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Ameliorating Saline Clay Soils with Corncob Biochar for Improving Chickpea (*Cicer arietinum* L.) Growth and Yield

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Abstract

Biochar is a carbon-rich material produced through the pyrolysis of agricultural waste. It effectively enhances the physical, chemical, and biological properties of salinity-affected soils. Chickpea (*Cicer arietinum* L.) is the world's third most important legume crop, currently cultivated in over 50 countries. However, no study has yet established recommended biochar application rates for this crop under saline soil conditions. Therefore, this study aimed to assess the chemical properties of a clay soil following the application of varying rates of biochar and NaCl, and to evaluate their subsequent effects on the growth and yield of *Cicer arietinum* L. To evaluate the effect of biochar, a completely randomized experimental design with ten replicates was implemented. The biochar was produced from corncobs (*Zea mays*) and applied at two rates (1.5% and 3%). Soil salinity levels were classified into three groups: non-saline ($S_1 = 1.2 \text{ dS} \cdot \text{m}^{-1}$), low/moderate salinity ($S_2 = 4.2 \text{ dS} \cdot \text{m}^{-1}$), and moderate salinity ($S_3 = 5.6 \text{ dS} \cdot \text{m}^{-1}$). The treatments were placed in pots for 100 days. The results demonstrated that biochar applications at 1.5% and 3% rates improved both soil chemical properties (pH, EC, SAR, and ESP) and the growth of *C. arietinum* across all evaluated treatments. The 3% biochar treatment showed superior effects compared to the 1.5% application. Therefore, biochar application in *C. arietinum* production emerges as an effective agronomic strategy to mitigate abiotic stress while simultaneously enhancing crop productivity and sustainability.

Keywords: crop resilience; soil health; salt tolerance; organic amendment



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1. Introduction

Soil salinity is a major constraint on agricultural productivity, rendering affected soils infertile and unproductive [1]. It is estimated that approximately 1125 million hectares of soil across the world are affected by this condition, and about 76 million saline-sodic hectares are a result of anthropogenic impacts on the environment [2]. Crops exposed to salinity face several physiological challenges, including ionic stress [3], osmotic stress [4], and the interruption of homeostasis [5]. These stresses are further compounded by a range of morphological, physiological, and biochemical effects that, overall, negatively affect nutrient acquisition, transpiration, and the photosynthetic apparatus function, thereby

causing decreased growth and, in most cases, death of the plants [6]. In recent years, biochar has gained importance in agriculture as a soil amendment, standing out for its multiple benefits: (a) improving agricultural production by providing essential nutrients (calcium, magnesium, phosphorus, and potassium) [7]; (b) optimizing soil physical (water retention, bulk density) and chemical properties (pH, electrical conductivity [EC], cation exchange capacity [CEC]) [8]; (c) contributing to carbon sequestration and nutrient cycling [9]; and (d) promoting plant health through extracellular microbial enzyme production [10]. Biochar is a carbon-rich material produced through the pyrolysis of agricultural residues, wood, or crop waste [11] under the complete absence (pyrolysis) or partial absence (gasification) of oxygen at temperatures ranging from 300 to 1000 °C [12]. This process leads to the conversion of biomass materials into a stable carbon substance.

Recently, several studies have demonstrated that biochar addition is effective in improving the physical, chemical, and biological properties of salt-affected soils [10]; for example, it has been found that biochar mitigates the adverse effects of saline soils on the production of tomato (*Solanum lycopersicum* L.) [13], barley (*Hordeum vulgare* L.) [14], sugar beet (*Beta vulgaris* L.), alfalfa (*Medicago sativa* L.), amaranth (*Amaranthus caudatus*), and corn (*Zea mays*) [15]. Given this demonstrated positive impact on crop resilience to salinity, the question arises regarding its potential application in one of the world's most important legumes. Chickpea (*Cicer arietinum* L.) is the third most important legume in the world [16], with an annual production of 14.2 million tons and an average yield of 0.96 t/ha [17]. Its cultivation extends to more than 50 countries, from the Indian subcontinent and North Africa to the Middle East, southern Europe, America and Australia [18]. This autogamous legume stands out for its high nutritional value for both human consumption and animal feed because it is rich in vitamins, minerals (such as calcium, phosphorus, magnesium and potassium) and essential amino acids lysine, methionine, threonine, valine and leucine, in addition to containing β -carotene [19]. These properties make it an essential food for low-income communities, especially in developing countries where animal proteins are scarce [20]. The increasing prevalence of soil salinity, whether due to natural processes or human activities, poses a significant threat to global agricultural production, particularly for salt-sensitive crops such as chickpea (*Cicer arietinum*) [21]. This situation highlights the need to investigate biochar's potential to (1) improve the soil chemical properties when salinity levels vary, and (2) enhance crop growth and yield under saline stress conditions.

Therefore, this study aimed to assess the chemical properties of a clay soil following the application of varying rates of biochar and NaCl, and to evaluate their subsequent effects on the growth and yield of *Cicer arietinum* L. We hypothesized that increasing the application rate of biochar will mitigate sodic salinity by reducing Na^+ accumulation, enhancing cationic exchange capacity (CEC), and improving the availability and uptake of macro- and micronutrients. These improvements are expected to enhance soil structure and fertility, thereby promoting greater growth and yield of *Cicer arietinum* L. under saline-sodic stress conditions.

2. Materials and Methods

2.1. Raw Material

Waste from corncobs (*Z. mays*) was obtained in the town of La Palma, in the municipality of Venustiano Carranza, in the region Ciénega de Chapala Michoacán, México (20°06'56" N, 102°39'12" W, at 1520 m.a.s.l.). The dry material was deposited in a pyrolysis reactor [22] and processed to an average temperature of 550 °C for 2 h. At the end of the pyrolyzation process, the biochar obtained was left to cool down and then ground and sieved using a mesh with an opening diameter of 0.5 mm.

2.2. Characterization of Biochar

The yield of the pyrolyzed raw material was determined using the following equation:

$$\text{Yield}(\%) = \frac{(\text{biochar weight})}{(\text{raw material weight})} * 100 \quad (1)$$

The pH and electrical conductivity (EC) were measured by adding biochar to deionized water at a ratio of 1:20 with stirring time of 1 h [23]. The pH of the solution was determined using a pH meter, Hanna HI-2211, and the EC was measured with a conductivity meter, Hanna HI-2300.

The cation exchange capacity (CEC) was measured by displacing the cations with 1N ammonium acetate [24], while the exchangeable bases were quantified in the leachate with atomic absorption spectrometry (SENS-AAS). To measure the moisture percentage and water holding capacity (WHC), the standardized method of Alef and Nannipieri [25] was used while, for bulk density, the method of Hussain et al. [26] was applied.

