ISSN: 2538-2152; ECOPERSIA 2026;14(2): 205-216.

# Interactive Effects of Biochar and Nano-Silica on Nutrient Levels and Yield Productivity in Saline Soils

## ARTICLEINFO

*Article Type*
**Original Research**

*Authors*
Noor Al-Huda Hassan Al-Asadi, *M.Sc.*[1*]
Salwa J. Fakher, *Ph.D.*[2]

**How to cite this article**
Hassan Al-Asadi N.A., Salwa J.F. Interactive Effects of Biochar and Nano-Silica on Nutrient Levels and Yield Productivity in Saline Soils. ECOPERSIA 2026;14(2): 205-216.

**DOI:**
10.48311/ecopersia.2026.120120.82889

[1] Department of Soil Sciences and Water Resources, College of Agriculture, University of Basrah, Basrah, Iraq.
[2] Assistant Professor, Department of Soil Sciences and Water Resources, College of Agriculture, University of Basrah, Basrah, Iraq.

*** Correspondence***
Address: Department of Soil Sciences and Water Resources, College of Agriculture, University of Basrah, Basrah, Iraq.
Tel: +9647765929779
E-mail: nooralhuda.hassan@uobasrah.edu.iq
ORCID: 0009-0007-0575-6180

***Article History***
Received: May 13, 2026
Revised: June 25, 2026
Accepted: June 26, 2026
Published: June 29, 2026

## ABSTRACT

**Aims:** This study aimed to evaluate the effectiveness of interactions between biochar and nano-Silica at different levels in improving the properties of degraded calcareous saline soils and enhancing their suitability for cultivation.

**Materials & Methods:** A field experiment was conducted during the 2024–2025 growing season at the Research Station of the University of Basrah, Iraq. The experimental design included twelve treatments comprising four levels of nano-Silica ($SiO_2$) (0, 200, 300, and 400 $kg.ha^{-1}$) and three levels of wheat biochar (WSBC) (0, 20, and 30 $t.ha^{-1}$) prepared locally from wheat straw residues.

**Findings:** Statistical analysis revealed a significant decrease ($P < 0.05$) in soil solution salinity (EC) from 11.41 $dS.m^{-1}$ to 3.96 $dS.m^{-1}$, and a reduction in pH from 7.85 to 7.42 at the maximum interaction (WSBC3 + Si4). Toxic and soluble ion concentrations declined sharply, with Sodium ($Na^+$) decreasing by 43.9%, Chloride ($Cl^-$) by 55.7%, and bicarbonate ($HCO^{-3}$) by 62.9%. Furthermore, the availability of macronutrients (N, P, K) increased by 145%, 168%, and 48%, respectively, due to improved ionic balance and plant uptake.

**Conclusion:** The integration of nano-Silica and biochar represents a sustainable strategy for reducing salinity and enhancing soil fertility. The study recommends adopting an intervention of 30 $t.ha^{-1}$ biochar plus 400 $kg.ha^{-1}$ nano-Silica for the effective reclamation of saline soils.

**Keywords:** Biochar; Salinity; Calcareous Soil; Nano-Silica; Nutrient availability; Wheat Straw.

## CITATION LINKS

[1] Bandak S., Movahedi-Naeini S.A., Mehri S., Ghorbani K., Kiani ... [2] Al-Daraji F.K., Ndewi D.R., Al-Shammari H.M. Modeling water su... [3] Ali A.H. The effect of irrigation water salinity on the growth... [4] Rehman S.U., Sarwar N., ul Din M.S., Al-Bakosh A.A.M., Khan S.... [5] Zhang X., Li Y., Kumar S., Zhao J., West P.C., Gerber J.S., Fo... [6] Zarei M, Karimi N, Modarres-Sanavy SAM. Comparison of the Effe... [7] Al-Daraji F.K., Ndewi D.R., Al-Shammari H.M. Modeling and anal... [8] Akhtar N., Ilyas N., Mashwani Z.U., Hayat R., Yasmin H., Noure... [9] Page A.L., Miller R.H., Keeney D.R. Methods of soil analysis, ... [10] Bremner J.M., Keeney D.R. Determination and isotope-ratio anal... [11] Amin, M., & Flowers, T. H. (2004). Evaluation of Kjeldahl dige... [12] Murphy T., Riley J.R. A modified single solution method for th... [13] Richards, L.A. Diagnosis and improvement of saline and alkali ... [14] Al-Saeedi A.H. Contribution of Nano-Silica in Affecting Some o... [15] Jabal A.H., Abdulkareem M.A. Soil salinity and nutrient availa... [16] Huang J., Zhu C., Kong Y., Chen J., Guan C., Wang G., Wang M.,... [17] Gu Y.Y., Liang X.Y., Zhang H.Y., Zhang Y.M., Zhao X.Y., Zhang ... [18] Gill S., Ramzan M., Naz G., Anjum S., Gulshan A.B., Hussain S.... [19] Al-Maliki A.H., Al-Mamory S.A. Role of nano-Silica in mitigati... [20] Alazzaz B.A., Al-Haddad S.A., Al-Obaidi M.A. Effect of biochar... [21] Liu J., Jiang J., Meng Y., Aihemaiti A., Xu Y., Xu H., Chen L.... [22] An X., Liu Q., Pan F., Chen T., Zhao A., Zhang L., Wu L., Wang... [23] Khan M., Khan A.U., Hasan M.A., Yadav K.K., Cabral-Pinto M.M.S... [24] Shabbir A., Khalid M.S., Arshad M., Hussain S., Murtaza B., Sh... [25] Zhu X., Chen B., Zhu L. Micro-and mesoporous structures of bio... [26] Karimi R., Adnan A. Impact of nano-silicon fertilizers on ion ... [27] Meena R.K., Singh P.B. Nano-fertilizers in agriculture: Mechan... [28] Jabal A.H. Ionic Composition and Prevailing Salt of Saline Soi... [29] Ahmed A.K., Hadres I.A., Albajary A., Oleksandr S. Study the e... [30] Rosa D., Petruccelli V., Iacobbi M.C., Di Giacinto S., Libutti... [31] Al-Aboudi R.J., Al-Asadi S.A. Effect of biochar and organic am... [32] Song S., Cong P., Wang C., Wang J., Wang Y., Zhang L., Li Z. P... [33] Aqaei P., Weisany W., Diyanat M., Kasraie P., Azizi K. Respons... [34] Zhou Z.Y., Yang L., Wang M.X., Zhou Z.F., Li Y.H., Zhang X.H. ... [35] Qayyum M.F., Haider G., Raza M.A., Khan S.A., Rizwan M., Hussa... [36] Al-Daraji F.K., Shareef N.F., Hasan W.B. Prediction of water s... [37] Khan Z.S., Rizwan M., Hafeez M., Ali S., Adrees M., Qayyum M.F... [38] Rea R.S., Islam M.R., Rahman M.M., Mix K., El-Desouky H.S., Al... [39] Forján R., Arias-Estévez M., Gallego J.L.R., Rodríguez-Vila A.... [40] Abideen Z., Waqif H., Munir N., El-Keblawy A., Hashem A., Al-A...

