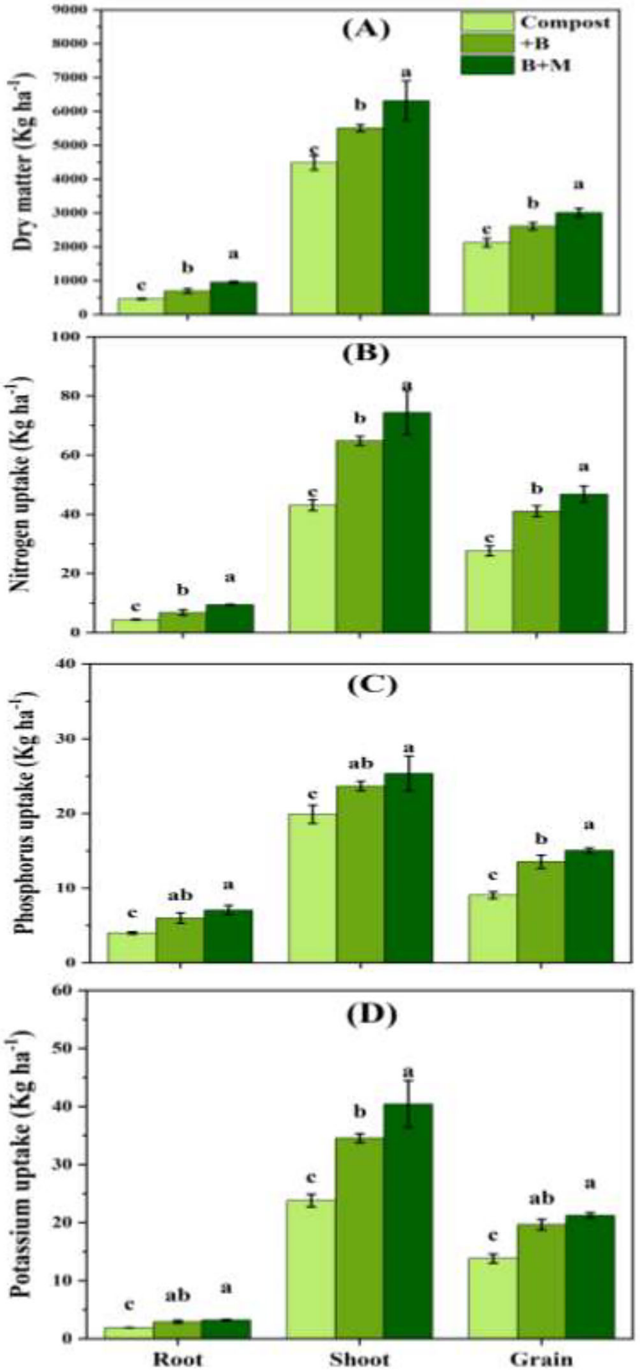

FIGURE 6 Effect of biochar amendments on dry matter and N, P, and K uptake in wheat organs grown under compost, biochar (+B), and biochar combined with chicken manure (B+M) treatments in saline-irrigated sandy soil (5 dS m^{-1}). Vertical bars indicate the standard deviation of the mean ($n = 3$), and different lowercase letters indicate significant differences by the Ducan test ($p < 0.05$, $n = 3$).

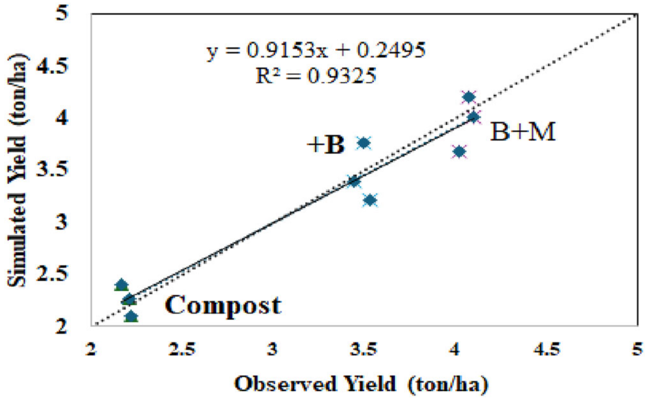

FIGURE 7 Scatter plot of observed versus simulated wheat yield (t ha^{-1}) under three treatments: compost, biochar (+B), and biochar combined with chicken manure (B+M). Each treatment includes three replicates. The solid line represents the fitted regression model.

