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Biochar-assisted reclamation of saline-sodic soil: Impact on soil properties, barley growth and yield

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ABSTRACT

Soil salinity and sodicity are major problems negatively affecting soil properties, fertility, and crop production. In this study, the effect of biochar and phosphogypsum (PG) treatments on the reclamation of saline-sodic silt loam soil was examined. The biochar (BC) treatments included 0.5% (BC0.5), 1% (BC1), and 2% (BC2); two treatments of PG (50 and 100%) of the gypsum requirement (GR) in addition to a control (C). Pot experiments were conducted to study the effect of the same treatments on barley growth. The addition of biochar to the saline-sodic soil positively improved soil hydraulic conductivity. BC0.5 had the highest hydraulic conductivity value, followed by BC1 and BC2. All treatments significantly ($p<0.05$) reduced soil EC, ESP, and SAR below threshold levels. In addition, biochar treatments significantly ($p<0.05$) reduced the time required for soil reclamation due to improved hydraulic properties and increased salt leaching rates. The best values for growth parameters (plant height, leaf area, plant fresh and dry weight, spike weight, weight of grains per spike, and weight of 1000 grains) were obtained with BC0.5 application followed by PG50 and PG100, respectively. However, a negative effect on plant growth was observed with increased biochar application, as indicated by a noticeable decrease in all growth indicators and chlorophyll content with BC2 and BC1. These findings suggest that biochar produced from calcium-rich raw materials can improve crop growth and soil reclamation.

Keywords: leaching, phosphogypsum, pot experiment, reclamation, saline-sodic soil.

INTRODUCTION

Saline-sodic soils present a significant global challenge for sustainable agriculture. These soils are characterized by high levels of salinity and sodicity, which adversely affect crop growth and productivity (Fouladidorhani et al., 2024; Gharaibeh et al., 2011). Salinity, resulting from the accumulation of soluble salts, and sodicity, which involves the presence of sodium ions, impair water infiltration, reduce nutrient availability, and create unfavorable conditions for plant growth and development (dos Santos et al., 2021; Gharaibeh et al., 2021; Zhang et al., 2021). Consequently, reclaiming saline-sodic soils is crucial for ensuring food security and the sustainable use of agricultural land. Traditionally, gypsum has been the primary chemical amendment used for reclaiming sodic and saline-sodic soils. Upon application, gypsum provides calcium (Ca), which displaces excess exchangeable sodium (Na). This displaced sodium is then washed out of the soil through irrigation or leaching (Gharaibeh et al., 2011). However, gypsum is a non-renewable resource with a high environmental burden from mining and processing. Therefore, more sustainable alternatives are needed to reduce the environmental impacts of agriculture and maintain soil productivity. Recent research has shown evidence that biochar may be used as an alternative to gypsum to treat saline-sodic soils.

Biochar has a porous structure and high surface area, which make it an attractive candidate for enhancing soil properties, improving nutrient retention, and reducing salinity and sodicity (Albalasmeh et al., 2023; Chaganti et al., 2015; Mohawesh et al., 2021). Studies have shown that biochar contains high levels of nutrients, such as Ca^{2+} and Mg^{2+} (Billa et al., 2019; Dai et al., 2017; Elkhlifi et al., 2023). These divalent cations may help improve saline-sodic soils by replacing Na^+ on exchange sites and enhancing leaching, thereby improving hydraulic conductivity and soil structure, which leads to better crop growth and increased production (Mahmoud et al., 2019; Rajkovich et al., 2012; Yue et al., 2016). dos Santos et al. (2021) found that applying biochar produced from corncob and sugarcane bagasse to saline-sodic soil reduced electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR), thus improving soil quality and maize growth, including plant height, shoot mass, and root mass. Similarly, Fouladidorhani et al. (2024) reported that biochar amendment increased hydraulic conductivity and decreased bulk density in saline-sodic soils, facilitating the leaching of excess salts and sodium ions. In a column study, incorporating 1% w/w wheat straw biochar into a saline-sodic silt loam increased hydraulic conductivity and improved leaching of Na^+ and decreased soil pH, SAR, and Na^+ concentration in the soil (Yue Zhang et al., 2020).

Another potential product is phosphogypsum (PG). PG is a calcium sulfate-rich by-product of phosphoric acid production. It is generated in vast quantities globally. The phosphate fertilizer industry produces over 230 million tonnes annually, yet only a small portion (15–35%) is reused; consequently, more than 6 billion tonnes have accumulated in global gypstacks (Elbagory et al., 2024). These stockpiles occupy significant land areas and pose environmental risks, including leachate pollution and the dispersion of radionuclides. Despite these limitations, recent research increasingly demonstrates that PG can offer substantial agronomic and environmental benefits.

PG primarily serves as a source of Ca^{2+} and SO_4^{2-}, enhancing soil structure by improving aggregation, cation exchange, and root penetration. Experimental findings indicate significant improvements in soil physical properties and crop performance across different soil types. For example, Elbagory et al. (2024) observed that combined PG and modified biochar treatments significantly increased soil organic carbon, nutrient availability, and wheat yields. Similarly, Gao et al. (2025) reported that PG treatments improved infiltration, reduced bulk density, and enhanced buckwheat growth.

Jordan is a major producer of rock phosphate. It is estimated that 3 million tonnes of GP are stockpiled in surface impoundments annually (Maina et al., 2025). Meanwhile, Jordan has been facing severe water shortages for the past several decades, leading to the use of unconventional treated wastewater (TWW) for irrigation, especially in the Jordan Valley (Ghor) region, which is the country's food bowl. Gharaibeh et al. (2024) reported that indigenous geological formations, intensive farming practices, intensive use of synthetic fertilizers, and the use of saline-sodic TWW (average salinity 12.0 $dS.m^{-1}$, sodicity 8.0) lead to the formation of saline-sodic soils. Thus, threatens the productivity of the Ghor. Tomatoes are an important crop of the Ghor. After harvest, large quantities of agricultural waste (tomato plants) are left behind with little use. Farmers usually manage the waste by burning it. Therefore, there is an opportunity to use what are essentially waste products to address the pressing issues of soil salinization and sodicity. The purpose of this study was to evaluate the optimal application rate of PG and biochar derived from agricultural waste (tomato plant) in mitigating the saline-sodic soil impact on crop growth and yield.

Despite increasing interest in biochar-based reclamation of salt-affected soils, significant uncertainty remains regarding optimal application rates and the interaction between biochar-derived salts and sodic soil chemistry. Previous studies have primarily focused on single amendments or modified biochars, with limited direct comparison between biochar derived from agricultural residues and industrial by-products such as phosphogypsum under identical experimental conditions. This study contributes to the literature by (i) evaluating tomato-residue biochar as a circular agricultural amendment for saline-sodic soils in the Jordan Valley, (ii) experimentally comparing biochar and phosphogypsum across multiple application rates using both column leaching and crop response experiments, and (iii) identifying a threshold biochar application rate beyond which soil salinity and plant growth may be negatively affected. These findings provide new insights into optimizing organic amendments for the reclamation of saline-sodic soils under water-scarce conditions.

MATERIALS AND METHODS

Soil sample collection and characterization

A surface (0–0.30 m) soil sample was collected from an agricultural area in the Jordan Valley (32° 02’ 59.9” N, 35° 33’ 09.5” E). The soil sample was air-dried, crushed with a rubber mallet, and passed through a 2 mm sieve. Soil characteristics were measured using standard soil analysis methods and are presented in Table 1.

