

Effect of Olive Fruit Residue Biochar on the Growth and Yield of Two Bread Wheat Cultivars

Salim H. Antar¹, Islam A. A. Alrijabo¹, Ammar H. Mahmood¹, Mahmood A. Ardini², William Okoyo³, Anmar Ahmed³, Mohannad Hamid³, Thakir Jasim Mohammed¹, Kalid Ekhleyf Nazzal⁴

¹ Center for Arid Farming and Conservation Agriculture Research, University of Mosul, Iraq

² DOA

³ World Food Program. U.N

⁴ Field Crops Dept., College of Agriculture and Forestry, University of Mosul, Iraq

ABSTRACT

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An experiment was conducted at the research station of the Center for Arid Farming and Conservation Agriculture Research C.AFCAR during the 2025–2026 growing season. The experiment comprised two factors: two bread wheat cultivars (Erbil and Khanaqin) and six biochar application rates (0, 100, 200, 300, 400, and 500 g m⁻²). Grains with a 90% germination rate were sown in October in pots with a 30 cm diameter, following the incorporation and thorough mixing of the biochar with the soil. A factorial arrangement within a completely randomized design was employed, and treatment means were compared using Duncan's multiple range tests at the 5% probability level. Plants were regularly irrigated and monitored until the end of the season.

The main results showed that difference between cultivars had no significant impact on the growth and yield of bread wheat. In contrast, the biochar processing applied at 500 g m⁻² it significantly outperformed all other concentrations, its positive effect progressively diminishing as the application rate decreased, achieving the lowest effect in control treatment. Specifically, the number of grains per spike recorded values of (23 and 29 grains.spike⁻¹); the 1000-grain weight recorded (41.17 and 48.0 g); and grain yield per pot recorded (9.33 and 17.0 g pot⁻¹) for the 0.0 and 500 g m⁻² application rates, respectively.

Regarding soil properties, the electrical conductivity (EC) increases from 655.00 µS cm⁻¹ in control to 798.33 µS cm⁻¹ at the 500 g m⁻² rate, while the soil nitrogen, phosphorus, and potassium contents reached 84.17, 81.67, and 212 ppm, respectively.

KEYWORDS: Olive fruit residue biochar; bread wheat; biochar application rates; grain yield; yield components; soil properties.

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Corresponding Author:
Salim H. Antar

INTRODUCTION

Olive (*Olea europaea*) production is among the most important agriculture projects in the world's (Katsafadou et al., 2025), it is of particular importance throughout the Mediterranean basin owing to its considerable economic contributions and nutritional significance. In the Bashiqa district of Nineveh Governorate in northern Iraq, the olive oil pressing and extraction industries produce large quantities of organic by-products, this includes fruit pulp, leaves, pruning wood, and wastewater from olive presses. These wastes pose a serious environmental risk unless it is properly managed. Therefore, there is a growing and urgent need to reuse this waste stream into value-added products that safeguard environmental integrity while bolstering agricultural output. Among the promising products is bio-fertilizer made from manufactured from olive processing waste.



Figure (1) Mobile Biochar production unit

Biochar derived from olive waste is a carbon-rich material, (note that the forms of carbon include aromatic, aliphatic, carbonyl, carboxyl, phenolic/ ether Carbon) a highly porous material produced by thermal conversion of agricultural waste, such as olive tree pruning's, stones, and pomace under oxygen depleted or oxygen free atmospheres, generally it occurs in thermal regimes between 300 and 700°C. Attributable to its stable carbon structure, Thanks to its large specific surface area, porous microstructure, and elevated Cation exchange capacity, olive based biochar improves soil moisture retention and nutrient holding ability, while simultaneously improving ameliorating the physical, chemical, and biological attributes of the soil matrix. therefore, integrating them into agricultural systems promotes improved soil fertility, stimulates vegetative growth, and underpins enduring agricultural sustainability (Lustosa Filho et al., 2024). These microbial agents cause the decomposition of organic matter; Thus, they are converted into simpler compounds rich in essential plant nutrients. Therefore, this category of fertilizers works to improve soil fertility and increase the concentrations of organic matter. Biochar stimulates beneficial microbial activity and improves soil texture and physical properties in the chemical and biological traits. The importance of biofertilizers lies in their role as a modern approach to promoting sustainable agricultural development. This, in turn, leads to a reduction in reliance on synthetic chemical fertilizers and a mitigation of their negative effects on the environment and public health. In addition, these bio-fertilizers facilitate the recycling of hazardous agricultural waste, transforming it from an environmental burden into a valuable economic asset., thus providing delivering dual environmental and financial advantages. Its use in application contributes to improving plant growth and increasing productivity, particularly in vegetable crops and fruit orchards, while simultaneously enhancing the overall efficiency of natural resource use.