aeration and aggregation (Bolan et al., 2024; Dikinya & Mufwanzala, 2010; Lin et al., 2022). Under saline conditions, biochar can adsorb and immobilize soluble salts on its surface and within its pore structure, thereby alleviating salinity stress in the rhizosphere (El-Naggar et al., 2019). This mechanism likely contributed to the reduced salinity effects and enhanced plant growth observed in biochar-amended soils. In addition, B+M improved nutrient availability through complementary mechanisms: manure provides readily mineralizable nutrients (particularly N and P), while biochar enhances nutrient retention and reduces leaching losses. This synergistic interaction is consistent with previous findings (Lin et al., 2022; Mukherjee et al., 2022) and promotes microbial activity and nutrient cycling, ultimately improving soil fertility and crop performance in saline sandy soils (Bolan et al., 2024). Biochar has been widely reported to improve soil hydraulic properties and WUE, particularly in coarse-textured and saline soils. By improving soil aggregation, reducing bulk density, and increasing porosity, biochar enhances hydraulic conductivity and facilitates water infiltration, which can promote the leaching of excess salts from the root zone (She et al., 2018). In the present study, WUE increased significantly ($p < 0.05$) under +B and B+M treatments compared with the compost treatment (Figure 4C). This improvement reflects biochar's ability to enhance soil moisture retention, reduce evaporative losses, and maintain favorable water availability for plant uptake under saline irrigation conditions. Similar findings have been reported by Lin et al. (2022), who demonstrated improved soil-water relations and sustained crop productivity following biochar application in arid and saline environments. In addition, biochar derived from calcium-rich feedstocks can promote the replacement of sodium ions on soil exchange sites through flocculation, thereby improving soil structure and reducing sodicity (Huang et al., 2023). In saline systems, elevated ionic strength and Ca^{2+} availability may also promote carbonate formation, while the high surface area and porosity of biochar provide favorable sites for inorganic carbon stabilization (Li et al., 2021). Collectively, these mechanisms highlight the role of biochar in improving soil structure, enhancing water retention, and mitigating salinity stress. The