## Introduction

Soil salinity is considered one of the most complex environmental and agricultural challenges in arid and semi-arid regions, exacerbated by the dynamic interactions among natural factors, human activities, and climate change [1,2]. The severity of this phenomenon is manifested in the deterioration of soil structure and permeability; it also increases the osmotic potential, thereby creating a state of "physiological drought" that hinders the ability of crops to absorb water and essential nutrients, in addition to the destructive effects resulting from the toxicity of accumulated Sodium and Chloride ions [3]. In the local context, strategic crops in the northern, central, and southern regions of Iraq face an existential threat due to a sharp increase in soil and irrigation water salinity and sodicity, resulting in a significant decline in productivity and food security [4]. Saline calcareous soils are inefficient in utilizing conventional fertilizers (N, P, K), as these suffer significant losses due to ammonia volatilization, phosphorus fixation, and leaching, thereby reducing nutrient use efficiency and exacerbating environmental pollution [5]. In response, the trend towards biochar and nano-enriched soil amendments has emerged as a sustainable alternative. Biochar stands out as a biodegradable organic amendment that increases cation exchange capacity (CEC) and enhances the soil's nutrient and water retention capacity [6]. Simultaneously, Silica nanoparticles (SiNPs), with their enormous surface area, activate plant antioxidant systems, enhance resistance to salt stress, and improve growth under water-scarce conditions [7, 8]. The synergistic interaction between biochar and nano-Silica has been shown to reduce electrical conductivity (EC) and improve the availability of macronutrients (N, P, K) in degraded saline soils [8] Therefore, the current study aimed to evaluate the effectiveness of the combined application of biochar and nano-Silica in rehabilitating the chemical and physical properties of the soil and maximizing nutrient availability to ensure sustainable production under increasing environmental stress conditions.

## Materials & Methods

The field experiment was conducted during the 2024-2025 wheat (*Triticum aestivum*) growing season at the Agricultural Research Station, College of Agriculture, University of Basrah (Karma Ali district), Iraq, located at 30.57081° N and 47.749870° E Random topsoil samples were collected at 0–30 cm depth to determine the initial physico-chemical properties. These samples were subsequently air-dried and processed through a 2 mm sieve. Soil electrical conductivity (EC) and pH were measured in 1:1 soil: water extracts and suspensions, respectively, following established protocols [9]. The available Nitrogen was quantified by steam distillation following the methods of Bremner [10, 11] (Table 1), after extraction with 2 M KCl. Available phosphorus was extracted using the Olsen method with 0.5 M $NaHCO_3$ and measured spectrophotometrically at 700 nm [12]. For cation analysis, available Potassium and dissolved Sodium and Potassium were determined using a flame photometer after extraction with 1 N $NH_4OAC$ [9]. Anionic concentrations were determined via titration; specifically, dissolved bicarbonate was measured using dilute sulfuric acid ($H_2SO_4$, 0.01 N) with phenolphthalein and methyl orange indicators [13], while dissolved Chloride was quantified by titration with silver nitrate ($AgNO_3$, 0.05 N) using a 5% Potassium chromate indicator [13]. Furthermore, biochar was synthesized from wheat straw residues. The production process involved pyrolysis at 450°C for 4 hours under anaerobic conditions.

### Experimental Design and Treatments

The experiment was conducted in a randomized complete block design (RCBD) ($P < 0.05$) with a factorial arrangement (3×4) with three replicates, totaling 36 experimental units, each measuring 4 $m^2$. A surface irrigation system was used for irrigation throughout the growing season. Fertilizer application was as follows: 120 $t.ha^{-1}$ of animal manure; 200 $kg.ha^{-1}$ (46% N) of Nitrogen fertilizer (urea) in three applications of 100 $kg.ha^{-1}$ (20.21% P) of Phosphate fertilizer (superPhosphate) and 120 $kg.ha^{-1}$ (40.43% K) of potash fertilizer (Potassium sulfate), in two applications, were added and mixed into the soil according to the fertilizer recommendation. before planting to. ensure homogeneity. The nano-Silica (Si): four levels (0, 200, 300, 400) $kg.ha^{-1}$ (Table 3), were added by

**Table 1)** Chemical and physical properties of the field soil.

| Property | | Value | Unit |
|---|---|---|---|
| **Soil Reaction (pH 1:1)** | | 8.5 | – |
| **Electrical Conductivity (EC)** | | 12 | $dS.m^{-1}$ |
| **Cation Exchange Capacity (CEC)** | | 34.27 | $Cmol^{+} Kg^{-1}$ |
| **Total Carbonates** | | 455 | $g.kg^{-1}$ |
| **Organic Matter** | | 4.5 | $g.kg^{-1}$ |
| **Available Phosphorus** | | 13.8 | $mg.kg^{-1}$ |
| **Available Nitrogen** | | 21.52 | $mg.kg^{-1}$ |
| **Available Potassium** | | 95.3 | $mg.kg^{-1}$ |
| **Available Silicon** | | 23.2 | $mg.kg^{-1}$ |
| **Soluble Cations and Anions** | ($Ca^{+2}$) | 16.9 | $mmol.L^{-1}$ |
| | ($Mg^{+2}$) | 15.62 | |
| | ($Na^{+}$) | 61.9 | |
| | ($K^{+}$) | 23.7 | |
| | ($CO_3^{-2}$) | 0.0 | |
| | ($HCO_3^{-}$) | 10.8 | |
| | ($SO_4^{-2}$) | 31.5 | |
| | ($Cl^{-}$) | 76.8 | |
| **ESP** | | 30.05 | – |
| **SAR** | | 10.85 | – |
| **Particle Size Distribution**<br>**Texture: Clay Loam** | Sand | 40 | % |
| | Silt | 20.4 | |
| | Clay | 39.6 | |
| **Particle Density** | | 2.55 | $Mg.m^{-3}$ |
| **Bulk Density** | | 1.59 | |
| **Total Porosity** | | 38 | % |