Production and characterization of biochar

Biochar was produced from tomato plant residues at a pyrolysis temperature of 350 °C for 2 hours. Tomatoes are a major crop in Jordan, contributing significantly to the agricultural sector. However, large amounts of residues are generated during farming and processing. These residues often go unused, creating waste disposal issues. Using them for biochar production provides a sustainable waste-management solution. At 350 °C, biochar retains more oxygen-containing functional groups, which enhance cation exchange capacity (CEC) and make it more effective for improving nutrient retention in soil. The pyrolysis temperature of 350 °C was selected

Table 1. Soil physical and chemical properties of the investigated soil

Parameters	Value	Method
pH	7	Soil-to-water Extract
EC (dS/m)	77.73	Soil-to-water Extract
Sand (%)	20	Hydrometer method
Silt (%)	79	
Clay (%)	1	
Soil Texture	Silt Loam	
Bulk density (g/cm^3)	1.33	Core method
Organic matter (%)	0.81	Walkley and Black
CEC (meq/100g)	35.56	Ammonium acetate method
ESP (%)	85.7	ESP formula
SAR	75.73	SAR formula
Hydraulic conductivity (cm/d)	41	Constant head method
Soluble Na (meq L^{-1})	0.23	Saturated paste extract
Soluble K (meq L^{-1})	0.01	Saturated paste extract
Soluble Ca (meq L^{-1})	0	Saturated paste extract
Extractable Na (meq L^{-1})	30.74	Ammonium acetate Extractant
Extractable K (meq L^{-1})	2.99	Ammonium acetate Extractant
Extractable Ca (meq L^{-1})	7.52	Ammonium acetate Extractant
Exchangeable Na (meq L^{-1})	30.51	Subtraction
Exchangeable K (meq L^{-1})	2.98	Subtraction
Exchangeable Ca (meq L^{-1})	7.52	Subtraction
P (mg/kg)	733.54	Olsen method
N %	6	Kjeldahl method

Note: EC – electrical conductivity; CEC – cation exchange capacity; ESP – exchangeable sodium percentage; SAR – sodium adsorption ratio; Na – sodium; K – potassium; Ca – calcium; P – phosphorus; N – nitrogen.

deliberately to optimise the biochar for saline–sodic reclamation. The principal functional requirement of such an amendment is a high capacity to supply and exchange divalent cations (Ca^{2+}, Mg^{2+}) for Na^+ on the soil exchange complex, which is governed largely by the CEC and the density of oxygen-containing surface functional groups. Increasing pyrolysis temperature progressively raises ash content, pH and aromaticity while lowering CEC and surface functional-group density (Albalasmeh et al., 2020; Joseph et al., 2021; Tomczyk et al., 2020). The biochar was then homogenized, ground to < 1 mm, and stored in a plastic jar for further physicochemical characterization. The produced biochar's EC and pH were measured according to Rhoades (1982) and ASTM D3838-05 (2017), respectively. The ash content of the biochar was determined according to the American Society for Testing and Materials (ASTM) D3176. Ultimate analysis (C, N, S, and H) was determined using an elemental analyzer (EuroVector, Italy). Oxygen (O) content was estimated by subtraction. The specific surface area was determined from N_2 sorption isotherms using the Brunauer–Emmett–Teller (BET) method. Biochar characteristics are presented in Table 2.

Phosphogypsum

Phosphogypsum (80% pure) was obtained as a by-product from a phosphate industrial production site in Jordan. The gypsum consisted mainly of $CaSO_4.2H_2O$ and contained some impurities, mainly CaO (variable), P_2O_5 (1–1.3%), and SiO_2 (1–1.2%). Gypsum particle size distribution was: 2% <53 µm, 24% 53–106 µm, 44% 106–300 µm, 19% 300–500 µm, and 11% 500–1.000 µm. trace metals and radionuclides were not quantified in this study.

Table 2. Biochar characteristics

Parameters	Value
Moisture content (%)	2.98
Ash content (%)	37.01
pH	9.62
EC (dS m^{-1})	6.87
SSA (m^2 g^{-1})	117.35
N (%)	3.78
C (%)	81.68
H (%)	5.12
S (%)	0.47
O (%)	8.95

Note: EC – electrical conductivity; SSA – specific surface area; N – nitrogen; C – carbon; H – hydrogen; S – sulfur; O – oxygen.

Soil incubation

The 2 mm sieved soil sample was portioned and mixed with different biochar and phosphogypsum rates. Treatments were prepared by mixing biochar with soil at different rates: 0.5%, 1%, and 2% by weight. In the case of PG, the gypsum requirement (GR) was first determined; PG was then applied at two rates (50% and 100% of GR). A control (C), which contained neither biochar nor PG, was also prepared. The treatments were incubated at field capacity for one month.

Soil column leaching experiment

After incubation, 1.39 kg of treated soil were packed to a bulk density of 1.33 g cm^{-3} into cylindrical plexiglass columns (11 cm internal diameter and 25 cm length). To facilitate drainage, 3 cm of gravel was placed at the bottom of the columns. A filter disc was placed at the bottom and on top of the soil to prevent soil disturbance and loss (Figure 1). Columns were leached with a 3 cm constant water depth maintained on top of each column using a water pump. Each treatment was replicated three times and arranged in a completely randomized design (CRD).

All soil columns were leached with approximately four pore volumes (PV) of tap water (EC of 0.6 dS m^{-1}). Leachates were collected at 100 mL intervals in polyethylene bottles to monitor the efficiency of different treatments. The leachate samples were analyzed for EC, pH, and soluble cations (Na^+, K^+, Ca^{2+} and Mg^{2+}). Leaching was stopped once the leachate reached a constant EC, and all columns were then left to drain freely. After termination, soil from each column was carefully removed, air-dried, and passed through a 2 mm sieve. Air-dried sieved soil samples (post-leaching) were then analyzed for their respective chemical properties (pH, EC, CEC, SAR, and ESP).

The sodium adsorption ratio was determined as in Equation 1:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \quad (1)$$

The exchangeable sodium percentage was calculated as in Equation 2:

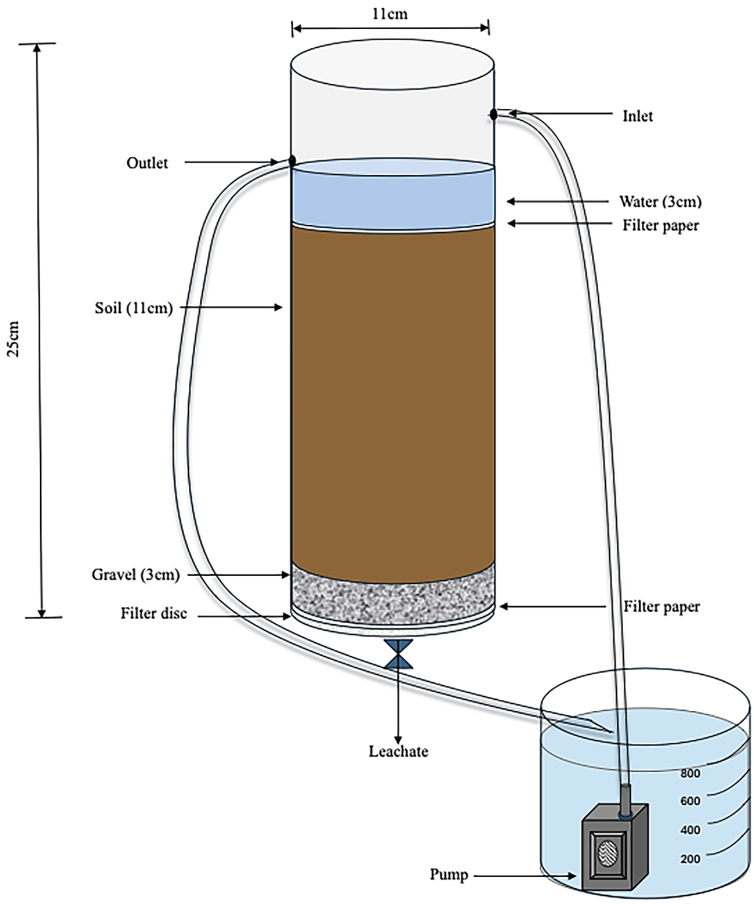

Figure 1. Schematic diagram of a column leaching experiment

$$ESP = \frac{Exchangeable\ \text{Na}^{+}}{CEC} \times 100 \quad (2)$$

Darcy's law was used to calculate saturated hydraulic conductivity (Ks) as in Equation 3:

$$K_s = \frac{V \times L}{A \times t \times \Delta H} \quad (3)$$

where: V is the collected leachate's volume (cm^3) within a time interval t (h), L is the soil column's length (cm), A is the cross-sectional area (cm^2) of the column, and (H_2 and H_1) are the respective pressure heads (cm) at the top and bottom of the soil column.