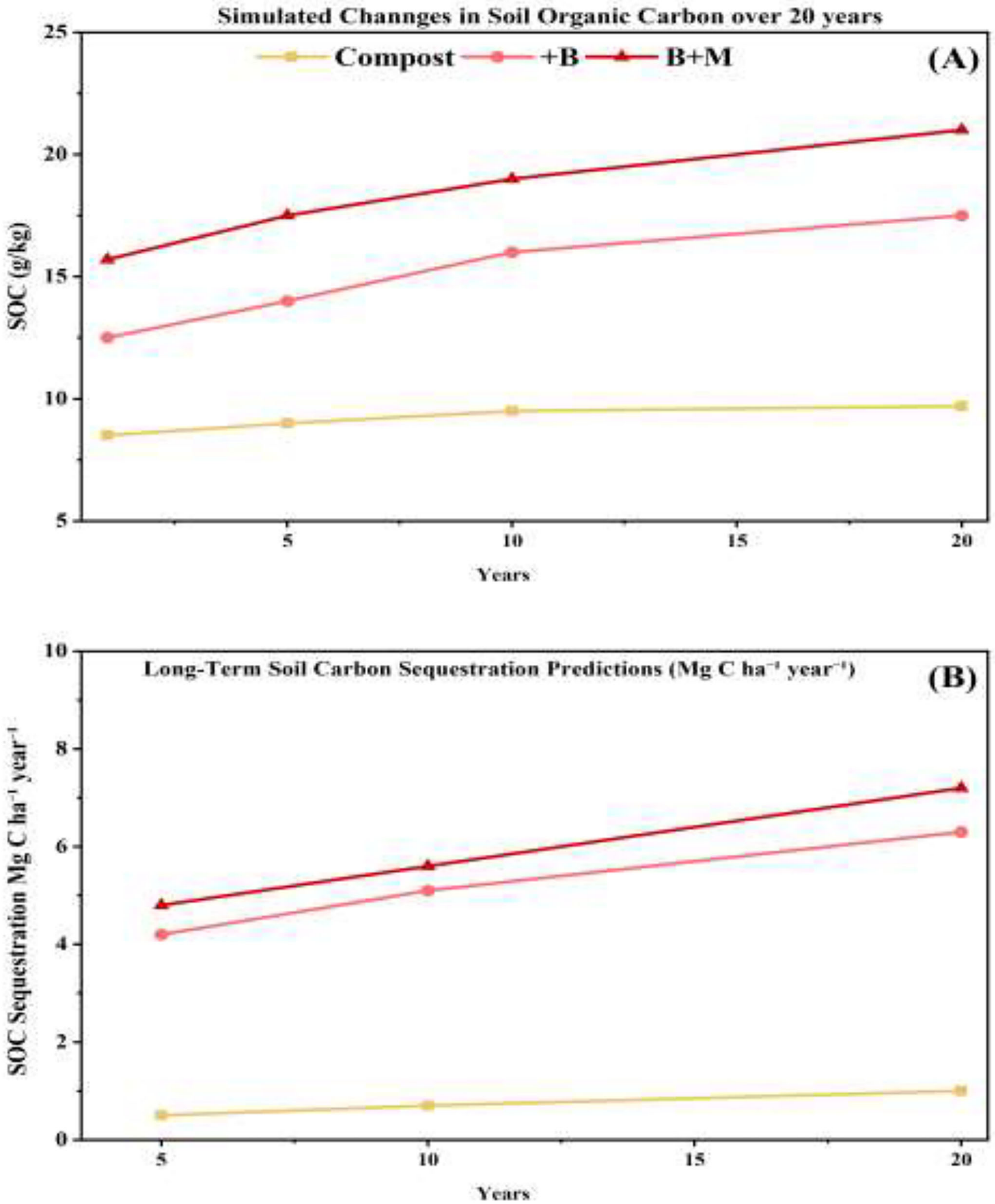

FIGURE 8 Simulated changes in soil organic carbon (SOC) and predicted SOC sequestration (Mg C ha^{-1} year^{-1}) over a 20-year period under three treatments: compost, biochar (+B), and biochar mixing with chicken manure (B+M).

significant increases in N, P, and K uptake by different wheat organs under biochar amendments (Figure 6) further underscores the improvement in nutrient availability in marginal soil. These findings are consistent with Bekchanova et al. (2024), who reported that biochar act as a nutrients reservoir, particularly in sandy or degraded soils, by enhancing nutrient retention and reducing losses. This synergistic interaction between biochar and manure enhances soil structure, stimulates microbial activity, and improves nutrient cycling, thereby increasing nutrient-use efficiency (Bekchanova et al., 2024; Nepal et al., 2023). In present study, the increased uptake of N, P, and K under biochar treatments suggests that nutrients were maintained in more plant-available forms. This effect is particularly important in saline environments, where high salt concentrations often limit nutrient availability and uptake by plant roots (Meena et al., 2019). Previous studies have shown that biochar can enhance P availability by reducing P fixation into unavailable forms, thereby improving plant uptake (Gao et al., 2019). Similarly, biochar can increase K availability in soil with low CEC by providing additional exchange sites and reducing leaching losses (S. Khan et al., 2024).