To determine the moisture content, the samples were placed in a stove at 105 °C for 2 h; for the volatile matter, the samples were placed in a muffle furnace at 950 °C for 6 min and, for the ashes, at 750 °C for 6 h. A sample of 1 g of biochar was used in each test. For the analysis of carbon, nitrogen, phosphorus, potassium, calcium, magnesium, and sodium, the methodology proposed by the International Biochar Initiative [23] was used. All determinations were made in triplicate.

For the adsorption analysis, 1 g of each biochar sample was taken and placed in 50 mL polypropylene tubes containing 40 mL of sodium chloride (NaCl) solution at 100 mM. The tubes were shaken for 24 h on a mechanical shaker at 150 rpm. After shaking, the supernatant was removed using centrifugation at 10,000 × g rpm for 5 min, and a clear 20 mL aliquot was taken and analyzed with an atomic absorption spectrometer (GBC SENS-AAS).

The sodium adsorption of biochar was calculated with the equation used by Awan et al. [27]:

$$CA = \frac{C_i - C_f}{m * V} \quad (2)$$

where CA is the Na⁺ adsorption capacity of the biochar, C_i (mg L⁻¹) and C_f (mg L⁻¹) are the initial and final concentrations of Na⁺ before and after the addition of biochar, V is the volume of the NaCl solution in the polypropylene tubes, and m is the dose of biochar (g).

Therefore, the biochar displayed the following physicochemical properties: yield was 12.3 ± 0.14%, apparent density was 0.27 ± 0.02 g cm⁻³, moisture was 11.6 ± 0.08%, volatile matter was 35 ± 1.48%, ash was 4.8 ± 0.22%, pH was 6.8 ± 0.2, electrical conductivity (EC) was 1.29 ± 0.16 dS m⁻¹, water holding capacity (WHC) (%) was 175.7 ± 3.32, cation exchange capacity (CEC) was 38.54 ± 0.36 cmol·kg⁻¹, carbon (C) was 430.8 ± 7.31 mg g⁻¹, nitrogen (N) was 21.3 ± 0.25 mg g⁻¹, C/N ratio was 20.2 ± 0.14, phosphorus (P) was 9.92 ± 0.17 mg g⁻¹, potassium (K) was 16.37 ± 0.27 mg g⁻¹, calcium (Ca) was 6.12 ± 0.12 mg g⁻¹, magnesium (Mg) was 4.28 ± 0.09 mg g⁻¹, sodium (Na) was 0.48 ± 0.01 mg g⁻¹, and sodium adsorption of biochar (CA) was 14.6 ± 0.15 mg g⁻¹ (Tables S1 and S2, and Figure S1).

2.3. Seed Material

The seeds of the crop *Cicer arietinum* L. X San Antonio 05 were obtained from a commercial seed and agrochemical company in the study region.

2.4. Initial Physicochemical Analysis of the Soil

The used soil was obtained from a plot in the municipality of Jiquilpan de Juárez, Michoacán, México (19°59'55.7" N, 102°42'25.7" W, at 1550 m.a.s.l.), with the following

characteristics: a vertisol soil with a clay loam texture [clay (62%), silt (12%), sand (26%)] according to the soil texture classification system of the United States Department of Agriculture (USDA) and in the World Reference Base for Soil Resources (WRB), bulk density (ρ_b) was $1.4 \pm 0.1 \text{ g cm}^{-3}$ [26], pH was 7.2 ± 0.2 , electrical conductivity (EC) was $1.2 \pm 0.16 \text{ dS} \cdot \text{m}^{-1}$, organic matter (% OM) was $1.4 \pm 0.1\%$, sodium adsorption ratio (SAR) was $6.5 \pm 0.12 (\text{mmol}_c \text{ L}^{-1})^{0.5}$, water retention capacity (WRC) was $91 \pm 2.76\%$, cation exchange capacity was $33 \pm 1.84 \text{ cmol}_c \cdot \text{kg}^{-1}$, and exchangeable sodium percentage (ESP) was $12.3 \pm 0.21\%$.

2.5. Treatments

Three levels of salinity were tested, in which different amounts of NaCl (analytical grade) were introduced to achieve different concentrations of salinity in the soil, beginning with $10.34 \text{ g} \cdot \text{pot}^{-1}$ NaCl to increase the base electrical conductivity from 1.2 to $4.2 \text{ dS} \cdot \text{m}^{-1}$ and $13.52 \text{ g} \cdot \text{pot}^{-1}$ NaCl to increase the conductivity from 1.2 to $5.6 \text{ dS} \cdot \text{m}^{-1}$. In particular, the same soil was used but with different saline concentrations, which were identified as follows: non-saline $1.2 \text{ dS} \cdot \text{m}^{-1}$ (S1), low/moderate salinity $4.2 \text{ dS} \cdot \text{m}^{-1}$ (S2), and moderate/medium salinity $5.6 \text{ dS} \cdot \text{m}^{-1}$ (S3). The salinity levels proposed were based on research by Kaur et al. [20] and Sobh et al. [25], who suggested that *C. arietinum* can tolerate moderate and marginal salinity.

Fifteen days before starting the experiment, the biochar was mixed in each of the salinized soils (S1, S2, and S3) at different proportions: NBCO (0% biochar, w/w), SBCO (1.5% biochar, $w/w \approx 18,711 \text{ kg ha}^{-1}$), and MBCO (3% biochar, $w/w \approx 37,422 \text{ kg ha}^{-1}$), respectively.

Therefore, the treatments were as follows: T1: [soil (S1) + *C. arietinum* + 0% biochar (NBCO)]; T2: [soil (S1) + *C. arietinum* + 1.5% biochar (SBCO)]; T3: [soil (S1) + *C. arietinum* + 3% biochar (MBCO)]; T4: [soil (S2) + *C. arietinum* + 0% biochar (NBCO)]; T5: [soil (S2) + *C. arietinum* + 1.5% biochar (SBCO)]; T6: [soil (S2) + *C. arietinum* + 3% biochar (MBCO)]; T7: [soil (S3) + *C. arietinum* + 0% biochar (NBCO)]; T8: [soil (S3) + *C. arietinum* + 1.5% biochar (SBCO)]; T9: [soil (S3) + *C. arietinum* + 3% biochar (MBCO)].

Each treatment comprised 10 experimental units. The experiment was replicated three times in a single experimental run, resulting in a total of 270 experimental units. The experimental design was completely randomized.