mixing it with the irrigation water in two applications to ensure efficient absorption. WSBC(Biochar): Three levels (0, 20, and 30) of t.ha$^{-1}$ (Table 2). To produce biochar, wheat straw residues were harvested from their respective locations and subsequently air-dried. The dried biomass was then pyrolyzed at 450°C for 4 hours. Following the thermal process, the resulting biochar was pulverized and ground for application. Finally, the biochar was added to the soil and thoroughly incorporated using an agricultural plow at a depth of 0-20 cm.

**Table 2)** Physical and chemical properties of biochar.

| Property | Unit | Value |
|---|---|---|
| **pH** | - | 8.1 |
| **Electrical Conductivity** | dS.m$^{-1}$ | 2.5 |
| **Organic Carbon** | % | 66 |
| **Bulk Density** | Mg.m$^{-3}$ | 0.47 |
| **Total Pore Size** | Cm$^3$.100g$^{-1}$ | 15.0 |
| **Single Pore Diameter** | Nm | 1.85 |
| **Surface Area** | m$^2$.g$^{-1}$ | 54.5 |
| **Total Nitrogen** | g.kg$^{-1}$ | 16.2 |
| **Total Phosphorus** | g.kg$^{-1}$ | 4.2 |
| **Total Potassium** | g.kg$^{-1}$ | 12.6 |
| **Total Silicon** | mg.kg$^{-1}$ | 92.4 |

**Table 3)** Physical and chemical properties of PERSILA nano Silica (produced by Fadak Group, Iran).

| Properties and Test Properties | Unit | Value |
|---|---|---|
| **Specific Surface Area (CTAB Adsorption)** | m$^2$.g$^{-1}$ | 220-250 |
| **Main Particle Size (TEM Image)** | nm | 20-30 |
| **Agglomerate Mean Particle Size** | nm | 10.5 |
| **Agglomerate Particle Size ($D_{50}$)** | nm | 11 |
| **Agglomerate Mean Particle Size ($D_{90}$)** | nm | 20 |
| **Tamped Density ISO-787-11** | Kg.m$^{-3}$ | 180-220 |
| **pH Value 5% in Water ISO787-9** | - | 6.5-7.5 |
| **DBP (Dibutyl Phthalate Absorption )** | ML.100g$^{-1}$ | 220-240 |
| **Loss on Drying (2 h 105°c)** | % | <7 |
| **$SiO_2$ ISO 3262/17** | % | ≥98.5 |
| **Sulfate ($SO_3$) (Max)** | % | 0.5 |
| **Pb** | ppm | 0.934 |
| **Cd** | ppm | 0.046 |
| **As** | ppm | 0.934 |
| **Hg** | ppm | 0.061 |

## Statistical Analyses

Data were statistically analyzed using GenStat software. The experiment was conducted as a factorial arrangement (3×4) within a Randomized Complete Block Design (RCBD). A two-way analysis of variance (ANOVA) was performed to evaluate the main effects of wheat straw biochar (WSBC), nano-Silica (Si), and their interaction (WSBC × Si). The significance of treatment effects was determined at the 5% probabilitylevel. When significant differences were detected, the treatments were separated using the Least Significant Difference (LSD) test at the 5% probability level.

## Findings

The results of the study on the interactive effects of biochar and nano-Silica on nutrient levels and yield productivity in saline soils are summarized in Tables 4-6.

**Table 4)** The interaction of biochar and nano-Silica and the interaction between them on soil salinity and pH at the initial, middle, and end of the season.

| Biochar (WSBC) t.ha$^{-1}$ | Nano-Silica (Si) kg.ha$^{-1}$ | Soil EC (dS.m$^{-1}$) | | | | | | Soil pH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Si Mean | Mid | Si Mean | End | Si Mean | Mid | Si Mean | End | Si Mean |
| **WSBC (0)** | Si (0) | 11.41 | **9.30** | 7.79 | **6.20** | 6.65 | **5.32** | 8.26 | **8.11** | 8.09 | **7.88** |
| | Si (200) | 9.99 | **7.60** | 6.11 | **5.12** | 6.30 | **5.07** | 8.18 | **8.07** | 8.04 | **7.81** |
| | Si (300) | 8.91 | **6.71** | 5.39 | **4.79** | 5.79 | **4.78** | 8.15 | **8.04** | 7.96 | **7.72** |
| | Si (400) | 6.88 | **5.62** | 4.76 | **4.24** | 5.27 | **4.51** | 8.11 | **8.00** | 7.92 | **7.71** |
| **Mean** | | **9.29** | - | **6.01** | - | **6.00** | - | **8.18** | - | **8.00** | - |
| **WSBC (20)** | Si (0) | 9.72 | **9.30** | 6.03 | **6.20** | 5.09 | **5.32** | 8.09 | **8.11** | 7.88 | **7.88** |
| | Si (200) | 7.52 | **7.60** | 4.89 | **5.12** | 4.76 | **5.07** | 8.06 | **8.07** | 7.80 | **7.81** |
| | Si (300) | 6.52 | **6.71** | 4.72 | **4.79** | 4.49 | **4.78** | 8.05 | **8.04** | 7.70 | **7.72** |
| | Si (400) | 5.46 | **5.62** | 4.41 | **4.24** | 4.30 | **4.51** | 8.01 | **8.00** | 7.71 | **7.71** |
| **Mean** | | **7.30** | - | **5.01** | - | **4.66** | - | **8.05** | - | **7.77** | - |
| **WSBC (30)** | Si (0) | 6.77 | **9.30** | 4.79 | **6.20** | 4.22 | **5.32** | 7.99 | **8.11** | 7.68 | **7.88** |
| | Si (200) | 5.30 | **7.60** | 4.36 | **5.12** | 4.15 | **5.07** | 7.96 | **8.07** | 7.60 | **7.81** |
| | Si (300) | 4.69 | **6.71** | 4.25 | **4.79** | 4.06 | **4.78** | 7.91 | **8.04** | 7.50 | **7.72** |
| | Si (400) | 4.52 | **5.62** | 3.54 | **4.24** | 3.96 | **4.51** | 7.88 | **8.00** | 7.49 | **7.71** |
| **Mean** | | **5.32** | - | **4.24** | - | **4.10** | - | **7.94** | - | **7.57** | - |
| **LSD $_{(0.05)}$ (WSBC×Si)** | | **0.57**** | - | **0.49**** | - | **0.14**** | | **0.02**** | | **ns** | |
| **LSD $_{(0.05)}$ (WSBC )** | | **0.28**** | | **0.25**** | | **0.29**** | | **0.01**** | | **0.01**** | |
| **LSD $_{(0.05)}$ (Si)** | | **0.33**** | | **0.08**** | | **0.08**** | | **0.01**** | | **0.02**** | |