Glasshouse pot experiment

Barley seeds (ACSAD variety) were grown in plastic pots (top diameter 25 cm, bottom diameter 19 cm, height 25 cm) under greenhouse conditions at the Jordan University of Science and Technology; each pot contained 8 kg of soil. Pot treatments included the following: biochar 0.5% (BC0.5), biochar 1% (BC1), biochar 2% (BC2), Phosphogypsum 50% (PG50), Phosphogypsum 100% (PG100), and a control (C). Barley (*Hordeum vulgare* L.) is an excellent model crop for studying the effectiveness of soil amendments in saline-sodic environments, given its tolerance to such stresses and its economic importance across various agricultural systems.

Four replicates of each treatment were used and arranged in a completely randomized design. The pots were irrigated to the field capacity, and each pot was planted with ten barley seeds. Following three weeks of germination, the number of seedlings was thinned to five per pot, and 10 g of diammonium phosphate (DAP) fertilizer was added to each treatment. The pots were weighed 3 times a week to ensure appropriate volumes of irrigation water were applied to maintain field capacity.

To evaluate crop response to applied treatments (BC0.5, BC1, BC2, PG50, PG100, and C), the growth parameters of barley were measured (chlorophyll content, tiller number per plant, plant height, spike length, awn length, leaves number per culm, and leaf area). At harvest, all plants were hand-harvested, and the weight of each plant (including grains), the number of spikes per plant, the number of grains per spike, spike weight, weight of grains per spike, and the weight of a thousand grains were measured.

Plant height was recorded from the soil surface to the tip of the spike on the main tiller (cm), spike length was recorded from the base of the spike to the tip (without awn) (cm), and awn length was recorded from the end of the spike till the tip of the awn (cm). The number of tillers, leaves, and spikes per plant were counted manually. Biomass was manually separated into vegetative plant parts and grains, and the grains were counted manually. Plant chlorophyll content was measured (from the heading stage to the maturity stage) using a chlorophyll meter (SPAD-502, Minolta, Japan). Nitrogen content of grains and plants was determined by the dry weight using the Kjeldahl method (Bremner and Jenkinson, 1960), and K and P content were determined by the dry-ashing method (Cottenie, 1982).

Statistical analysis

Data analysis was performed using the statistical analysis software program R. Significant differences between means were analyzed by Tukey's HSD (honestly significant difference) test at a significance level α = 0.05. All measurements in this study were conducted on three replicates for the leaching columns and four replicates for the pot experiments. All reported data points denote the means of the replicates.

RESULT AND DISCUSSION

Leachate EC

The effect of different application rates of phosphogypsum and biochar on leachate EC is depicted in Figure 2. Initially, the EC increased to a maximum at approximately 1.2 pore-volume (PV), then decreased as leaching progressed, reaching about 4 dS/m after 4 PV. This trend was observed in other studies (Gharaibeh et al., 2009b, 2011b; Jalali and Ranjbar, 2009a). The control had the highest leachate EC 1.2 PV, followed by PG50 > PG100 > BC2 > BC1 > BC0.5, respectively (Figure 2). Chaganti et al. (2015) reported that the value of EC of the leachate from soils treated with organic amendments and gypsum was greater than that of EC of leachate from untreated soil. In our study, this was true for the BC0.5 and BC1 cases after 4 PV (Table 3). However, for the two PG treatments and BC2, the EC was higher than in the control. This can be due to excess Na flushed from the soil by

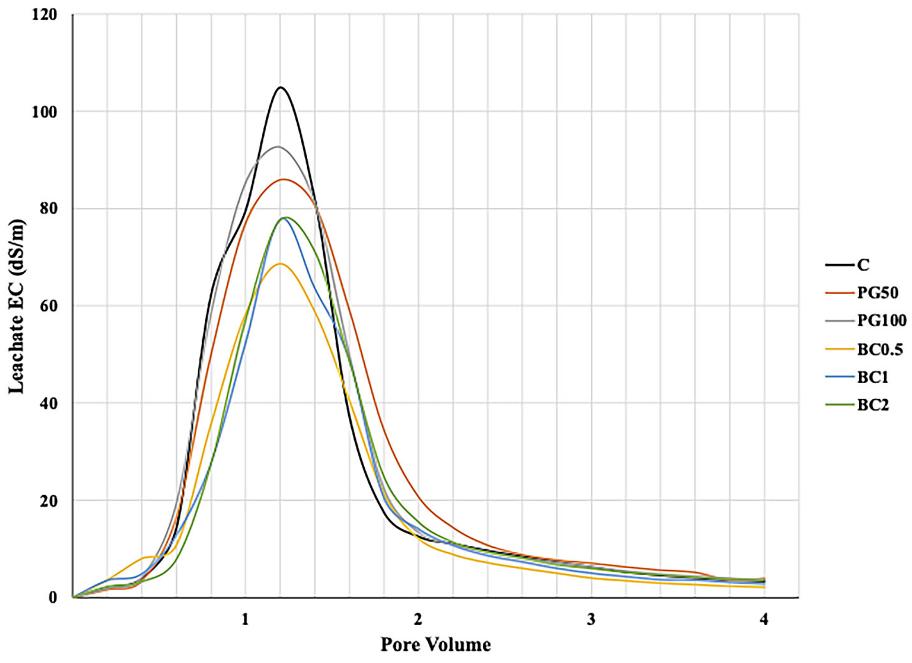

Figure 2. Effluent electrical conductivity (EC) as a function of pore volumes of leaching water for all treatments. C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%

Table 3. Effluent electrical conductivity (EC) after the 4th PV flush

Treatment	EC (dS m^{-1})
C	3.38
PG50	3.93
PG100	3.65
BC0.5	2.13
BC1	2.81
BC2	3.54

Note: C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%.

the abundance of Ca and Mg, as well as to leaching of ions introduced by treatment, such as the ash content of the biochar and the trace metals in the PG. Further, PG will initially dissociate, releasing Ca^{2+} and SO_4^{-}, increasing the EC of the leachate. Additionally, changes to the soil structure due to treatment may enhance ion mobility.

Leachate SAR

Figure 3 shows leachate SAR as a function of PV for all treatments. Sodium (Na), calcium (Ca), and magnesium (Mg) leachate concentrations were determined, and subsequently, effluent SAR was calculated using equation (Equation 1).

Figure 3 shows that the SAR of effluent increased to a maximum at 1.6 PV for all treatments, except BC1 and PG50, which peaked at around 1.8 PV. The SAR profile for PG exceeded that of the biochar treatments (Figure 3).

Applying PG50 resulted in a higher Na^+ concentration in leachate than other treatments. The availability of divalent cations (Ca^{+2}) from phosphogypsum increased cation exchange rate and subsequent Na^+ release into the soil solution (Gharaibeh et al., 2014). Furthermore, dissolution of sodium-bearing impurities in PG may have added Na loads. Nevertheless, this is likely to be a temporary effect before long-term amelioration processes take effect. In this particular case, the fact that PG was used at 50% of the soil's gypsum requirement could also have contributed, given the insufficient supply of Ca and Mg required to exchange the Na in the soil, let alone the added sodium from impurities.

No significant difference in Na^+ leached exists between PG100 and the control. Typically, PG is around 98% gypsum, and Na^+ leaching from impurities may have counteracted the effect of Ca^{+2}. Nevertheless, this is likely to be a short-term effect, and once the Na^+ is flushed out of the system, it is expected that the SAR will reduce. For biochar treatments, cumulative Na^+ losses are lower than in the control. Although BC0.5 had the lowest SAR value among all treatments, no significant differences were observed among the SAR values of

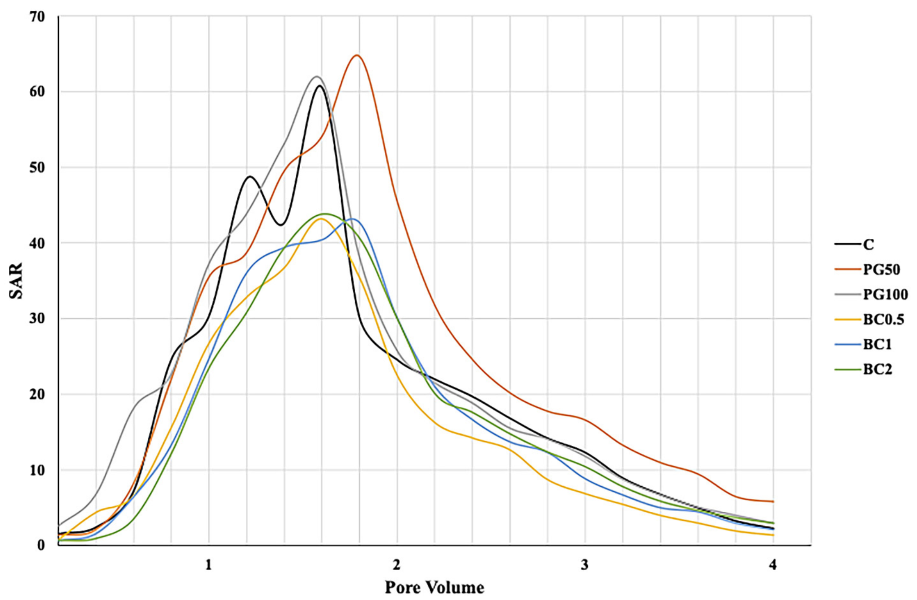

Figure 3. Effluent SAR as a function of pore volumes of leaching water for all treatments. C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%

biochar treatments (BC0.5<BC1<BC2). The higher SAR values in BC1 and BC2 may be attributed to Na^+ contributed by the ash content of the biochar.