2.6. Greenhouse Experiment

Unperforated pots, 40 cm in height and 35 cm in diameter, were used. Each pot was filled with 12 kg of a soil/biochar mixture in different proportions, according to the established treatments. The mixture of soil with NaCl (according to the established treatments) and the biochar was manually homogenized until visual uniformity was achieved. For the preparation of the soil samples, they were dried only in the shade and at room temperature, without any additional pretreatment (such as sieving, sterilization, or thermal drying), in order to preserve the natural properties of the soil. This approach was chosen to simulate field conditions, where soils are typically unmodified prior to amendment application.

During the 15-day incubation period, soil moisture was maintained at 60% of water holding capacity (WHC) by daily monitoring and replenishment with water [25]. This level was chosen to ensure optimal microbial activity while preventing waterlogging.

A chickpea seedling was transplanted into each of these pots which, at the time of transplanting exhibited the following characteristics: 30 days of germination, a height of $16.7 \pm 1.63 \text{ cm}$, a root length of $9.42 \pm 1.34 \text{ cm}$, a fresh weight of $9.71 \pm 0.85 \text{ g}$, a stem diameter of $0.6 \pm 0.03 \text{ cm}$, and a leaf area of $66.7 \pm 1.7 \text{ cm}^2$.

The experiment was completed 100 days after transplanting (phenological cycle of the plant). On average, the temperature and relative humidity conditions in the greenhouse were 36/10 °C (day/night) and 60% ($\pm 10\%$), respectively.

2.7. Chemical Analysis of Water

The pots were watered manually up to 70% of their water holding capacity (container capacity). The irrigation water had the following characteristics: EC was $0.5 \pm 0.18 \text{ dS}\cdot\text{m}^{-1}$, pH was 8.81 ± 0.15 , and sodium adsorption ratio (SAR) was $1.93 \pm 0.06 (\text{mmol L}^{-1})^{0.5}$. The water contained $155 \pm 23 \text{ mg L}^{-1}$ of total dissolved solids (TDS), $0.42 \pm 0.02 \text{ mmol L}^{-1} \text{ Ca}^{2+}$, $3.61 \pm 0.11 \text{ mmol L}^{-1} \text{ Mg}^{2+}$, $2.75 \pm 0.09 \text{ mmol L}^{-1} \text{ Na}^{+}$, $0.26 \pm 0.01 \text{ mmol L}^{-1} \text{ K}^{+}$, $1.47 \pm 0.04 \text{ mmol L}^{-1} \text{ CO}_3^{-2}$, $5.01 \pm 0.14 \text{ mmol L}^{-1} \text{ HCO}_3^{-2}$, and $0.15 \pm 0.02 \text{ mmol L}^{-1} \text{ SO}_4^{-2}$.

2.8. Chemical Analysis of the Soil

At the end of the experiment (100 days), a chemical analysis of the soil for each treatment was carried out. The soil samples were dried, ground, and sieved with a 2 mm sieve before adding distilled water. The saturated pastes obtained were covered and left overnight at room temperature. Afterward, a vacuum extraction was performed. The electrical conductivity (EC), pH, and Na^{+} , Ca^{2+} , and Mg^{2+} concentrations were measured in the extracts. The sodium adsorption ratio (SAR), and the exchangeable sodium percentage (ESP) were calculated using the formulas described by Robbins [28]:

$$\text{SAR} = \frac{\text{Na}^{+}}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} \quad (3)$$

where SAR is the sodium adsorption ratio $[(\text{mmol}_c \cdot \text{L}^{-1})^{1/2}]$.

$$\text{CEC} = (200) (V) (N) \quad (4)$$

where CEC is the cation exchange capacity ($\text{cmol}_c \text{ Kg}^{-1}$), V is the volume (ml) of HCl, and N is the normality of HCl.

$$\text{ESP}(\%) = \frac{\text{Na}^{+}}{\text{CEC}} (100) \quad (5)$$

where ESP (%) is the exchangeable sodium percentage, and Na^{+} is the sodium exchangeable ($\text{mmol}_c \text{ L}^{-1}$).

The soil cations were determined in HNO_3 extracts and saturated paste extracts. The measurements of the content of Na^{+} , K^{+} , Ca^{2+} , and Mg^{2+} were performed with atomic absorption spectroscopy [29], using an atomic absorption spectrometer (GBC SENS-AAS).

2.9. Chemical Analysis of Plants

The plant material from each replicate and treatment was chemically analyzed 100 days after transplanting. Plants were first washed with distilled water, and the roots, stems, and leaves were then separated and quantified for their fresh and dry weights (g). Samples were oven-dried at 70 °C for 48 h before being ground. Ion extraction was carried out according to EPA Method 3052 with an Anton Paar Multiwave GO, which was used for the acid digestion of the samples [30].

Plant cation content was determined with atomic absorption spectroscopy (GBC SENS-AAS) after extraction in HNO_3 . This analysis measured Na^{+} , K^{+} , Ca^{2+} , and Mg^{2+} levels. Chloride determinations were obtained with the Mohr method using K_2CrO_7 as an indicator in the titration of Cl ions with a AgNO_3 standard solution [31].

2.10. Morphometric Variables

At 100 days after transplanting, in each treatment, the length of the primary root and the height of the chickpea plants were measured with a Stanley Black and Decker® FatMax® measuring tape (model H-1842, New Britain, CT, USA), from the soil surface to the tip of the mature leaf. The diameter of the plant stems and the equatorial diameter of the fruits were measured with a Vernier caliper (model H-7352, INSIZE, Suzhou, China). The leaf area was measured using the free software ImageJ version 1.52 [32], and the fruits were counted manually. The plants (stems and leaves) and fruits were washed with distilled water and quantified with their fresh weight (g) using a precision balance (Brainweigh Ltd.® model B5000, London, UK). Finally, the plants were dried in a stove at 70 °C for 48 h to record the dry weight [33]. The fruit yield per treatment (yield FW, g plant⁻¹) was determined based on the average fruit number per plant and average fresh fruit weight.

2.11. Data Analysis

The data obtained from the evaluated variables were subjected to the Shapiro–Wilk normality test ($p \leq 0.05$) and Levene's test to check for homogeneity of variance. A two-way analysis of variance (ANOVA) and Tukey's test for comparing mean values ($p \leq 0.05$) were applied to the variables that met the criteria for both tests.

The variables that did not meet the criteria for the test of normality or homogeneity of variance were transformed to the natural logarithm (ln) until normality and homoscedasticity were observed; subsequently, the two-way analysis of variance (ANOVA) and Tukey's test for comparing mean values ($p \leq 0.05$) were performed.