4.2 | Effect of biochar on CO_2 sequestration in marginal soil

Soil CO_2 emissions are a key component of the terrestrial carbon cycle and are strongly influenced by soil type, environmental conditions, and organic amendments. Biochar is widely recognized for its potential to improve carbon sequestration due to its high content of stable, recalcitrant carbon; however, its effects on short-term CO_2 emissions can vary considerably (Al-Wabel et al., 2020; Ennis et al., 2012). In saline or nutrient-poor soils, biochar application may initially increase CO_2 flux as a result of stimulated microbial activity and enhanced decomposition of labile organic matter (Ali et al., 2021). In the present study, biochar amendments significantly increased CO_2 emissions in saline sandy soil (Figure 3). This increase can be attributed to several interacting mechanisms, including stimulation of microbial activity, a priming effect on native SOC, and increased mineralization of labile carbon fractions introduced with the amendments (He et al., 2017; S. Liu et al., 2016). Similar trends have been reported in previous studies, with increases in CO_2 emissions of up to 22.14% following biochar application (He et al., 2017), highlights its dual role in soil carbon dynamics. The interaction between biochar, SOC, and nutrient inputs further influences CO_2 fluxes. Systems with higher tend to exhibit greater CO_2 emissions following biochar addition due to enhanced microbial decomposition. This effect can be amplified by N fertilization, which stimulates microbial activity and SOC mineralization (Kimetu & Lehmann, 2010). Consistent with these findings, our results showed increased SOC levels in biochar-amended treatments under saline irrigation (Table 4). This response is particularly important in marginal soil, where carbon cycling processes differ from those in more fertile systems (Ali et al., 2021; S. Khan et al., 2024). Despite the short-term increase in CO_2 emissions, biochar contributes to long-term carbon sequestration through multiple pathways. Its porous structure and high surface area facilitate the stabilization of organic carbon and promote the formation and retention of SIC through carbonate chemistry, further enhancing SIC accumulation in nutrient-limited soils (Ali et al., 2021; He et al., 2017). The elevated SIC observed in biochar-amended treatments supports its role in stabilizing carbon and reducing long-term (Kimetu & Lehmann, 2010). These findings underscore the dual role of biochar in soil carbon dynamics: while it may temporarily increase CO_2 emissions due to enhanced microbial activity, it also contributes to the buildup of stable carbon pools (SOC and SIC) over time. To maximize these benefits while minimizing short-term GHG emissions, integrated management strategies are required. Approaches such as optimizing irrigation regimes, combining biochar with controlled-release fertilizers, or integrating high carbon-fixing crops may help mitigate initial CO_2 emissions while enhancing long-term soil carbon storage (Ennis et al., 2012; He et al., 2017; Lin et al., 2022; S. Liu et al., 2016). Future research should therefore focus on developing integrated soil management practices that balance microbial activity and carbon stabilization, particularly under saline and marginal soil conditions.

4.3 | Predictive accuracy and long-term biochar effects on wheat productivity and SOC