Soil EC, ESP, and SAR post-leaching

The application of biochar and phosphogypsum resulted in substantial reductions in soil electrical conductivity, exchangeable sodium percentage, and sodium adsorption ratio following the leaching process (Figure 4). Compared with the initial soil conditions, all treatments reduced soil salinity to levels below the commonly accepted threshold of saline soils (EC < 4 dS m^{-1}) (Richards, 1954). The reduction in EC ranged from 95.6% in the BC2 treatment to 96.1% in the BC0.5 treatment, indicating that leaching effectively removed soluble salts from the soil profile.

The strong decline in EC primarily reflects the high solubility and mobility of the salts present in the saline–sodic soil, which were readily flushed from the soil matrix during leaching. Similar reductions in soil salinity have been reported in column leaching experiments conducted on saline soils amended with organic and mineral amendments (Chaganti et al., 2015; Fouladidorhani et al., 2020). However, although all treatments achieved substantial salinity reduction, the BC0.5 treatment consistently produced the lowest final EC values. This finding suggests that moderate biochar addition improved soil hydraulic properties and enhanced salt leaching efficiency. Biochar can influence salt transport through several physical and chemical mechanisms. The highly porous structure and low bulk density of biochar particles can improve soil aggregation and increase pore connectivity, thereby facilitating water movement through the soil profile. Improved pore continuity enhances the downward transport of soluble salts during irrigation or leaching events. Furthermore, biochar contains functional surface groups and exchangeable cations such as Ca^{2+} and Mg^{2+} that can interact with soil colloids and reduce clay dispersion, improving soil structural stability (Blanco-Canqui, 2017).

In addition to reducing soil salinity, all treatments substantially decreased soil sodicity, as indicated by significant reductions in ESP and SAR values. The initial ESP of the soil exceeded 85%, indicating extremely sodic conditions, typically associated with poor soil structure, reduced permeability, and limited plant growth. After leaching, ESP values declined dramatically across all treatments, falling below the commonly accepted threshold of 15% that defines sodic soils (Richards, 1954). Among the treatments, BC0.5 achieved the lowest ESP value (1.36%), indicating the most effective removal of exchangeable sodium from soil colloids. This improvement can be attributed to the combined physical and chemical effects of biochar addition. Biochar contains appreciable quantities of divalent cations in its ash fraction, particularly Ca^{2+} and Mg^{2+}, which can replace Na^+ on soil exchange sites through cation exchange reactions (Tsai et al., 2012). The displaced sodium then enters the soil solution and is subsequently removed through leaching. The cation exchange reaction can be represented as:

$$2Na^+ - Clay + Ca^{2+} \rightarrow Ca^{2+} - Clay + 2Na^+ \quad (4)$$

This reaction reduces the proportion of sodium occupying exchange sites and promotes the formation of more stable soil aggregates. Several studies have reported similar improvements in sodic soil properties following biochar application, highlighting the role of biochar-derived calcium and magnesium in enhancing cation exchange processes and facilitating sodium leaching (Chaganti et al., 2015; Zhou et al., 2021).

Interestingly, the PG50 treatment resulted in slightly higher ESP values compared with the control after leaching. This observation may be related to the incomplete gypsum requirement supplied in this treatment. When the calcium supply is insufficient to replace exchangeable sodium fully, partial cation exchange may occur without adequate removal of displaced sodium from the soil profile (Gharaibeh et al., 2014). In addition, impurities within phosphogypsum may introduce additional sodium into the system, temporarily offsetting the benefits of calcium addition. The PG100 treatment produced greater sodicity reduction than PG50, suggesting that higher calcium inputs enhanced sodium displacement from exchange sites. However, the improvement remained less pronounced than that observed with the BC0.5 treatment. This result indicates that although phosphogypsum effectively supplies calcium for sodium exchange, its ability to improve soil structure and hydraulic properties may be more limited than that of biochar amendments.

Higher biochar application rates (BC1 and BC2) did not further improve soil chemical conditions and, in some cases, resulted in slightly higher ESP and SAR values compared with BC0.5. This finding suggests that excessive biochar application

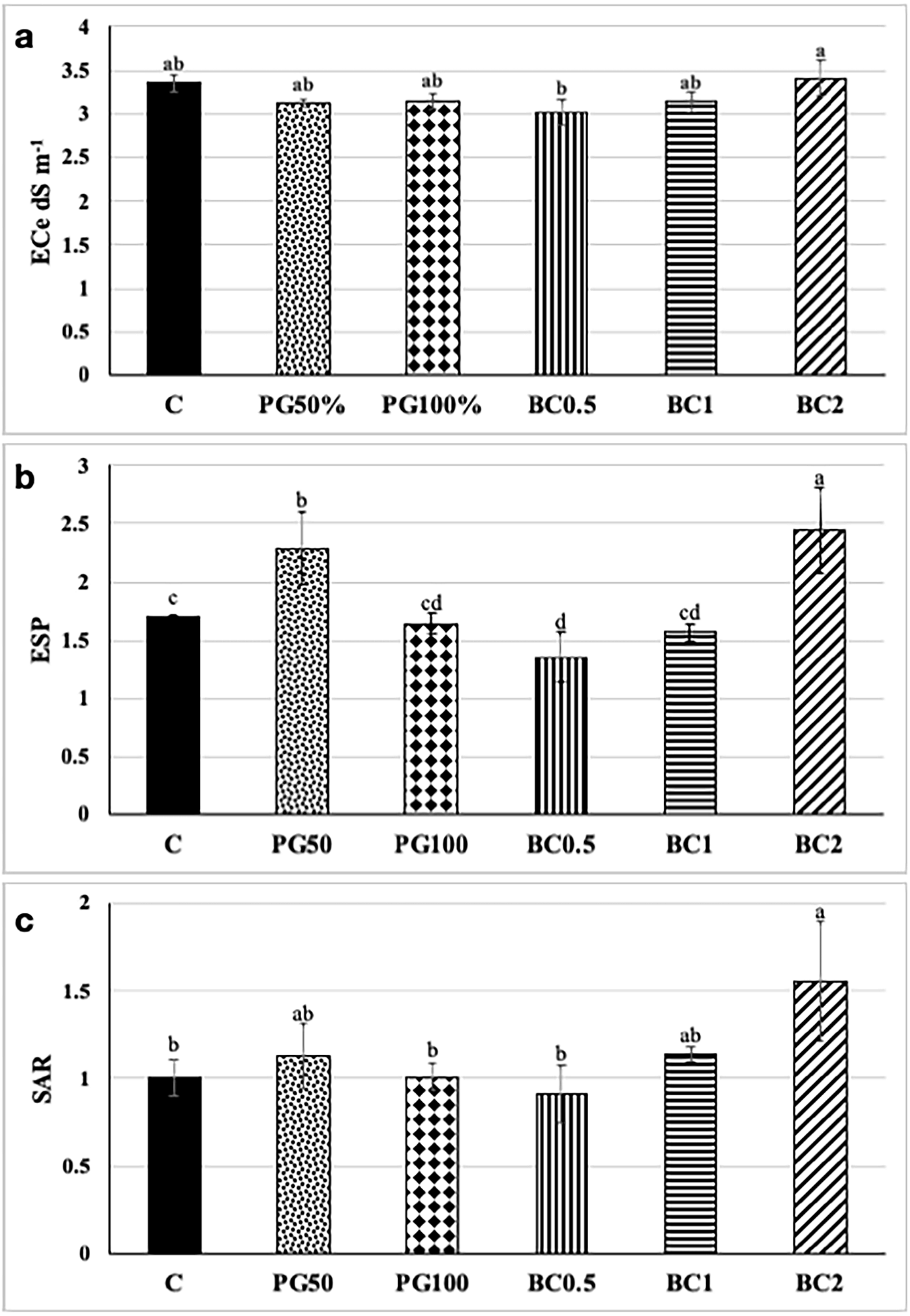

Figure 4. Soil electrical conductivity (ECe) (a), exchangeable sodium percentage (ESP) (b), and soil sodium adsorption ratio (SAR) (c) after the leaching process for all treatments. C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. Means followed by the same letters are not statistically different at ($P<0.05$) according to LSD