The data that did not match both tests were subjected to a non-parametric Kruskal–Wallis analysis and the Wilcoxon rank sum test, following the methodology of Jiang [34]. Preliminary data evaluation showed that data distribution deviated from Gaussianity according to the normality test. Therefore, data were transformed. For all cases, the software Statistical Analysis System (SAS) Version 9.1 [35] was used.

3. Results

3.1. Cation Concentrations in Shoot and Root Tissues

The study evaluated the accumulation of key cations (Na⁺, K⁺, Ca²⁺, Mg²⁺, and Cl⁻) in the shoots and roots of *Cicer arietinum* under three salinity levels (non-saline, low/moderate, and moderate/high) and two biochar application rates (1.5% and 3%) over 100 days.

Under saline conditions (S2 and S3), Na⁺ became the dominant ion in both roots and shoots, while in non-saline conditions (S1), K⁺ was most abundant (Table 1). Biochar application significantly influenced ion uptake, with the 3% treatment consistently enhancing the accumulation of K⁺, Ca²⁺, and Mg²⁺, particularly in shoot tissues. This suggests improved nutrient translocation and uptake efficiency under biochar amendment.

Na⁺ and Cl⁻ levels increased dramatically under high salinity, but biochar mitigated this effect by reducing their accumulation in both roots and shoots. Conversely, K⁺, Ca²⁺, and Mg²⁺ levels rose with biochar, especially under moderate salinity, indicating a compensatory nutrient uptake mechanism.

Overall, biochar improved the plant's ionic balance under saline stress by reducing toxic ion accumulation (Na⁺, Cl⁻) and enhancing essential nutrient uptake (K⁺, Ca²⁺, Mg²⁺), with the most pronounced effects observed at the 3% application rate.

Table 1. Contents of Na⁺, K⁺, Ca²⁺, Mg²⁺, and Cl[−] in *Cicer arietinum* at 100 days after transplanting.

		mg g ^{−1} DW					
Treatments	Part of the Plant	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl [−]	
S1 (1.2 dS·m ^{−1})	(T1) NBCO	R	0.80 ^{nm} ± 0.01	1.65 ⁿ ± 0.02	1.02 ^k ± 0.01	0.28 ^l ± 0.01	0.60 ^{nm} ± 0.01
		SL	1.71 ^l ± 0.02	4.36 ^g ± 0.07	2.81 ^{gf} ± 0.04	1.20 ^g ± 0.02	1.24 ^l ± 0.02
	(T2) SBCO	R	0.50 ^{no} ± 0.01	3.06 ^k ± 0.05	2.25 ^h ± 0.03	0.76 ⁱ ± 0.01	0.42 ^{no} ± 0.01
		SL	1.06 ^m ± 0.01	6.64 ^d ± 0.11	5.29 ^c ± 0.09	2.13 ^d ± 0.03	0.79 ^m ± 0.01
	(T3) MBCO	R	0.39 ^o ± 0.01	3.32 ^j ± 0.05	2.96 ^f ± 0.05	0.98 ^h ± 0.01	0.29 ^o ± 0.01
		SL	0.66 ^{no} ± 0.01	7.63 ^b ± 0.13	6.55 ^b ± 0.11	2.57 ^c ± 0.04	0.50 ^{nmo} ± 0.01
S2 (4.2 dS·m ^{−1})	(T4) NBCO	R	4.84 ^h ± 0.08	2.10 ^{ml} ± 0.03	1.52 ⁱ ± 0.02	0.62 ^j ± 0.01	3.6 ^h ± 0.06
		SL	10.29 ^d ± 0.17	5.42 ^e ± 0.09	4.56 ^d ± 0.07	2.08 ^d ± 0.03	7.71 ^d ± 0.13
	(T5) SBCO	R	3.28 ^j ± 0.05	4.08 ^h ± 0.07	2.72 ^g ± 0.04	1.18 ^g ± 0.02	2.45 ^j ± 0.04
		SL	8.35 ^e ± 0.14	7.23 ^c ± 0.12	6.73 ^b ± 0.11	2.96 ^b ± 0.05	6.26 ^e ± 0.11
	(T6) MBCO	R	2.77 ^k ± 0.04	4.57 ^{fg} ± 0.07	3.70 ^e ± 0.06	1.48 ^f ± 0.02	2.08 ^k ± 0.03
		SL	7.22 ^f ± 0.12	8.53 ^a ± 0.14	7.57 ^a ± 0.12	3.53 ^a ± 0.06	5.42 ^f ± 0.09
S3 (5.6 dS·m ^{−1})	(T7) NBCO	R	8.57 ^e ± 0.14	1.09 ^o ± 0.01	0.45 ^l ± 0.01	0.34 ^l ± 0.01	6.43 ^e ± 0.11
		SL	18.82 ^a ± 0.32	2.04 ^m ± 0.03	1.28 ^j ± 0.02	0.79 ⁱ ± 0.01	14.12 ^a ± 0.24
	(T8) SBCO	R	5.50 ^g ± 0.09	2.27 ^l ± 0.03	1.18 ^{kl} ± 0.02	0.44 ^k ± 0.01	4.12 ^g ± 0.07
		SL	13.38 ^b ± 0.22	3.70 ⁱ ± 0.06	2.83 ^{gf} ± 0.04	1.73 ^e ± 0.03	10.87 ^b ± 0.18
	(T9) MBCO	R	4.35 ⁱ ± 0.07	2.90 ^k ± 0.04	1.61 ⁱ ± 0.02	0.66 ^j ± 0.01	3.26 ⁱ ± 0.05
		SL	11.96 ^c ± 0.20	4.72 ^f ± 0.08	3.87 ^e ± 0.06	2.12 ^d ± 0.03	9.24 ^c ± 0.15

In each column, different letters represent significant differences according to Tukey's test ($p \leq 0.05$). Values are averages of 10 replicates ± standard error. (NBCO: 0% biochar; SBCO: 1.5% biochar; MBCO: 3% biochar; R: roots; SL: shoot [stems and leaves]).

3.2. Chemical Properties of Soil After Exposure to Different Salinity and Biochar Concentrations

Following 100 days of exposure to different NaCl concentrations and biochar application rates, statistically significant enhancements ($p \leq 0.05$) in soil chemical properties were recorded across all salinity levels, including non-saline (S1), low to moderate salinity (S2), and moderate to high salinity (S3) conditions (Table 2). Biochar application led to consistent reductions in soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP), with the most pronounced effects in the S2 group.