**Note:** ** represents a significant difference at the 0.05 level, and ns shows an insignificant difference between study treatments.

## Discussion

The statistical analysis of the study showed highly significant differences ($P < 0.05$) in soil electrical conductivity when biochar and nano-Silica were added and combined at different weight percentages over two periods (Table 4). High salinity levels were observed in the control treatment at 11.41dS.m$^{-1}$. In contrast, the average salinity levels in the intervention treatment (WSBC300+Si400) decreased to 4.52dS.m$^{-1}$ at the beginning of the season. They reached their lowest point in the middle of the season, and at the end of the season, a slight increase was observed. The results showed variation in soil pH response to the interaction between biochar and nano-Silica across growth stages (Table 4). Mid-season results showed a highly significant interaction with pH decreasing from 8.26 in the control treatment to 7.88 in the (WSBC30 + Si400) interaction. However, end-of-season results revealed that the interaction became insignificant, with the overall trend of decreasing pH values continuing to 7.49. The results showed a highly statistically significant interaction effect ($P<0.05$) between biochar and nano-Silica levels in reducing dissolved and toxic ion concentrations in the soil solution. The treatment with maximum interaction (WSBC30 + Si400) resulted in a sharp decrease in Sodium ($Na^+$) and Chloride ($Cl^-$) levels, reaching 17.47 and 23.16 mmol.L$^{-1}$, respectively, at the end of the season (Table 5). The results revealed the effectiveness of this interaction in reducing the accumulation of bicarbonate ions ($HCO_3^-$) throughout the experimental period, with the lowest concentration (3.12 mmol.L$^{-1}$) recorded at the end of the season (Table 5). Regarding soluble Potassium ($K^+$), a significant decrease in its concentration in the soil solution was observed, reaching 2.547 mmol.L$^{-1}$ in the reactive treatment (Table 5).

Statistical analysis revealed highly significant differences ($P<0.05$) at mid-season and ($P = 0.05$) at the end of the season between the ratios of biochar and nano-Silica levels in enhancing soil available Nitrogen content (Table 6). At mid-season, Nitrogen availability increased from (23.40) mg.kg$^{-1}$ in the control treatment to reach a peak of (45.49) mg.kg$^{-1}$ in the intervention treatment (WSBC30 + Si400). Despite a relative decrease in Nitrogen levels at the end of the season, the same intervention maintained its significant superiority, recording (37.82) mg.kg$^{-1}$. Statistical results showed a highly significant interaction ($P < 0.005$) between biochar and nano-Silica in raising soil phosphorus availability levels during mid- and late-season periods (Table 6). At mid-season, phosphorus values increased from 23.86 mg.kg$^{-1}$ in the control treatment to a maximum of 47.47 mg.kg$^{-1}$ in the (WSBC30 + Si400) interaction. Despite plant uptake of the element, the superior interaction maintained high availability levels at the end of the season, reaching 47.02 mg.kg$^{-1}$. Statistical analysis revealed a highly significant interaction ($P < 0.005$) between biochar and nano-Silica in influencing soil Potassium availability during the mid- and late-season stages (Table 6). At mid-season, available Potassium levels reached 207.4 mg.kg$^{-1}$ in the interaction treatment (WSBC30 + Si400) compared to 92.2 mg.kg$^{-1}$ in the control treatment. This advantage persisted until the end of the season, with the same treatment maintaining the highest value at 147.61 mg.kg$^{-1}$.

### Soil Salinity (EC)

The significant decrease in EC values is attributed to the complementary, dual roles of the added amendments in modifying the chemical and physical properties of saline soils (Table 4). Nano-Silica, with its large surface area and high reactivity, helps reduce dissolved ion concentrations in the soil solution and enhances the adsorption complex's ability to retain nutrients [14,15]. In parallel, biochar demonstrated high efficacy in accelerating the leaching of harmful salt ions by improving porosity and water permeability, thus reducing the physiological stress of salinity on the plant [16,17]. The synergistic interaction between biochar and nano-Silica resulted in a significant advantage in salinity reduction; Silica acted as an ion regulator, while biochar acted as a water reservoir and structural enhancer,

**Table 5)** Effect of the interaction between biochar and nano-Silica on soluble (Na, Cl, K, $HCO_3$) in the soil mid- and end of the season.