may introduce additional soluble salts. Biochar derived from plant residues often contains significant concentrations of alkali metals such as potassium and sodium, which can increase soil salinity when applied in large quantities. Moreover, the relatively low pyrolysis temperature used to produce the biochar (350 °C) may result in higher concentrations of soluble minerals and residual organic compounds, thereby increasing ionic strength in the soil solution (Albalasmeh et al., 2024). Overall, the results indicate that moderate biochar application (0.5%) provided the greatest improvement in soil chemical properties by simultaneously enhancing salt leaching and reducing sodium saturation of soil exchange sites. These findings highlight the importance of optimizing amendment rates when using biochar for the reclamation of saline–sodic soils.

Saturated hydraulic conductivity

Saturated hydraulic conductivity (Ks) is a key indicator of soil physical quality and strongly influences the efficiency of leaching processes in saline–sodic soils. In this study, significant differences in Ks were observed among treatments (Figure 5). The control soil exhibited the lowest hydraulic conductivity (0.11 cm h^{-1}), reflecting the severe structural degradation typically associated with highly sodic soils. High sodium concentrations cause clay particle dispersion, reducing soil porosity, blocking soil pores, and restricting water infiltration. The application of biochar significantly improved hydraulic conductivity compared with the control and phosphogypsum treatments. Among all treatments, BC0.5 produced the highest Ks value (14.2 cm h^{-1}), representing a dramatic improvement in soil permeability. The BC1 and BC2 treatments also increased hydraulic conductivity, but to a lesser extent than BC0.5.

The improvement in Ks following biochar application can be attributed to several structural modifications within the soil matrix. First, biochar particles can act as binding agents, promoting soil aggregation by facilitating interactions among soil minerals, organic matter, and microbial exudates. These interactions stabilize macroaggregates and reduce clay dispersion, thereby improving soil structure and enhancing water flow pathways (Blanco-Canqui, 2017). Second, the highly porous nature of biochar can introduce additional macropores into the soil system. These macropores increase the connectivity of the soil pore network and facilitate rapid water movement through the soil profile. Enhanced pore connectivity is particularly important in saline–sodic soils where dispersed clay particles often clog soil pores and severely restrict infiltration. Third, biochar may indirectly enhance hydraulic conductivity by promoting microbial activity and root development. Soil microorganisms can produce extracellular polysaccharides that bind soil particles together and stabilize aggregates (Albalasmeh and Ghezzehei, 2014). Similarly, increased root growth can create biopores that improve soil aeration and water movement. These biological processes contribute to long-term improvements in soil structure following biochar amendment.

Despite the overall improvement in hydraulic conductivity with biochar addition, a clear decline in Ks was observed as the biochar application rate increased from BC0.5 to BC2. This reduction may reflect the potential negative effects of excessive biochar addition on soil physical properties. High concentrations of biochar may disrupt soil pore continuity or create zones of localized hydrophobicity due to residual organic compounds produced during low-temperature pyrolysis. Such compounds can reduce soil wettability and impede water infiltration. Another

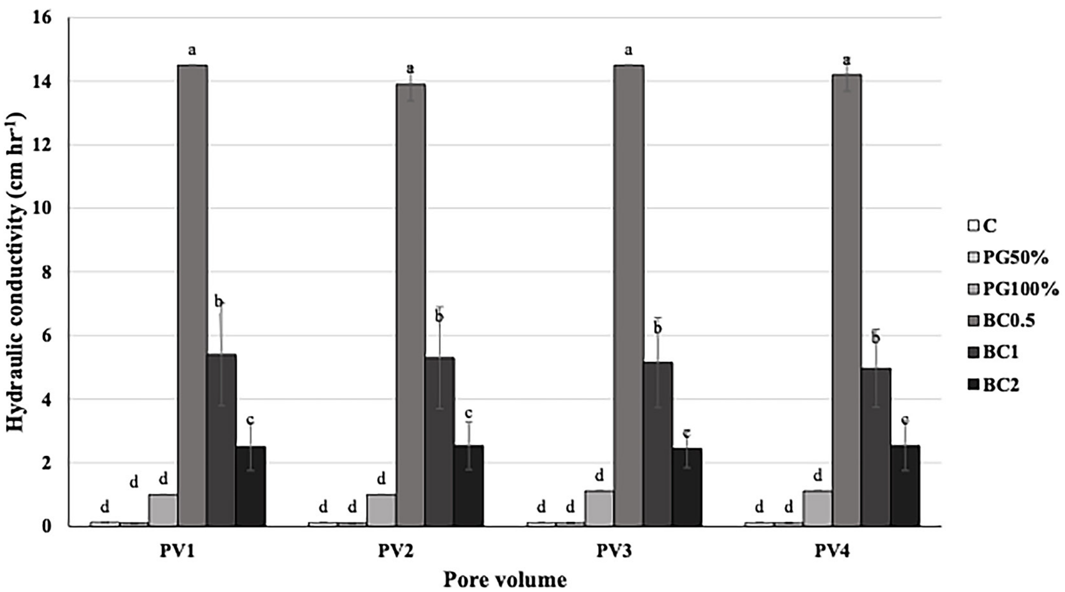

Figure 5. Soil-saturated hydraulic conductivity for all treatments. C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference at (P<0.05) according to LSD

possible explanation for the decline in hydraulic conductivity at higher biochar rates relates to the increased water-holding capacity of biochar-amended soils. Biochar has a high internal surface area and can retain significant amounts of water within its pore structure. When applied at excessive rates, biochar may retain water within its pores rather than facilitating downward water movement through the soil matrix, thereby reducing effective hydraulic conductivity.

Compared with biochar treatments, phosphogypsum amendments produced more modest improvements in hydraulic conductivity. The PG50 treatment showed no significant difference from the control soil, suggesting that the applied calcium was insufficient to overcome the strong dispersive effects of exchangeable sodium. The PG100 treatment produced some improvement in Ks, but the increase remained substantially lower than that observed with biochar amendments. The relatively limited effect of phosphogypsum on hydraulic conductivity can be explained by its mode of action. Gypsum primarily functions as a chemical amendment, supplying soluble calcium to displace sodium. Although this process eventually improves soil structure by reducing clay dispersion, structural improvements often occur gradually and may require prolonged leaching and repeated amendment applications before significant changes in hydraulic conductivity become evident.

The significant improvement in hydraulic conductivity observed in the BC0.5 treatment underscores the potential of biochar as a multifunctional soil amendment that simultaneously improves soil chemical and physical properties. Enhanced hydraulic conductivity not only facilitates more efficient salt leaching but also improves irrigation efficiency and root development, thereby enhancing crop productivity in saline–sodic environments.

Overall, the results demonstrate that moderate biochar application provides the most effective improvement in soil permeability and leaching efficiency, whereas excessive biochar addition may reduce these benefits. These findings emphasize the importance of identifying optimal biochar application rates when using biochar as a soil reclamation strategy.