In the non-saline group (S1), 3% biochar (T3) reduced pH by 2.4%, EC by 37.25%, SAR by 42.4%, and ESP by 35.88%, outperforming the 1.5% treatment (T2). In the S2 group, 3% biochar (T6) achieved the greatest reductions: 3.04% in pH, 53.14% in EC, 48.43% in SAR, and 43.31% in ESP. The 1.5% treatment (T5) also showed significant improvements. In the S3 group, 3% biochar (T9) reduced pH by 2%, EC by 33.52%, SAR by 37.85%, and ESP by 29.88%, with slightly lower reductions observed in T8 (1.5%).

The relative effectiveness of the treatments in reducing soil chemical stress indicators was determined based on the magnitude of observed reductions. For pH, the most effective treatments, in descending order, were T3, T2, T1, T6, T5, T9, T4, T8, and T7. In terms of SAR reduction, the treatments ranked as follows: T3, T6, T2, T5, T9, T1, T8, T4, and T7. For ESP, the order of effectiveness was T3, T6, T2, T5, T9, T8, T1, T4, and T7.

These results highlight the potential of biochar, particularly at 3%, to mitigate salinity-induced soil degradation and improve soil health under varying saline conditions.

Table 2. Soil chemical properties at 100 days after being exposed to different concentrations of salinity and biochar.

Parameters	Treatments								
	S1 (1.2 dS·m ^{−1})			S2 (4.2 dS·m ^{−1})			S3 (5.6 dS·m ^{−1})		
	(T1) NBCO	(T2) SBCO	(T3) MBCO	(T4) NBCO	(T5) SBCO	(T6) MBCO	(T7) NBCO	(T8) SBCO	(T9) MBCO
pH	7.49 ^f ± 0.03	7.39 ^g ± 0.03	7.31 ^h ± 0.03	7.87 ^c ± 0.03	7.75 ^d ± 0.03	7.63 ^e ± 0.03	8.02 ^a ± 0.03	7.94 ^b ± 0.03	7.86 ^c ± 0.03
EC (dS·m ^{−1})	1.02 ^g ± 0.04	0.76 ^h ± 0.04	0.64 ^h ± 0.05	3.82 ^c ± 0.05	2.27 ^e ± 0.04	1.79 ^f ± 0.04	5.34 ^a ± 0.04	4.03 ^b ± 0.05	3.55 ^d ± 0.04
Na ⁺ (mmolc·L ^{−1})	15.17 ^d ± 0.27	7.64 ^g ± 0.13	5.76 ^h ± 0.10	28.02 ^b ± 0.50	10.24 ^f ± 0.18	5.61 ^h ± 0.10	39.72 ^a ± 0.71	23.69 ^c ± 0.42	12.73 ^e ± 0.22
Ca ²⁺ (mmolc·L ^{−1})	5.65 ^d ± 0.10	3.27 ^e ± 0.06	2.86 ^f ± 0.05	12.41 ^b ± 0.22	5.37 ^d ± 0.10	2.13 ^g ± 0.04	19.24 ^a ± 0.34	12.64 ^b ± 0.22	6.53 ^c ± 0.11
Mg ²⁺ (mmolc·L ^{−1})	3.47 ^d ± 0.06	2.09 ^f ± 0.03	1.31 ^g ± 0.02	8.79 ^c ± 0.15	2.62 ^e ± 0.04	1.04 ^g ± 0.02	16.21 ^a ± 0.29	10.41 ^b ± 0.18	2.70 ^e ± 0.04
Na ⁺ (cmolc·kg ^{−1})	3.11 ^c ± 0.05	2.22 ^f ± 0.04	1.99 ^g ± 0.03	3.68 ^b ± 0.06	2.39 ^e ± 0.04	2.09 ^{gf} ± 0.03	4.02 ^a ± 0.07	3.03 ^c ± 0.05	2.82 ^d ± 0.05
K ⁺ (cmolc·kg ^{−1})	1.93 ^c ± 0.03	1.31 ^d ± 0.02	0.75 ^f ± 0.01	2.13 ^b ± 0.03	1.08 ^e ± 0.01	0.57 ^g ± 0.01	2.44 ^a ± 0.04	1.87 ^c ± 0.03	0.78 ^f ± 0.01
Ca ²⁺ (cmolc·kg ^{−1})	37.92 ^c ± 0.68	30.44 ^e ± 0.54	23.17 ^g ± 0.41	40.37 ^b ± 0.72	27.54 ^f ± 0.49	18.63 ^h ± 0.03	43.52 ^a ± 0.78	32.20 ^d ± 0.57	22.76 ^g ± 0.40
Mg ²⁺ (cmolc·kg ^{−1})	13.01 ^a ± 0.23	9.88 ^d ± 0.17	7.84 ^e ± 0.14	10.82 ^c ± 0.19	4.26 ^h ± 0.07	2.88 ⁱ ± 0.05	11.75 ^b ± 0.21	6.75 ^f ± 0.12	4.81 ^g ± 0.08
SAR (mmolc·L ^{−1}) ^{0.5}	6.91 ^c ± 0.12	4.67 ^f ± 0.08	3.98 ^{gf} ± 0.07	8.63 ^b ± 0.15	5.12 ^e ± 0.09	4.45 ^f ± 0.08	9.43 ^a ± 0.17	6.97 ^c ± 0.12	5.86 ^d ± 0.10
ESP (%)	9.42 ^c ± 0.17	6.71 ^f ± 0.12	6.04 ^g ± 0.11	11.15 ^b ± 0.20	7.25 ^e ± 0.13	6.32 ^{gf} ± 0.11	12.18 ^a ± 0.22	9.18 ^c ± 0.16	8.54 ^d ± 0.15

In each row, different letters represent significant differences according to Tukey's test ($p \leq 0.05$). Values are averages of 10 replicates ± standard error. (NBCO: 0% biochar; SBCO: 1.5% biochar; MBCO: 3% biochar).

3.3. Morphometric Variables of *C. arietinum* Under Varying Salinity and Biochar Doses

Table 3 presents the morphometric characteristics of *Cicer arietinum* after 100 days of exposure to varying salinity levels and biochar application rates. Significant improvements ($p \leq 0.05$) in all measured morphometric parameters were observed across the three salinity groups (S1, S2, and S3) with the application of 3% and 5% biochar. The most notable increases were generally associated with 3% and 1.5% biochar treatments. Overall, the magnitude of improvement was highest in the S1 group, followed by S2, and lowest in S3.

Table 3. Morphometric variables of *C. arietinum* at 100 days after being exposed to different concentrations of salinity and biochar.