| Biochar (WSBC) ($t.ha^{-1}$) | Nano-Si ($kg.ha^{-1}$) | Mid-Season ($mmol.L^{-1}$) | | | | | | | | End-of-Season ($mmol.L^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Na^+$ | Si Mean | $K^+$ | Si Mean | $Cl^-$ | Si Mean | $HCO_3^-$ | Si Mean | $Na^+$ | Si Mean | $K^+$ | Si Mean | $Cl^-$ | Si Mean | $HCO_3^-$ | Si Mean |
| WSBC (0) | Si (0) | 35.65 | **28.51** | 16.08 | **11.75** | 51.07 | **37.08** | 5.667 | **4.22** | 30.90 | **24.35** | 7.65 | **11.75** | 40.91 | **32.33** | 8.47 | **6.02** |
| | Si (200) | 32.14 | **26.66** | 12.52 | **10.35** | 42.52 | **33.18** | 4.50 | **3.61** | 27.02 | **22.72** | 6.68 | **10.35** | 34.15 | **29.66** | 6.66 | **5.23** |
| | Si (300) | 29.35 | **25.12** | 10.97 | **9.40** | 35.55 | **29.74** | 4.27 | **3.42** | 24.83 | **21.53** | 5.89 | **9.40** | 30.98 | **27.98** | 5.90 | **4.88** |
| | Si (400) | 28.36 | **24.14** | 10.62 | **8.27** | 33.13 | **28.36** | 4.00 | **3.09** | 23.52 | **20.53** | 5.38 | **8.27** | 30.13 | **26.92** | 5.40 | **4.36** |
| **Mean** | | **31.38** | - | **12.55** | - | **40.57** | - | **4.61** | - | **26.57** | - | **6.40** | - | **34.04** | - | **6.61** | - |
| WSBC (20) | Si (0) | 26.94 | **28.51** | 10.40 | **11.75** | 31.49 | **37.08** | 4.00 | **4.22** | 22.17 | **24.35** | 4.87 | **11.75** | 29.14 | **32.33** | 5.20 | **6.02** |
| | Si (200) | 25.21 | **26.66** | 10.10 | **10.35** | 30.22 | **33.18** | 3.63 | **3.61** | 21.60 | **22.72** | 4.53 | **10.35** | 28.28 | **29.66** | 4.85 | **5.23** |
| | Si (300) | 24.46 | **25.12** | 9.73 | **9.40** | 29.67 | **29.74** | 3.50 | **3.42** | 21.19 | **21.53** | 4.23 | **9.40** | 27.48 | **27.98** | 4.75 | **4.88** |
| | Si (400) | 24.05 | **24.14** | 9.42 | **8.27** | 29.35 | **28.36** | 3.17 | **3.09** | 20.59 | **20.53** | 3.90 | **8.27** | 27.09 | **26.92** | 4.49 | **4.36** |
| **Mean** | | **25.17** | - | **9.91** | - | **30.18** | - | **3.58** | - | **21.39** | - | **4.38** | - | **28.00** | - | **4.82** | - |
| WSBC (30) | Si (0) | 22.95 | **28.51** | 8.78 | **11.75** | 28.67 | **37.08** | 3.00 | **4.22** | 19.97 | **24.35** | 3.67 | **11.75** | 26.93 | **32.33** | 4.39 | **6.02** |
| | Si (200) | 22.62 | **26.66** | 8.44 | **10.35** | 26.81 | **33.18** | 2.70 | **3.61** | 19.53 | **22.72** | 3.29 | **10.35** | 26.54 | **29.66** | 4.17 | **5.23** |
| | Si (300) | 21.56 | **25.12** | 7.49 | **9.40** | 24.00 | **29.74** | 2.50 | **3.42** | 18.58 | **21.53** | 2.96 | **9.40** | 25.48 | **27.98** | 4.00 | **4.88** |
| | Si (400) | 20.00 | **24.14** | 4.78 | **8.27** | 22.60 | **28.36** | 2.10 | **3.09** | 17.47 | **20.53** | 2.55 | **8.27** | 23.16 | **26.92** | 3.12 | **4.36** |
| **Mean** | | **21.78** | - | **7.37** | - | **25.52** | - | **2.58** | - | **18.89** | - | **3.12** | - | **25.53** | - | **3.92** | - |
| **$LSD_{(0.05)}$ (WSBC×Si)** | | **0.93**** | | **1.31**** | | **1.90**** | | **0.31**** | | **1.30**** | | **0.37**** | | **1.27**** | | **0.86**** | |
| **$LSD_{(0.05)}$ (WSBC)** | | **0.47**** | | **0.66**** | | **0.95**** | | **0.16**** | | **0.65**** | | **0.18**** | | **0.63**** | | **0.16**** | |
| **$LSD_{(0.05)}$ (Si)** | | **0.54**** | | **0.76**** | | **1.1**** | | **0.18**** | | **0.75**** | | **0.21**** | | **0.73**** | | **0.49**** | |

**Note:** ** represents a significant difference at the 0.05 level, and ns shows an insignificant difference between study treatments.

creating a stable and optimal growth environment [18].

### Soil pH

The significant decrease in pH values during the middle of the season (Table 4) is attributed to the synergistic effect of the amendments. Nano-Silica has a high surface area, which increases the efficiency of chemical reactions in the soil solution and enhances ion exchange, thereby reducing alkalinity [14,19]. Biochar also contributes to the formation of organic and inorganic acids resulting from the bio- and chemical oxidation processes of its components [20]. In addition to the role of biochar in converting Sodium bicarbonate and carbonate to their Calcium ions, which reduces soil alkalinity [21]. The lack of significance at the end of the season is due to the high buffering capacity of calcareous soils, which resist continuous changes in pH, and to a decrease in the chemical activity of nano-Silica over time, resulting from the consumption of active reaction sites [20].

### Dissolved Sodium, Chloride, Potassium, and Bicarbonate Ions

This significant reduction (Table 5) is attributed to the synergistic effect of the amendments: biochar increased macroporosity and improved drainage efficiency, facilitating water movement and leaching salts away from the root zone [22]. Simultaneously, thanks to their high adsorption capacity and large surface area, Silica nanoparticles reduced the availability of these ions in the soil solution and prevented their free existence, thus limiting their direct toxicity [23]. Furthermore, the use of interference increased the cation exchange capacity (CEC), promoting Sodium fixation at the exchange complex rather than its abundance in the aqueous solution. This shift played a crucial regulatory role in reducing root membrane permeability to Sodium and stimulating the selective adsorption of Potassium ($K^+$) ions, ultimately improving the ionic balance within the plant [24].