Effect of amendments on barley growth and yield in a glasshouse setting

Plant morphological characteristics

Table 4 shows the effects of biochar and phosphogypsum on crop morphological characteristics grown in saline-sodic soil. Table 4 shows no significant difference in tiller number per plant between C, PG50, PG100, and BC0.5. However, increasing the biochar rate (BC1 and BC2) significantly decreased tiller number per plant

Table 4. Effect of biochar and phosphogypsum on plant morphological properties

Parameter	Units	Treatments					
		C	PG50	PG100	BC0.5	BC1	BC2
Tillers number		8.0a	11.0a	11.0a	12.0a	3.0b	2.0b
Leaves number per culm		5.0a	5.0a	4.0a	4.0a	5.0a	6.0a
Plant height	cm	46.7cd	64.8ab	56.8bc	75.0a	35.3de	26.0e
Spike length	cm	3.0ab	5.9a	6.5bc	7.5a	2.8ab	0.8b
Awn length	cm	10.3a	10.4a	10.9a	10.2a	2.7b	1.5b
Leaf area	cm^2	8.3b	13.8a	9.8ab	15.8a	2.6c	0.5c
Plant weight	g	54.7c	104.6ab	88.4bc	129.5a	9.0d	2.5d
Plant dry weight	g	53.56c	96.34b	85.48b	126.71a	8.87d	2.45d
Spike weight	g	0.7c	1.5ab	1.3b	2.04a	0.2c	0.1c
Number of spikes per plant		10.0a	12.0a	10.0a	11.0a	3.0b	1.0b
Number of grains per spike		28.0ab	36.0a	35.0a	41.0a	13.0b	11.0b
Weight of grains per spike	g	0.6c	1.3b	1.1b	1.8a	0.1c	0.04c
Weight of 1000-grains	g	19.4c	35.5a	31.7ab	43.1a	8.9c	4.4c

Note: C control is the unamended soil, PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference among the treatments at ($P<0.05$) according to LSD.

compared to all other treatments. The decline in growth at the higher biochar rates (BC1 and BC2) is attributable to several interacting mechanisms. First, the biochar carried an appreciable intrinsic salt and alkali load (ash content 37.0%, EC 6.87 dS m^{-1}, pH 9.62; Table 2); applied at 1–2% w/w, this measurably increased topsoil EC, ESP and SAR (Figures 4, 7 and 8), re-imposing osmotic and Na^{+}-specific stress in the root zone. Second, the high internal porosity and water-holding capacity of biochar increased water retention; because irrigation was applied to field capacity, the higher-rate treatments received proportionally less drainage and salts were not leached below the root zone, consistent with the elevated and inverted EC depth profile observed for BC2. Third, the relatively low pyrolysis temperature (350 °C) favors retention of water-soluble and condensable organic compounds (e.g., volatile organic acids, tars and polycyclic aromatic hydrocarbons) that can inhibit germination and root elongation and induce localized hydrophobicity; such inhibition is characteristically dose-dependent, appearing only at high application rates (Joseph et al., 2021). Finally, the reduction in shoot K^{+} at BC2 (Table 4) is consistent with Na^{+}–K^{+} antagonism under the elevated sodicity of this treatment. The net outcome is a clear dose–response: at 0.5% the structural and leaching benefits of biochar dominate, whereas at 1–2% the additional salt loading, impaired leaching and possible organic phytotoxicity outweigh these benefits.

Table 4 shows that there was no significant difference among treatments in the number of leaves per culm. For plant height, the tallest plants were observed at BC0.5 and PG50, respectively. As the rate of biochar addition increased, plant height decreased significantly, with the shortest plants observed in BC2 and BC1. Additionally, there was no significant difference in plant height between C and PG100. Many studies have reported similar results, showing that applying biochar and gypsum to saline-sodic soils increases plant height (Ali et al., 2021; Amer, 2015; Bayoumy et al., 2019). This result can be explained by the ability of biochar and phosphogypsum to provide the soil with divalent cations Ca^{+2} and Mg^{+2} that replace Na^{+} at the exchange sites in the soil, facilitating the leaching process of salts and Na^{+} out of the root zone and improving soil structure, which increases the soil's ability to retain water and nutrients and facilitating their access to the plant, and stimulating crop growth (Mahmoud et al., 2020).

Measuring spike length, the longest spike was observed at BC0.5, followed by PG50, PG100, C, and BC1, respectively. However, there was no significant difference in spike length between all treatments. The BC2 treatment produced the shortest spike, with a significant difference between BC0.5 and BC2, likely due to the higher EC and ESP in the top soil layer in the BC2 treatment. Results indicated that spike length decreased with increasing biochar application rate. For awn length, there was no significant difference among all treatments except for BC2 and BC1, which were significantly shorter.

The plant leaf area was largest at BC0.5, PG50, and PG100, with no significant difference observed among these treatments. While PG50 and PG100 showed no significant difference compared to the control, the leaf area at BC0.5 was significantly larger than that of the control. Leaf area decreased significantly with increasing biochar application rates, with the smallest leaf areas observed at BC2 and BC1. This result aligns with Li et al. (2020), who observed a similar effect of biochar on soybean plants at varying soil doses. The highest leaf area at BC0.5, PG50, and PG100 can be explained by the release of biochar- and phosphogypsum-derived divalent cations, Ca^{2+} and Mg^{2+}, which replace Na^{+} at exchange sites in the soil, thereby improving physical properties and reducing salt stress in the root zone (Chaganti et al., 2015). This process enhances soil structure and soil health (Huang et al., 2019), thereby reducing soil salinity and sodicity and facilitating improvements in soil properties (Bayoumy et al., 2019). As a result, these conditions could provide better soil environments for plant growth and enhance crop growth and productivity.

Results in Table 4 revealed that the highest plant fresh weights (FW) were observed in the order of BC0.5, PG50, PG100, C, BC1, and BC2, respectively. The FW at BC0.5 was significantly higher than the control. However, the FW decreased significantly with increased biochar rate. Regarding plant dry weight (DW), BC0.5 showed significantly higher values compared to all other treatments, followed by PG50 and PG100, which were significantly higher than the control. A significant decrease in DW was observed with increased biochar application. Sánchez et al. (2022) reported that applying biochar made from almond shells to saline soil resulted in higher FW at lower biochar rates. This could be attributed to the decrease in soil salinity in the root zone and its leaching to the soil's lower layers with irrigation water (Sánchez et al., 2022).

Table 4 indicates that both spike weight and grain weight per spike were significantly higher at BC0.5 compared to all other treatments. This result agrees with Mahmoud et al. (2019), who reported an increase in maize seed yield with biochar application (5, 10, and 19 ton ha^{-1}) to saline-sodic soil. This can be explained by biochar's ability to reduce soil bulk density, increase soil porosity, and boost organic carbon content (Albalasmeh et al., 2024), which stimulates microbial growth and activity, and therefore enhances biological decomposition, plant growth, and overall production (Pampuro et al., 2020; Zhou et al., 2021). Spike weight and grain weight per spike at PG50 and PG100 were higher compared to C, BC1, and BC2. Data in Table 4 shows a significant decrease in both spike weight and grain weight per spike with increasing biochar rates in BC2 and BC1. This may be due to high salinity in the topsoil layer, which prevented most plants from reaching seed set.

Table 4 indicates that the 1000-grain weight was highest at BC0.5, followed by PG50, PG100, C, BC1, and BC2, respectively. The 1000-grain weight at BC0.5 and PG50 was significantly higher than the control. This result can be explained by the fact that BC0.5 and PG50 provide the soil with Ca^{2+} and Mg^{2+}, which replace Na^{+} at the exchange sites, thus facilitating Na^{+} and salts leaching out of the root zone, reducing EC and ESP, thereby enhancing plant growth and increasing production (Fouladidorhani et al., 2020; Mahmoud et al., 2019; Yaojun Zhang et al., 2020; Zhou et al., 2021). In addition, when the biochar rate was increased to BC2 and BC1, a significant reduction in grain weight was observed. Based on DW and 1000-grain weight, it is evident that BC0.5 followed by G50 had the best yield return.

Plant nutrients

Table 5 illustrates the effect of biochar and phosphogypsum on plant nutrients NPK in both shoots and grains. Data in Table 5 indicate that neither biochar nor phosphogypsum significantly affected the nitrogen content (N) in the shoots of plants grown in saline-sodic soil. However, the N content in the grains was significantly lower in BC1 and BC0.5 compared to the control. These results align with Agbna et al. (2017), who observed a similar reduction in ammonium N and nitrate N in soil treated with straw wheat biochar. This reduction may be attributed to biochar's ability to increase the C/N ratio and stimulate microbial activity in the soil (Chen et al., 2020; Yao et al., 2021b), thereby enhancing the uptake of alkali-hydrolyzable nitrogen by microorganisms. In the BC2 treatment, seeds failed to develop, as the plants died prematurely due to high soil salinity.