Parameters	Treatments								
	S1 (1.2 dS·m ⁻¹)			S2 (4.2 dS·m ⁻¹)			S3 (5.6 dS·m ⁻¹)		
	(T1) NBCO	(T2) SBCO	(T3) MBCO	(T4) NBCO	(T5) SBCO	(T6) MBCO	(T7) NBCO	(T8) SBCO	(T9) MBCO
Plant height (cm)	53.04 ^c ± 0.95	57.25 ^b ± 1.03	62.01 ^a ± 1.11	44.86 ^{fe} ± 0.80	49.57 ^d ± 0.89	55.75 ^b ± 1.01	36.32 ^g ± 0.65	43.82 ^f ± 0.78	46.49 ^e ± 0.83
Root length (cm)	33.76 ^{dc} ± 0.60	41.26 ^b ± 0.74	46.77 ^a ± 0.84	28.36 ^e ± 0.51	35.09 ^c ± 0.63	40.24 ^b ± 0.72	22.98 ^f ± 0.41	29.91 ^e ± 0.53	33.13 ^d ± 0.59
Plant fresh weight (g)	229.81 ^c ± 4.13	263.54 ^b ± 4.74	295.31 ^a ± 5.31	191.59 ^e ± 3.44	222.91 ^{dc} ± 4.01	254.07 ^b ± 4.57	159.33 ^f ± 2.86	193.90 ^e ± 3.49	211.37 ^d ± 3.80
Plant dry weight (g)	74.68 ^c ± 1.34	85.64 ^b ± 1.54	95.96 ^a ± 1.72	62.26 ^e ± 1.12	72.44 ^{dc} ± 1.30	82.56 ^b ± 1.48	51.78 ^f ± 0.93	63.01 ^e ± 1.13	68.69 ^d ± 1.23
Plant stem diameter (cm)	0.65 ^e ± 0.01	0.74 ^c ± 0.01	0.87 ^a ± 0.01	0.58 ^f ± 0.01	0.66 ^e ± 0.01	0.78 ^b ± 0.01	0.48 ^g ± 0.01	0.57 ^f ± 0.01	0.71 ^d ± 0.01
Leaf area (cm ²)	2370 ^c ± 42.6	2719 ^b ± 48.9	3047 ^a ± 54.8	1979 ^e ± 35.6	2302 ^{dc} ± 41.43	2624 ^b ± 47.2	1651 ^f ± 29.7	2012 ^e ± 36.21	2185 ^d ± 39.3
Fruit fresh weight (g)	0.22 ^{cd} ± 0.008	0.26 ^b ± 0.011	0.29 ^a ± 0.012	0.17 ^e ± 0.002	0.21 ^d ± 0.008	0.24 ^{cb} ± 0.012	0.14 ^f ± 0.01	0.17 ^e ± 0.002	0.20 ^d ± 0.007
Fruit dry weight (g)	0.09 ^{cb} ± 0.005	0.10 ^b ± 0.005	0.12 ^a ± 0.005	0.07 ^d ± 0.003	0.09 ^{cb} ± 0.004	0.10 ^b ± 0.005	0.05 ^e ± 0.002	0.07 ^d ± 0.003	0.08 ^{cd} ± 0.004
Number of pods (plant ⁻¹)	32.10 ^f ± 0.57	38.72 ^b ± 0.69	44.46 ^a ± 0.80	25.60 ^f ± 0.46	32.67 ^d ± 0.58	36.56 ^c ± 0.65	21.28 ^g ± 0.38	25.92 ^f ± 0.46	29.24 ^e ± 0.52
Number of fruits (plant ⁻¹)	87.96 ^b ± 1.58	95.52 ^a ± 1.90	99.82 ^a ± 2.19	70.15 ^{fe} ± 1.26	80.54 ^{cd} ± 1.61	84.19 ^b ± 1.80	66.31 ^f ± 1.05	72.03 ^e ± 1.27	77.12 ^d ± 1.44
Yield FW (g·plant ⁻¹)	19.35 ^c ± 0.34	24.83 ^b ± 0.42	28.94 ^a ± 0.70	11.92 ^f ± 0.21	16.91 ^d ± 0.35	20.20 ^c ± 0.55	8.16 ^g ± 0.11	12.24 ^f ± 0.21	15.42 ^e ± 0.30

In each row, different letters represent significant differences according to Tukey's test ($p \leq 0.05$). Values are averages of 10 replicates ± standard error. (NBCO: 0% biochar; SBCO: 1.5% biochar; MBCO: 3% biochar).

In the non-saline group (S1), treatments T3 and T2 significantly enhanced all morphometric variables compared to T1, with T3 showing the highest increases in plant height, root length, biomass, stem diameter, leaf area, fruit weight, pod number, fruit number, and yield. Similar trends were observed in the low/moderate salinity group (S2), where T6 and T5 outperformed T4, and in the moderate/high salinity group (S3), where T9 and T8 showed the greatest improvements over T7.

Conversely, treatments T4 and T7 exhibited significant reductions ($p \leq 0.05$) in all morphometric parameters compared to T1. Additionally, T5 and T8 showed lower values than T2, and T6 and T9 were less effective than T3, indicating that higher salinity levels diminished the positive effects of biochar.

4. Discussion

4.1. Impact of Soil Salinity and Biochar's Remediation Potential

An increase in NaCl in the soil leads to increases in soil pH, EC, SAR, and ESP, generating conditions of ionic and osmotic stress, thus disrupting crop homeostasis [36]. This negatively affects nutrient uptake, transpiration, and photosynthetic function in plants,

causing cellular membrane disorders, damage to the photosynthetic apparatus, and high toxicity when its concentration in plant tissues is excessive, reducing their physiological activities [37]. In light of this, biochar has been employed as a promising soil amendment to enhance soil properties [38].

4.2. Mechanisms of Biochar in Mitigating Salinity Stress

When applying doses of 1.5% and 3% biochar in the soils of the different groups (S1, S2, and S3), increased accumulation of K^+ , Ca^{2+} , and Mg^{2+} was observed, both in the root and in the shoot of the *C. arietinum* crop, perhaps because biochar acts as an ion exchanger that promotes competition with Na^+ for the same subcellular sites in the plants [39] and improves the absorption of essential nutrients [40].

It was also observed that applying 1.5% and 3% biochar to the soils of different groups (S1, S2, and S3) significantly reduced Na^+ and Cl^- concentrations, thereby improving soil chemical properties (pH, EC, SAR, and ESP) and enhancing the growth of *C. arietinum* crops.