This is attributed to biochar's role in increasing cation exchange capacity (CEC) and attracting divalent cations to its active surfaces, thereby altering chemical equilibrium and reducing the solubility of carbonate compounds [25]. Additionally, nano-Silica plays a regulatory role by controlling the pH of the root zone, limiting the negative effects of bicarbonate, and converting soluble elements into stable precipitates [26]. Furthermore, the chemical reaction between Silica and free Calcium in calcareous soils led to the formation of hydrated Calcium Silicate complexes, which reduced the activity of free Calcium and shifted the bicarbonate concentration balance downward within the soil [27]. The reduction in soil solution Potassium concentration is attributed to the plant's enhanced Potassium uptake efficiency, driven by the synergistic effect of the amendments. Biochar acts as a supportive medium, improving soil structure and nutrient retention, thereby reducing the toxic effects of Sodium and promoting Potassium uptake [24]. Simultaneously, the high surface area of nano-Silica helps regulate ionic balance at exchange sites, limiting the uptake of competing Sodium ions and increasing the $K^+/Na^+$ ratio within plant tissues, a vital indicator of salt tolerance [23,28]. The synergistic interaction improves physiological functions, thereby increasing Potassium demand and the efficient uptake of Potassium from the soil solution [18,29]. This synergistic approach not only reduces the uptake of toxic ions but also ensures the sustainable availability of essential elements in the root zone.

### Soil Nitrogen Availability

This pivotal role (Table 6) of the interaction is attributed to biochar's high capacity to reduce bulk Density and increase soil cation exchange capacity (CEC), thereby protecting nutrients from leaching and volatilization for extended periods [30]. Furthermore, nano-Silica, with its enormous surface area, helped regulate nitrification and stimulate microbial activity in the soil, thereby accelerating organic Nitrogen mineralization while maintaining soil pH within the optimal range for plant growth [8]. The interaction between biochar and nano-Silica enhances the soil's ability to retain ammonium ions, reduces total Nitrogen loss, and increases its absorption efficiency [19, 31].

### Soil Phosphorus Availability

Biochar played a pivotal role (Table 6) in enhancing soil fertility by increasing phosphorus availability. It acts as a source and storage of the element in its soluble

**Table 6)** Interactive effects of biochar and nano-Silica on available N, P, and K in the soil at mid- and end of the season.

| Biochar (WSBC) (t.ha$^{-1}$) | Nano- (Si) (kg.ha$^{-1}$) | N (mg.kg$^{-1}$) | | | | P (mg.kg$^{-1}$) | | | | K (mg.kg$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mid | Si Mean | End | Si Mean | Mid | Si Mean | End | Si Mean | Mid | Si Mean | End | Si Mean |
| WSBC (0) | Si (0) | 23.40 | **30.16** | 18.69 | **25.43** | 23.86 | **34.45** | 23.75 | **30.99** | 92.20 | **118.13** | 65.95 | **94.10** |
| | Si (200) | 28.43 | **33.25** | 22.43 | **28.11** | 30.88 | **38.13** | 25.14 | **32.63** | 101.90 | **125.47** | 73.90 | **100.28** |
| | Si (300) | 29.38 | **34.89** | 24.54 | **29.21** | 33.01 | **40.35** | 26.68 | **35.19** | 111.30 | **136.93** | 80.60 | **105.11** |
| | Si (400) | 29.71 | **36.78** | 25.94 | **30.60** | 34.29 | **41.53** | 30.24 | **37.80** | 113.50 | **151.80** | 92.25 | **115.45** |
| Mean | | **27.73** | - | **22.90** | - | **30.51** | - | **26.45** | - | **104.73** | - | **78.18** | - |
| WSBC (20) | Si (0) | 30.84 | **30.16** | 27.11 | **25.43** | 35.99 | **34.45** | 30.83 | **30.99** | 118.00 | **118.13** | 97.07 | **94.10** |
| | Si (200) | 32.59 | **33.25** | 27.81 | **28.11** | 39.29 | **38.13** | 32.48 | **32.63** | 122.30 | **125.47** | 100.70 | **100.28** |
| | Si (300) | 33.66 | **34.89** | 28.04 | **29.21** | 42.18 | **40.35** | 35.17 | **35.19** | 126.00 | **136.93** | 103.13 | **105.11** |
| | Si (400) | 35.13 | **36.78** | 28.04 | **30.60** | 42.82 | **41.53** | 36.15 | **37.80** | 134.50 | **151.80** | 106.50 | **115.45** |
| Mean | | **33.06** | - | **27.75** | - | **40.07** | - | **33.66** | - | **125.20** | - | **101.85** | - |
| WSBC (30) | Si (0) | 36.23 | **30.16** | 30.49 | **25.43** | 43.50 | **34.45** | 38.40 | **30.99** | 144.20 | **118.13** | 119.28 | **94.10** |
| | Si (200) | 38.72 | **33.25** | 34.10 | **28.11** | 44.23 | **38.13** | 40.26 | **32.63** | 152.20 | **125.47** | 126.25 | **100.28** |
| | Si (300) | 41.62 | **34.89** | 35.05 | **29.21** | 45.85 | **40.35** | 43.73 | **35.19** | 173.50 | **136.93** | 131.60 | **105.11** |
| | Si (400) | 45.49 | **36.78** | 37.82 | **30.60** | 47.47 | **41.53** | 47.02 | **37.80** | 207.40 | **151.80** | 147.61 | **115.45** |
| Mean | | **40.52** | - | **34.37** | - | **45.26** | - | **42.35** | - | **169.33** | - | **131.19** | - |
| **LSD $_{(0.05)}$(WSBCxSi)** | | **1.45**** | | **2.29**** | | **0.84**** | | **1.07**** | | **10.83**** | | **3.98**** | |
| **LSD $_{(0.05)}$(WSBC)** | | **0.72**** | | **0.42**** | | **5.42**** | | **1.15**** | | **0.54**** | | **1.99**** | |
| **LSD $_{(0.05)}$(Si)** | | **0.84**** | | **0.48**** | | **6.62**** | | **1.32**** | | **0.62**** | | **2.29**** | |

**Note:** ** represents a significant difference at the 0.05 level.

and exchangeable forms and, due to its high porosity, helps regulate pH and prevent precipitation [3]. This effect was reflected positively in physiological indicators and in the growth of both root and shoot systems, as the direct relationship between phosphorus availability and increased dry matter led to enhanced plant uptake efficiency [19,31,32]. In parallel, nano-Silica contributed to reducing phosphorus leaching by its structure, surface area, and increased CEC, thereby keeping Phosphates available for absorption [19]. Silicon also enhanced the solubility and mobility of nutrients in soil, making them more available to plants and ultimately improving crop yield [33,34].