The results indicated no significant difference in shoot phosphorus (P) content across all treatments, except for BC2, where shoot P content was significantly higher. This increase may be due to biochar either contributing phosphorus or enhancing the soil's capacity to absorb and transfer nutrients, including phosphorus, to the plants (Yao et al., 2021). Regarding phosphorus content in the grains, no significant differences were observed among treatments. Regarding potassium (K) content in the shoots, as shown in Table 5, there was no significant difference among treatments,

Table 5. Effect of biochar on plant nutrients

TreatmentS	Shoot			Grains		
	N%	P mg. g^{-1}	K mg. g^{-1}	N%	P mg. g^{-1}	K mg. g^{-1}
C	2.24a	12.52bc	25.99ab	3.5a	27.99a	11.26a
PG50	1.39a	7.12c	30.11ab	2.21ab	27.38a	8.83ab
PG100	1.61a	9.84bc	30.17a	2.06ab	24.80a	6.09ab
BC0.5	1.55a	13.59ab	31.03a	1.55bc	26.03a	7.67ab
BC1	0.74a	12.52bc	21.08bc	0.74bc	19.91ab	3.29ab
BC2	0.88a	18.83a	16.37c	*0.00c	*0.00b	*0.00b

Note: C is the control (unamended soil), PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference at ($P<0.05$) according to LSD. * Plants died before full seed formation.

except for BC2, which had significantly lower K content than the control. Figure 4 shows that BC2 had the highest ESP and SAR values; therefore, this reduction is likely due to the high soil salinity, which was not effectively leached from the root zone, thereby hindering nutrient uptake by the plants. The high salinity and sodicity of the soil (BC2) had caused significant damage to plant development. In fact, in BC2, the plants died in the early stages of their life cycle before reaching the full seed formation stage.

The effect of biochar and phosphogypsum on the soil at the end of the crop

Figure 6 demonstrates the impact of biochar and phosphogypsum on soil pH at the end of the crop cycle. The data revealed no significant differences in pH across treatments and soil layers. However, it was observed that the pH in L2 (the middle 8–16 cm layer of the soil) was slightly higher than in the PG100 and BC2 cases. This rise in pH may be attributed to the higher concentration of sodium leached from the top layer (Abrol et al., 1988).

Figure 7 shows the effect of biochar on soil electrical conductivity (EC). EC values increased progressively with depth, except for BC2. This pattern may be due to the enhancement of soil aggregate stability and hydraulic properties from the addition of biochar (BC0.5), which improves water movement in the soil and facilitates the leaching of salts out of the root zone (Ni et al., 2023). The BC2 treatment, however, showed an opposite

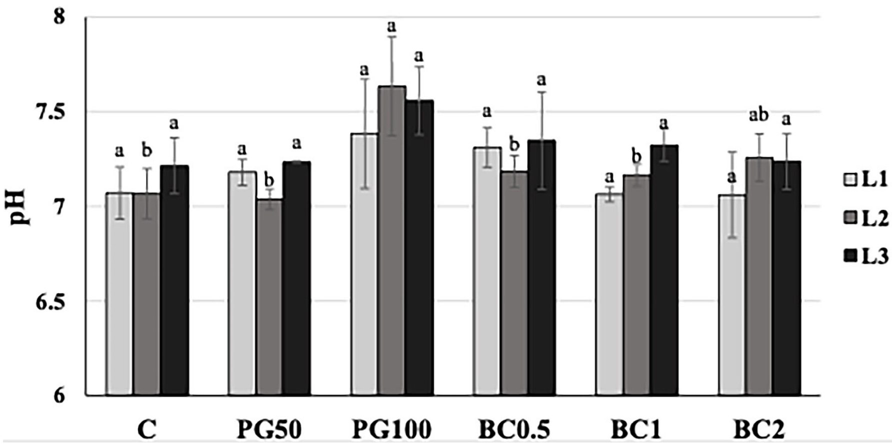

Figure 6. Effect of biochar and phosphogypsum on soil pH at the end of the crop cycle (experiment). L1 is the top layer of the soil, L2 is the middle layer of the soil, and L3 is the bottom layer of the soil. Control is the unamended soil, PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, BC2 is biochar 2%. The same letters mean no significant difference at (P<0.05) according to LSD

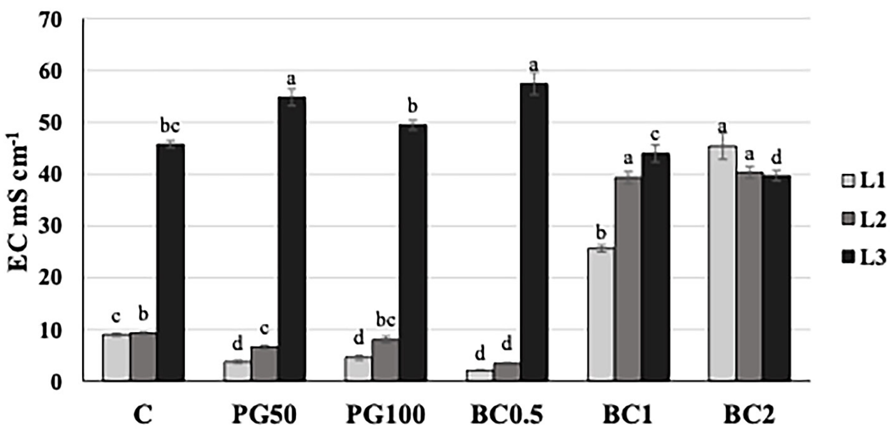

Figure 7. Effect of biochar on soil EC at the end of the crop cycle (experiment). EC is the electrical conductivity, L1 is the top layer of the soil, L2 is the middle layer of the soil, and L3 is the bottom layer of the soil. C is the unamended soil, PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference at (P<0.05) according to LSD

trend to the rest. This can be attributed to the ineffectiveness of BC2 in mitigating soil salinity and sodicity before planting (Figure 4). Furthermore, the highest EC in the top layer was found in BC2, BC1, and C, respectively. The increase in salinity in L1 with higher biochar rates (BC2 and BC1) may be due to biochar's high water-holding capacity (Yang et al., 2019). which can result in insufficient water for washing and leaching salts out of the root zone, as irrigation was based on the soil's field capacity. Moreover, this may also be attributed to the biochar's high ash content, as ash often contains significant amounts of soluble salts, including sodium (Na). In the case of PG50 and PG100, improving soil physical properties by exchanging divalent cations with sodium, facilitating water movement, and promoting salt leaching to the deeper soil layer (L3) and out of the root zone, thereby enhancing plant growth in these treatments (Saifullah et al., 2018).

Figure 8 shows the effects of biochar on soil exchangeable sodium percentage (ESP). The ESP values generally increased with depth, except for BC2, which showed the opposite trend. The lowest ESP values in the top soil layer were observed at BC0.5, followed by PG50, with no significant difference between them. ESP values increased, with no significant differences from PG50, at PG100 and C. The reduction in ESP at BC0.5 may be due to a decrease in exchangeable Na^+, thereby improving soil hydraulic properties after biochar application. This enhancement facilitates water movement and leaching of Na^+ from the top layer (L1), thereby reducing Na^+ concentration and lowering the soil's ESP. Several studies have reported similar findings, indicating that biochar application to saline-sodic soils effectively reduced soil ESP (Bayoumy et al., 2019; Chaganti et al., 2015; Fouladidorhani et al., 2020; Mahmoud et al., 2019; Zhou et al., 2021).

In addition, the application of phosphogypsum (PG50 and PG100) supplies divalent cations, such as Ca^{2+} and Mg^{2+}, which replace Na^+ at exchange sites. This replacement facilitates the leaching of Na^+ from the top layer (L1) (Fouladidorhani et al., 2020; Gharaibeh et al., 2010), thereby decreasing ESP in L1. However, as Na^+ moves with the irrigation water and accumulates in the lower layers (L2 and L3), the ESP values increase in these layers.