Various studies have attributed the benefits of biochar to several key factors. These include enhanced leaching of Na^+ in soil, leading to improved root growth and vigor [41]; increased adsorption and retention of Na^+ on biochar surfaces due to physical trapping in fine pores [42]; reduced upward movement of saline water, as biochar cover minimizes water evaporation [43]; facilitated release of H^+ from the ion exchange complex, increasing Ca^{2+} and Mg^{2+} levels in soil [10]; promotion of cation absorption in plants, resulting in H^+ release from roots to balance charges [44]; stimulation of root exudate secretion (e.g., polysaccharides, amino acids, and organic acids), enhancing nutrient availability and altering soil conditions [45]; increased acid functional groups during oxidation [46]; and provision of exchangeable Ca^{2+} and Mg^{2+} , enabling replacement of Na^+ in soil colloids [47]. Collectively, these factors create an optimal environment for healthy plant growth and development [48].

Thus, biochar produced from corncobs showed a reduction in the SAR and ESP of the soil when applied to the soil in greater proportions. This is because it selectively adsorbs sodium (Na^+) in its porous, negatively charged structure while simultaneously releasing divalent cations (Ca^{2+} , Mg^{2+}), which displace Na^+ from the exchange sites. As a result, the cation ratio in the soil solution (SAR) improved, and the availability of soluble and exchangeable cations (Ca^{2+} , Mg^{2+} , K^+) for the crop increased. These nutrients were absorbed by the plant roots and translocated to the aerial part.

These findings align with those of Zhou et al. [49], who noted that reducing Na^+ uptake in crops through biochar application significantly improves K^+ uptake and maintains the optimal K^+/Na^+ ratio. This is further supported by Moradi et al. [50] and Bacha and Iqbal [51], who also highlighted biochar's role in enhancing soil fertility and mitigating salinity, thereby creating a more favorable environment for plant growth, as discussed earlier.

It is essential to note that improvements in the chemical properties of saline soils are also contingent upon the rate and type of biochar applied. As Huang et al. [39] emphasized, these factors must be carefully considered before biochar is applied to saline-affected soils, as they can significantly impact soil ecology and biochemistry. Similarly, Wang et al. [52] pointed out that the benefits of biochar are highly dependent on the pyrolysis conditions, including temperature, duration, feedstock type, initial soil physicochemical properties, and the interaction time between biochar and soil.

In the present study, we observed that applying 1.5% and 3% biochar—produced from corncob residues (*Z. mays*) pyrolyzed at 550 °C for 2 h—to a clay soil affected by NaCl at varying concentrations (S1, S2, and S3) resulted in significant improvements in chemical properties (pH, EC, SAR, and ESP) after 100 days of interaction.

The stable and porous structure of corncob biochar is likely to be a key factor in these results, as it significantly increases the specific surface area available for adsorbing Na^+ from the soil. As a consequence, soil fertility is improved and crop-damaging salinity is reduced [53].

4.3. Influence of Biochar on the Growth and Yield of *Cicer arietinum*

According to Alkharabsheh et al. [54], increased biochar addition significantly enhances soil nutrient availability and stimulates crop production. However, the beneficial effects of biochar on soil typically depend on soil type and properties, soil buffering capacity, and sufficient interaction time between biochar and the soil microenvironment [38].

In the present study, it was found that the application of biochar at doses of 1.5% and 3% in the soils of the different groups (S1, S2, and S3) significantly improved the growth and development of *C. arietinum*, which was evident in all the morphometric variables evaluated. In contrast, in the treatments without biochar, a notable decrease was observed in the growth, development, and yield of the *C. arietinum* crop.

Potential mechanisms by which biochar may have promoted the growth of *Cicer arietinum* include (a) the supply of macronutrients and micronutrients, (b) increased soil organic carbon content, and (c) reduction in Na^+ via electrostatic adsorption [38]. Collectively, these factors improve soil fertility, enhancing crop nutrient uptake efficiency.

Another mechanism that may explain biochar's positive effects on *C. arietinum* cultivation involves its ability to induce biochemical changes in foliar tissue [55]. Biochar application has been associated with reduced concentrations of proline, oxalic acid, and certain phenolic compounds, as was observed in *Pennisetum glaucum* after being cultivated in a saline soil [55,56]. These biochemical modifications could explain the increases in leaf area and overall crop growth [57,58].

On the other hand, the enhanced productivity of the *C. arietinum* crop following biochar application in soils (S1, S2, and S3) can be attributed to biochar's ability to improve plant morphology through several indirect benefits, including reducing oxidative stress by degrading O_2^- concentrations [59]; mitigating osmotic stress by enhancing water retention capacity [60]; decreasing the production of phytohormones such as abscisic acid (ABA) and jasmonic acid (JA), thereby increasing the crop's salinity tolerance [61]; and stimulating microbial and enzymatic activities in the soil [62].

Schmierer et al. [63] noted that nitrogen (N) has a significant impact on the organic structure, physiological characteristics, and synthesis and distribution of biomass in plants, and is the factor that most affects dry matter production. On the other hand, phosphorus (P) has a notable influence on leaf area, photosynthesis, and carbon metabolism, which in turn affects tillering, biomass accumulation, and crop yield [64]. Regarding potassium (K), ref. [65] reported that this cation regulates stomatal movement, osmotic adjustment, charge balance, steady-state enzyme activation, membrane potential, and membrane protein transport. Therefore, the complex interactions between N, P, and K determine nutrient homeostasis and, consequently, plant growth and development [66].

In line with the importance of K in plant development, the K/Na ratio is considered a crucial factor in improving crop growth and yield. Enhancing K availability through the use of biochar can optimize this ratio, thereby promoting plant growth and productivity [67].

Other micronutrients such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) also play critical roles in plant physiological processes. These micronutrients actively participate in various metabolic activities; for example, the Ca^{2+} serves as an intracellular messenger for many signal transductions, including abscisic acid (ABA), reactive oxygen species (ROS), and nitric oxide (NO) [57]. Furthermore, Ca^{2+} has been reported to help resist adverse damage (to some extent) in abiotically stressed plants through several mechanisms, including

the regulation of the sodium/potassium ion (Na^+/K^+) ratio, ABA concentration, cell wall/plasma membrane stabilization, recognition of the $\text{Ca}^{2+}/\text{Ca}^{2+}$ -dependent protein kinase system (CDPKs), and initiation of specific gene expression [68].

On the other hand, magnesium (Mg^{2+}) is a vital cation in various physiological and biochemical processes in plants, such as photosynthesis, carbohydrate partitioning, and protein synthesis [69]. Its function as a cofactor and allosteric modulator of over 300 enzymes, including carboxylases, phosphatases, kinases, RNA polymerases, and ATPases, is fundamental for plant growth and development, as it participates in key processes such as cell division and regulation of cellular processes.