The validated DSSAT-CENTURY model effectively reproduced observed wheat yields under saline-irrigated sandy soil conditions, demonstrating strong predictive accuracy across amendment treatments (R^2 = 0.93; RMSE = 0.32 t ha^{-1}; Figure 7). This agreement confirms the model's capacity to capture treatment-induced differences in crop performance resulting from improvements in soil structure, nutrient status, and water retention (Jeffery et al., 2017; Lehmann et al., 2011; Major et al., 2010). Minor discrepancies between simulated and observed yields were within acceptable ranges, indicating robust model calibration. Beyond short-term validation, the DSSAT-CENTURY simulations projected substantial long-term gains in SOC over a 20-year period. SOC accumulation followed a continuous upward trend, reaching 21.0 g kg^{-1} under B+M, 17.5 g kg^{-1} under +B, and 9.7 g kg^{-1} under the compost treatment (Figure 8). The initial rapid increase during the first decade likely reflects the decomposition of labile organic inputs and the incorporation of biochar into soil aggregates, while the later plateau suggests stabilization within more recalcitrant carbon pools (Amelung et al., 2020). The modeled annual SOC sequestration rates (7.2 Mg C ha^{-1} $year^{-1}$ for B+M and 6.3 Mg C ha^{-1} $year^{-1}$ for +B) exceed global agricultural averages, which typically range from 0.3 to 1.0 Mg C ha^{-1} $year^{-1}$ (Amelung et al., 2020; Lal, 2016). These results highlight the strong potential of biochar-based interventions to enhance soil carbon stocks, particularly in sandy soils with low initial organic matter. The model's performance also demonstrates the sensitivity of SOC dynamics to organic inputs and microbial stabilization processes, consistent with findings from long-term field studies (Major et al., 2010; Yuan et al., 2023). However, several limitations should be acknowledged. First, this study was conducted in a coarse-textured sandy soil, which is characterized by low organic matter content, rapid drainage, and limited nutrient retention. Therefore, caution is required when extrapolating these results to other soil types, particularly fine-textured or clay-rich soils, where biochar-soil interactions and carbon stabilization mechanisms may differ. Second, although the DSSAT-CENTURY model showed strong performance in simulating wheat yield, its validation was primarily based on crop productivity data. The model does not explicitly account for detailed biochar-specific SOC dynamics, such as long-term stability, priming effects, or interactions with mineral-associated organic matter. As a result, projections of SOC sequestration may involve some uncertainty and should be interpreted with caution. Additionally, model assumptions such as constant climatic conditions and management practices introduce further uncertainty into long-term simulations. The predicted SOC increase in the compost treatment (9.7 g kg^{-1}) reflects continuous carbon inputs from compost decomposition and crop residue incorporation simulated by the CENTURY module. Although these processes contribute to gradual SOC accumulation, their effects are less pronounced than in biochar-amended systems. Overall, the DSSAT-CENTURY model captured both the immediate agronomic benefits and the long-term carbon sequestration potential of biochar and manure amendments. The co-application of these materials improved wheat productivity and enhanced soil carbon stability, supporting sustainable crop production and climate change mitigation in saline, marginal agroecosystems. Nevertheless, long-term field validation and integration of more advanced SOC modeling approaches are recommended to refine these projections and improve their applicability across diverse soil systems.

5 | CONCLUSION

This study demonstrates that biochar application particularly when co-applied with chicken manure, substantially improves soil fertility, nutrient availability, and carbon storage in saline-irrigated sandy soils. The combined amendment enhanced CEC and macronutrient (N, P, and K), leading to significant improvements in wheat productivity while maintaining stable soil pH. These benefits were accompanied by pronounced increases in both soil organic and inorganic carbon pools, indicating enhanced biological activity and improved long-term carbon stabilization. Although short-term increases in CO_2 emissions were observed, these were associated with elevated microbial activity and intensified nutrient cycling, reflecting more active and functionally improved soil processes. Long-term simulations using the DSSAT-CENTURY model further projected sustained SOC accumulation over a 20-year period, highlighting the considerable carbon sequestration potential of biochar manure amendments in coarse-textured, low-carbon soils. However, several limitations should be acknowledged. The DSSAT model was calibrated using data from a single growing season, and therefore long-term SOC projections remain subject to uncertainty. In addition, the model validation was primarily based on crop yield and does not explicitly account for detailed biochar-specific carbon dynamics. Furthermore, the study was conducted in a coarse-textured sandy soil, and thus caution is required when extrapolating these findings to other soil types with different physicochemical properties. Biochar aging processes, particularly under saline irrigation, may also alter its chemical structure, porosity, and stability, thereby influencing long-term carbon retention. Future research should focus on (i) quantifying the effects of biochar aging and salinity on carbon stability and microbial dynamics, (ii) integrating long-term field experiments with improved model representation of SOC processes, and (iii) developing optimized biochar formulations tailored to specific soil and climatic conditions. Overall, this study provides strong evidence that integrating biochar with organic amendments is an effective, climate-resilient strategy for enhancing soil fertility, increasing carbon sequestration, and sustaining wheat productivity in saline, marginal environments.

AUTHOR CONTRIBUTIONS

Mohamed G. Moussa: Conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing—original draft; writing—review and editing. **Khalil Ammar**: Investigation. **Ahmed H. El-Naggar**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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