### Soil Potassium Availability

Adding biochar enhances soil fertility and sustainability by acting as a nutrient reservoir, reducing nutrient loss through leaching, and ensuring the continuous availability of nutrients for plants (Table 6) [2,3]. The high availability and exchangeability of Potassium is attributed to the active surface area and porosity of straw-derived charcoal, which is already rich in soluble salts, thus increasing the element's retention capacity and reducing its loss [35]. Simultaneously, nano-Silica reduces soil solution Sodium concentrations, limiting ionic competition with Potassium and increasing its availability. Its high surface area and increased cation exchange capacity (CEC) led to a reduction in Potassium leaching rates of up to 60% [19,36]. The synergistic interaction between coal and nano-Silica significantly improved the availability of Nitrogen, phosphorus, and Potassium (N, P, K) by enhancing soil physical and chemical properties [3,7]. This integration not only enhanced nutrient and water retention but also mitigated the effects of water stress, thereby positively impacting metabolic activity and biomass accumulation, and thereby increasing wheat productivity [38,39,40].

## Conclusion

The results of this study conclude that the combined application of biochar and nano-Silica is a highly effective strategy for calcareous saline soils, as the soil solution salinity (EC) decreased by 7.45 units (from 11.41 to 3.96 dS.m$^{-1}$), leading to a significant reduction in osmotic stress in the root zone. Furthermore, the availability of macronutrients (N, P, K) increased by 145%, 168%, and 48%, respectively, due to improved cation exchange capacity and reduced nutrient leaching. Nano-Silica also enhanced ionic balance ($K^+/Na^+$) and increased the plant's Potassium uptake efficiency despite harsh saline conditions. Therefore, we recommend adopting the intervention of 30 t.ha$^{-1}$ biochar plus 400 kg.ha$^{-1}$ nano-Silica as a sustainable strategy for reclaiming saline soils and improving nutrient utilization efficiency.

## Acknowledgments

The authors are indebted to the Department of Soil Science and Water Resources, College of Agriculture, University of Basrah, for their support of this project.

**Authors' Contribution: Noor Al-Huda Hassan. Al-Asadi:** Conceptualization, Methodology, Field Experiments, Data Collection, Laboratory Analysis, and Writing Original Draft**; Salwa J. Fakher:** Supervision, Project Administration, Experimental Design, Validation, Data Interpretation, and Final Revision and Editing of the Manuscript.

**Ethical Permission:** The authors declare that this study does not involve human or animal subjects, and all institutional guidelines for environmental research were strictly followed

**Conflicts of Interest:** The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

**Funding/Supports:** This research was self-funded by the authors and did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**AI Use Declaration:** The authors declare that no Generative AI tools were used in the creation or intellectual content of this manuscript.

## References

1. Bandak S., Movahedi-Naeini S.A., Mehri S., Ghorbani K., Kiani F. A longitudinal analysis of soil salinity changes using remotely sensed imageries. Sci. Rep. 2024; 14(1):10383.
2. Al-Daraji F.K., Ndewi D.R., Al-Shammari H.M. Modeling water supply in adjacent areas of Shatt Al-Arab River in southern Iraq using geomatics techniques. IOP Conf. Ser.: Earth Environ. Sci. 2024; 1371:082027.
3. Ali A.H. The effect of irrigation water salinity on the growth and productivity of wheat crops in southern Iraq, and mitigation methods using organic soil amendments. Al-Furat J. Innov. Agric. Sci. 2025; 1:33-42.
4. Rehman S.U., Sarwar N., ul Din M.S., Al-Bakosh A.A.M., Khan S.A. Impact of soil salinity on wheat growth and yield: Challenges, mechanisms, and management strategies. Sch. J. Agric. Vet. Sci. 2025; 12:109–119.
5. Zhang X., Li Y., Kumar S., Zhao J., West P.C., Gerber J.S., Foley J.A. Global-scale prevalence of low nutrient use efficiency across major crops. Nat. Commun. 2025; 16:4521.
6. Zarei M, Karimi N, Modarres-Sanavy SAM. Comparison of the Effects of Nano and Bulk Zinc Oxide on the Growth and Physiological Characteristics of *Dracocephalum moldavica* L. ECOPERSIA 2020; 8(3): 163-172.
7. Al-Daraji F.K., Ndewi D.R., Al-Shammari H.M. Modeling and analysis of land surface temperature variations in Basrah Governorate, Iraq. Springer Proc. Earth Environ. Sci. 2023; 345–362.
8. Akhtar N., Ilyas N., Mashwani Z.U., Hayat R., Yasmin H., Noureldeen A., Ahmad P. Synergistic effects of plant growth-promoting rhizobacteria and silicon dioxide nanoparticles for amelioration of drought stress in wheat. Plant Physiol. Biochem. 2021; 166:160–176.
9. Page A.L., Miller R.H., Keeney D.R. Methods of soil analysis, Part 2. 2nd ed. Am. Soc. Agron. Madison, WI; 1982.
10. Bremner J.M., Keeney D.R. Determination and isotope-ratio analysis of different forms of Nitrogen in soils: 3. Exchangeable ammonium, nitrate and nitrite by extraction-distillation methods. Soil Sci. Soc. Am. Proc. 1966; 30:577-582.
11. Amin, M., & Flowers, T. H. (2004). Evaluation of Kjeldahl digestion method. J. Res. 2004; 15(2):159-179.
12. Murphy T., Riley J.R. A modified single solution method for the determination of Phosphate in natural waters. Anal. Chim. Acta. 1962; 27:31-36.
13. Richards, L.A. Diagnosis and improvement of saline and alkali soils. USDA Agriculture Handbook No. 60. Washington, DC; 1954.
14. Al-Saeedi A.H. Contribution of Nano-Silica in Affecting Some of the Physico-Chemical Properties of Cultivated Soil with the Common Bean (*Phaseolus vulgaris*). J. Adv. Agric. Res. 2021; 25:390-394.
15. Jabal A.H., Abdulkareem M.A. Soil salinity and nutrient availability influenced by silicon application to tomato irrigation with different saline water. Bionatura. 2023; 8:90.
16. Huang J., Zhu C., Kong Y., Chen J., Guan C., Wang G., Wang M., Zhang L., Li Z. Biochar application alleviated rice salt stress via modifying soil properties and regulating soil bacterial abundance and community structure. Agronomy. 2022; 12:409.
17. Gu Y.Y., Liang X.Y., Zhang H.Y., Zhang Y.M., Zhao X.Y., Zhang L.J., Li J.P. Effect of biochar and bioorganic fertilizer on the microbial diversity in the rhizosphere soil of Sesbania cannabina in saline-alkaline soil. Front. Microbiol. 2023; 14:1190716.
18. Gill S., Ramzan M., Naz G., Anjum S., Gulshan A.B., Hussain S., Zulfiqar U., Ahmad N., Shaker M.A. Effect of silicon nanoparticle-based biochar on wheat growth, antioxidants, and nutrient concentration under salinity stress. Sci. Rep. 2024; 14:6380.
19. Al-Maliki A.H., Al-Mamory S.A. Role of nano-Silica in mitigating salinity stress and improving growth parameters of tomato plants. Int. J. Veg. Sci. 2022; 28:345-358.
20. Alazzaz B.A., Al-Haddad S.A., Al-Obaidi M.A. Effect of biochar application on some chemical and physical properties of calcareous soil. Iraqi J. Agric. Sci. 2020; 51:1020–1030.