According to Tian et al. [70], the Mg concentrations required for optimal plant growth should range from 1.5 to 3.5 mg g^{-1} of dry weight in vegetative tissues, as concentrations below this threshold tend to result in reduced plant growth and altered biomass distribution among organs. This situation was observed in the present study, specifically in treatments where a higher concentration of biochar (3%) was applied.

On the other hand, soil with biochar applied to it enhanced the crop productivity of *C. arietinum* (chickpea) thanks to its indirect benefits. This beneficial effect can be partly attributed to biochar's ability to mitigate oxidative stress through mechanisms such as neutralizing oxygen free radicals, deactivating reactive oxygen species, enhancing the plant's endogenous antioxidant activity, and modulating soil pH [71].

According to Li et al. [72], biochar can increase soil porosity and water absorption capacity, enabling it to retain more water and release it gradually due to its porous structure, which traps and retains water, reducing leaching losses. Additionally, studies—including that of Palansooriya et al. [73]—have shown that biochar enhances soil microbial activity by providing a suitable habitat for beneficial microorganisms (e.g., bacteria and fungi) which, in turn, improve soil structure and water retention. Furthermore, research by Juriga et al. [74] indicated that biochar also acts as a soil amendment, correcting soil structure and porosity while mitigating compaction and promoting permeability. These are factors that, overall, could have favored the growth and development of *C. arietinum* under saline stress.

Other studies, such as that by Egamberdieva et al. [61], have also highlighted biochar's ability to enhance plant tolerance to NaCl by reducing the production of stress-related phytohormones and improving soil conditions. This is attributed to its capacity to adsorb salts and limit their bioavailability—a factor that likely contributed to the healthy growth and development of the *C. arietinum* crop, and increased yield under saline stress conditions. These findings are consistent with those of Moradi et al. [50] and Bacha and Iqbal, [51], who pointed out that biochar improves soil fertility and plays an important role in reducing soil salinity.

In this way, the biochar produced from corncobs demonstrated the ability to significantly enhance the development of *C. arietinum* under moderately saline conditions, increasing root and shoot growth as well as biomass production, resulting in more resilient plants with higher yields—as observed in this study when applying biochar doses of 1.5% and 3%. This improvement was achieved due to three key properties of the biochar used. First, its porosity enhanced soil water retention, promoting the leaching of accumulated salts and improving root aeration. Second, its remarkable adsorption capacity allowed it to capture toxic ions such as sodium (Na^+) and chloride (Cl^-), reducing their availability to the crop while retaining essential nutrients such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), thereby preventing their loss through leaching. Finally, its mineral contribution enriched the soil with nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients while also regulating pH toward neutral levels, mitigating saline stress (EC). These synergistic mechanisms not only reduced NaCl toxicity but may also

have contributed to improving soil fertility and stimulated microbial activity, optimizing conditions for proper *C. arietinum* crop growth.

4.4. Field Application Potential and Comparison with Other Amendments

Although this study was conducted under greenhouse conditions, its findings demonstrate significant potential for field applications. The biochar doses used [1.5% ($\approx 18.7 \text{ Mg ha}^{-1}$) and 3% ($\approx 37.4 \text{ Mg ha}^{-1}$)] to remediate saline soils fall within the ranges employed in previous studies across different regions. For instance, Sun et al. [75] applied 7.5, 15, and 30 Mg ha^{-1} of wheat straw biochar in a field experiment in China, successfully reducing salinity and improving the yield of corn and barley in rotation. Similarly, Ali et al. [55] tested doses of 5 to 20 Mg ha^{-1} of corn cob biochar in Egypt, proving its effectiveness in enhancing *Pennisetum glaucum* L. productivity in saline soils.

Furthermore, it is important to highlight that, when comparing the amount of biochar used in this study with the doses of other amendments commonly employed in agronomic practice to mitigate soil salinity, such as gypsum [$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$], the results are comparable. For example, in the study by Aljughaiman [76], agricultural gypsum was applied at rates of 20 and 40 Mg ha^{-1} to improve wheat yield under saline conditions—at a magnitude similar to the quantities used in this work.

While the efficacy of biochar in improving soil chemical properties depends on multiple factors—including initial soil salinity, feedstock material, pyrolysis conditions (slow or fast), biochar physicochemical characteristics (particle size, porosity, and surface area), application rate, and soil persistence [77]—its large-scale implementation remains challenging due to high costs and technical production limitations [78]; however, using corn cobs as a feedstock could help reduce costs, as studies show that the raw material and its accessibility represents more than 11% of the total cost of biochar production [79].

5. Conclusions

This study demonstrated that the application of corncob-derived biochar at rates of 1.5% and 3% significantly improved the chemical properties of clay soil—specifically pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP)—under non-leaching conditions across varying salinity levels ($S_1 = 1.2 \text{ dS m}^{-1}$, $S_2 = 4.2 \text{ dS m}^{-1}$, and $S_3 = 5.6 \text{ dS m}^{-1}$). These enhancements were accompanied by notable improvements in the growth and productivity of *Cicer arietinum* L., including increases in plant height, root length, biomass accumulation, stem diameter, leaf area, pod number, and fruit yield.

Yield data revealed that the 3% biochar treatment consistently outperformed the 1.5% application, achieving increases of 1.66%, 19.5%, and 26% in S_1 , S_2 , and S_3 , respectively. These findings underscore the superior efficacy of the higher biochar dose in mitigating salinity stress and enhancing crop performance. Overall, the use of 3% corncob biochar presents a promising and sustainable strategy for improving soil quality and agricultural productivity in saline environments.

This research focused on the short-term impacts of biochar under controlled conditions. Nevertheless, future investigations should address its long-term performance in real-world field settings, considering diverse soil types and varying salinity levels. Additionally, examining its integration with other soil remediation strategies could enhance both its efficiency and sustainability. Further studies should also include multi-season field trials, assessments of soil microbial communities, and analyses of economic viability.

The findings of this research are particularly relevant for sustainable and circular agriculture, as they demonstrate that the proper processing and reuse of byproducts (corncob waste-based biochar) can not only optimize the yield of marginal areas, such as

saline soils, but also contribute to the conservation of environmental resources, thereby closing the productive cycles.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/soilsystems9030071/s1>, Table S1: Physicochemical characterization of the biochar; Table S2: Energy spectrum analysis for biochar surface; Figure S1: Micrograph of corncob biochar, the micropores have an average diameter of 28 μm and the micropores of about 2 μm .

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Abbreviations

The following abbreviations are used in this manuscript:

EC	Electrical conductivity
SAR	Sodium absorption ratio
ESP	Exchangeable sodium percentage
CEC	Cation exchange capacity

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