The effect of biochar and phosphogypsum on soil aggregate stability at the end of the crop cycle is shown in Figure 9. In the top layer, the highest aggregate stability was observed with BC0.5, followed by BC2 and BC1, with no significant difference among them. This result aligns with Herath et al. (2013), who found that application of biochar derived from cornstarch significantly increased soil aggregate stability. The authors attributed this improvement to microbial activities hosted by biochar, which release secretions that bind soil particles together, a finding confirmed by electron microscope images showing microbial products and fungal hyphae within biochar pores (Herath et al., 2013). Kim et al. (2016) also reported that adding biochar to soil increases aggregate stability by increasing organic carbon, thereby enhancing macroaggregate stability.

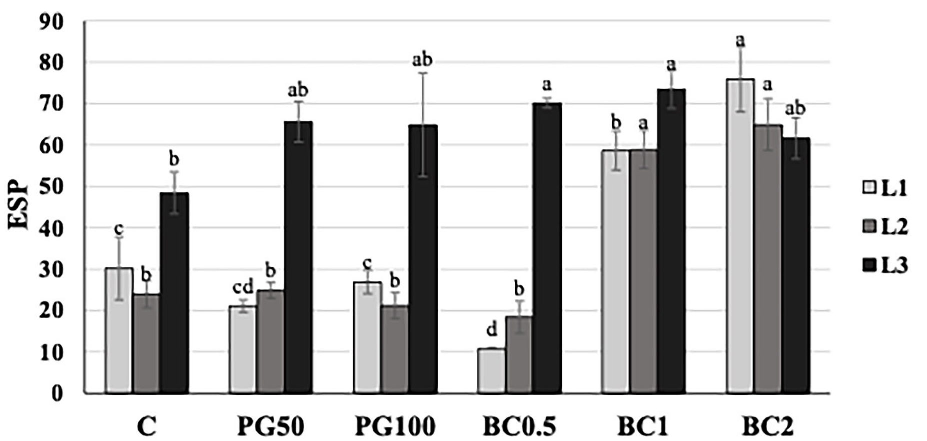

Figure 8. The effect of biochar on soil ESP at the end of the crop cycle (experiment). ESP is the exchangeable sodium percentage, L1 is the top layer of the soil, L2 is the middle layer of the soil, and L3 is the bottom layer of the soil. Control is the unamended soil, PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference at ($P<0.05$) according to LSD

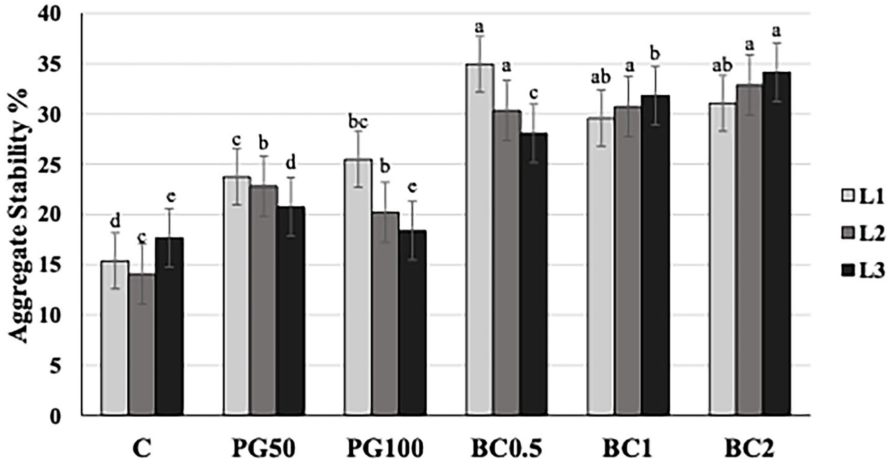

Figure 9. The effect of biochar on soil aggregate stability after harvesting. L1 is the top layer of the soil, L2 is the middle layer of the soil, and L3 is the bottom layer of the soil. Control is the unamended soil, PG50 is phosphogypsum 50%, PG100 is phosphogypsum 100%, BC0.5 is biochar 0.5%, BC1 is biochar 1%, and BC2 is biochar 2%. The same letters mean no significant difference at ($P<0.05$) according to LSD

Soil aggregate stability was significantly higher with (PG50 and PG100) compared to the control. This improvement is likely due to phosphogypsum providing divalent cations such as Ca^{2+} and Mg^{2+}, which promote the formation of soil aggregates. This result is consistent with Muneer and Oades (1989), who reported that gypsum application led to enhanced soil floccules and aggregate formation, thus increasing soil stability. Results indicated that soil aggregate stability decreased in the middle and bottom layers in BC0.5, PG100, PG50, and C. This decline can be attributed to increased soil salinity, resulting from Na^+ accumulation in the lower layers, which was caused by leaching of salts from the upper layer by irrigation water. The accumulation of sodium negatively affects soil structure, leading to the dispersion of soil particles (Gharaibeh et al., 2011; Hanay et al., 2004). No significant differences in soil aggregate stability were observed between BC2 and BC1, which may be due to lower Na^+ concentrations and soil salinity across the three layers. Additionally, due to the higher biochar content, which contributed to greater soil water-holding capacity and, in turn, less moisture loss, these treatments received less irrigation water than others, which was insufficient to leach salts and Na^+ into the lower layers.

Limitations and future research

This study evaluated biochar produced at a single pyrolysis temperature (350 °C), selected to maximize CEC and surface functional-group retention; the influence of pyrolysis temperature on reclamation performance was therefore not examined. Future research should compare biochar pyrolyzed across a range of temperatures (e.g., 350, 500 and 700 °C) to identify the temperature that best balances cation-exchange capacity, alkalinity, soluble-salt content and the formation of potentially phytotoxic compounds in saline–sodic reclamation. The adverse effects of the higher biochar rates on salinity and sodicity were directly quantified through ECe, ESP and SAR measurements in the leaching columns and in the depth-resolved post-harvest soil (Figures 4, 7 and 8); however, the contribution of phytotoxic organic compounds was inferred from the low pyrolysis temperature and supporting literature rather than measured directly. Future work will confirm this mechanism using standardized seed-germination and root-elongation bioassays (germination index) on biochar water extracts, quantification of water-extractable organic carbon and dissolved organic compounds, GC–MS/HPLC determination of polycyclic aromatic hydrocarbons and volatile/condensable organics, and screening for environmentally persistent free radicals. The heavy-metal and radionuclide contents of the biochar and phosphogypsum were not quantified in this study. The biochar was produced from uncontaminated tomato-crop residue and applied at low rates (0.5–2% w/w), and phosphogypsum was used at agronomic doses, which limits cumulative loading; nevertheless, because pyrolysis can concentrate feedstock metals and phosphogypsum may carry trace metals and naturally occurring radionuclides, future characterisation by ICP-OES/ICP-MS (As, Cd, Cr, Cu, Ni, Pb and Zn) and, for phosphogypsum, gamma spectrometry (^{226}Ra, ^{232}Th and ^{238}U series), benchmarked against IBI/EBC and international radiological guidance, is warranted to confirm the environmental safety of repeated field application.

CONCLUSIONS

This study investigated the potential use of biochar derived from tomato shoot residues and compared it to phosphogypsum, applied at different rates, to reclaim saline-sodic soil in a column experiment. The study further assessed their impact on barley growth and yield in a glasshouse experiment. Results showed that all treatments, including the control, significantly reduced soil electrical conductivity, exchangeable sodium percentage, and sodium adsorption ratio due to the removal of salts and Na^+ during leaching. Biochar application notably improved hydraulic conductivity by enhancing soil physical properties, with the highest hydraulic conductivity observed at the lowest rate of 0.5% by mass (BC0.5), followed by 1% (BC1) and 2% (BC2).

In the pot experiments, measurements of plant growth indicators (plant fresh and dry weight, plant height, leaf area, spike weight, weight of grains per spike, and weight of 1000 grains) showed that BC0.5 yielded the best results, followed by PG50 and PG100. However, increasing the biochar ratio decreased all measured morphological plant traits and chlorophyll content at BC2 and BC1. While this work demonstrates the potential beneficial effects of biochar, it also raises concerns over high application rates that may produce counterproductive results. It also warrants investigation of long-term repeated application of biochar. It is recommended that a long-term study involving repeated applications of biochar and at different frequencies be conducted to establish the long-term utility of biochar. Although PG treatments showed less efficiency than biochar during the trial, the long-term effect should be evaluated to affirm its impact over time.

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