21. Liu J., Jiang J., Meng Y., Aihemaiti A., Xu Y., Xu H., Chen L. Preparation, environmental application and prospect of biochar-supported metal nanoparticles: A review. J. Hazard. Mater. 2020; 388:122026.
22. An X., Liu Q., Pan F., Chen T., Zhao A., Zhang L., Wu L., Wang J. Research advances in the impacts of biochar on the physicochemical properties and microbial communities of saline soils. Sustainability. 2023; 15:14439.
23. Khan M., Khan A.U., Hasan M.A., Yadav K.K., Cabral-Pinto M.M.S., Simal-Gandara J. Agro-nanotechnology as an emerging field: A novel sustainable approach for improving plant growth by reducing biotic stress. Appl. Sci. 2021; 11:2282.
24. Shabbir A., Khalid M.S., Arshad M., Hussain S., Murtaza B., Shah N.S., Murtaza G. Biochar mitigates arsenic-induced human health risks and phytotoxicity in quinoa under saline conditions by modulating ionic and oxidative stress responses. Environ. Pollut. 2021; 287:117348.
25. Zhu X., Chen B., Zhu L. Micro-and mesoporous structures of biochar: Mechanisms of nutrient retention and ion exchange in soil systems. J. Clean. Prod. 2024; 412:137-152.
26. Karimi R., Adnan A. Impact of nano-silicon fertilizers on ion dynamics and nutrient retention in arid calcareous soils. J. Soil Sci. Plant Nutr. 2021; 21:2145-2158.
27. Meena R.K., Singh P.B. Nano-fertilizers in agriculture: Mechanisms and functions of nano-Silica in soil health. Int. J. Agric. Res. 2020; 15:88-95.
28. Jabal A.H. Ionic Composition and Prevailing Salt of Saline Soil Grown with Cauliflower Plants under Nano-Silicon and Phosphorus Application. Sci. Res. J. Agric. Life Sci. 2024; 4:1-10.
29. Ahmed A.K., Hadres I.A., Albajary A., Oleksandr S. Study the effect of soil compaction and biochar on some soil physical parameters. Diyala J. Agric. Sci. 2025; 17(1):78–90.
30. Rosa D., Petruccelli V., Iacobbi M.C., Di Giacinto S., Libutti A., Rivelli A.R. Functionalized biochar from waste as a slow-release nutrient source: Application on tomato plants. Heliyon. 2024; 10(9): e29455.
31. Al-Aboudi R.J., Al-Asadi S.A. Effect of biochar and organic amendments on nutrient availability in saline soils of southern Iraq. Basrah J. Agric. Sci. 2021; 34:112-125.
32. Song S., Cong P., Wang C., Wang J., Wang Y., Zhang L., Li Z. Properties of biochar obtained from tropical crop wastes under different pyrolysis temperatures and its application on acidic soil. Agronomy. 2023; 13:921.
33. Aqaei P., Weisany W., Diyanat M., Kasraie P., Azizi K. Response of maize (*Zea mays* L.) to Potassium nano-Silica application under drought stress. J. Plant Nutr. 2020; 43:1205–1216.
34. Zhou Z.Y., Yang L., Wang M.X., Zhou Z.F., Li Y.H., Zhang X.H. Biochar Amendment Promoted the Maize Growth and Changed Bacterial Community Assembly in a Phenanthrene-Contaminated Soil. J. Soil Sci. Plant Nutr. 2023; 23:3010–3022.
35. Qayyum M.F., Haider G., Raza M.A., Khan S.A., Rizwan M., Hussain S., Abbasi G.H., Ok Y.S. Straw-based biochar mediated Potassium availability and increased growth and yield of cotton (*Gossypium hirsutum* L). J. Saudi Chem. Soc. 2020; 24:963-973.
36. Al-Daraji F.K., Shareef N.F., Hasan W.B. Prediction of water storage volume in soil surface layers using geomatics techniques. IOP Conf. Ser.: Earth Environ. Sci. 2025; 1487(1):012191.
37. Khan Z.S., Rizwan M., Hafeez M., Ali S., Adrees M., Qayyum M.F., Khalid M.S., Ur Rehman M.Z., Sarwar M.A. Effects of silicon nanoparticles on growth and physiology of wheat in cadmium contaminated soil under different soil moisture levels. Environ. Sci. Pollut. Res. 2020; 27:4958–4968.
38. Rea R.S., Islam M.R., Rahman M.M., Mix K., El-Desouky H.S., Al-Bakosh A.A.M., Khan S.A. Growth, nutrient accumulation, and drought tolerance in crop plants with silicon application: A review. Sustainability 2022; 14:4525.
39. Forján R., Arias-Estévez M., Gallego J.L.R., Rodríguez-Vila A., Covelo E.F. Biochar-nanoparticle combinations enhance the biogeochemical recovery of a post-mining soil. Sci. Total Environ. 2024; 922:172451.
40. Abideen Z., Waqif H., Munir N., El-Keblawy A., Hashem A., Al-Arkani A.S., Abd-Allah E.F. Algal-mediated nanoparticles, phycochar, and biofertilizers for mitigating abiotic stresses in plants: A review. Agronomy 2022; 12:1788.