Due to its importance, biochar has received considerable attention as a promising soil improver for wheat cultivation. This is due to its ability to modify the physical and chemical properties of soils and promote more favorable growing conditions. When soil incorporation into the soil, biochar contributes raises soil organic carbon level, it improves soil porosity and texture cohesion, increases its water retention capacity, and enhances its cation exchange capacity, thereby promoting the plant's retention and availability of vital nutrients. Furthermore, biochar provides a suitable conducive microhabitat for advantageous soil microorganisms, which in turn facilitate nutrient cycling and plant growth uptake. A substantial body of research has documented that biochar application in wheat cropping systems boosts fertilizer and water use efficiencies increases the soil's ability to retain water by a 10-40 % ,it reduces nitrogen loss through washing and volatilization , it increases the soil 's retention of phosphorus and potassium , increased microbial activity in the soil , while also increasing grain yield and its constituent components, particularly in soils characterized by low organic matter content or subject to water deficit conditions. As such, biochar offers a sustainable management pathway for augmenting wheat productivity without compromising long-term soil health (Khan et al., 2024). Wheat is the leading grain and the most important food crop. Its importance is derived from the properties of gluten, which is achene string of endosperm protein in which the grain, kneaded, and after fermentation, to be baked to produce also of bread wheat (Ibrahim et al., 2024). wheat is the main food crop, its cultivation is concentrated in the northern, rain-fed regions, especially in Nineveh Governorate. Bread wheat (*Triticum aestivum* L.) is considered one of the most important strategic crops that support global food security, because it represents a major source of food energy for more than a third of the world's population.

Conversion olive waste into biofertilizer has emerged as a topic of great to researchers' interest among agricultural and environmental researchers and practitioners, given its proven effectiveness in agricultural waste management and its ability to reconcile the competing demands of increasing agricultural production with the conservation of environmental assets and natural resources for future generations. Therefore, this study was planned to determine the response of the bread wheat crop to biochar fertilizer; based on the study's results, this environmentally friendly fertilizer may be utilized in the activities of the C.AFCAR.

MATERIALS AND METHODS

The pot experiment was conducted at the experimental station of the Center for Arid Farming and Conservation Agriculture Research throughout (2025–2026) cropping season. The experimental design includes two main factors. The first factor involved

two cultivars of bread wheat, Erbil and Khanaqin. The second factor consisted of six biochar application rates (0, 100, 200, 300, 400, and 500 g m⁻²).

Five grains of each cultivar that showed a 90% germination percentage were sown during October 2025 in pots with a diameter of 30 cm. The biochar material was thoroughly incorporated and homogenized with the growing medium before sowing. The experiment was designed according to a factorial arrangement within a completely randomized design. Mean comparisons were made between all treatment combinations using Duncan's multiple range test, with statistical significance set at the 5% probability threshold.

The Crops management, including regular irrigation, until the growth cycle was complete and harvesting took place in June 2026.

After harvest, several growth and yield traits as plant height, tillers number, Flag leaf area, spike length, number of grains per spike, weight of 1000 grain, grain yield.pot⁻¹, Biological yield.pot⁻¹, and grain protein %, were evaluated in the laboratory of the agronomy department at the C.AFCAR.

In parallel, soil samples were analyzed to determine a physical and chemical parameters including electrical conductivity (EC), pH, sodium (Na), calcium (Ca), magnesium (Mg), chloride (Cl), carbonate (CO₃), sulfate (SO₄), available nitrogen (N), available phosphorus (P), available potassium (K), lead (Pb), calcium carbonate (CaCO₃), and soil organic matter content.

RESULTS AND DISCUSSION

1. Effect of Cultivar Variation on Growth and Grain Yield of Bread Wheat.

The table (1) shown that the results no statistically significant differences among the tested wheat cultivars with respect to most growth and yield related traits. The only exception was observed in the number of grains per spike, the Khanaqin cultivar showed demonstrated a notable superiority over the Erbil cultivar, achieving an increase in 7.625%. This general lack of noticeable variation between the two cultivars may be ascribed to the relatively high degree of genetic and phenotypic uniformity often exhibited by wheat genotypes that are well adapted to a specific growing environment, which tends to stabilize their growth patterns and yield potential. This observation is consistent with the findings previously documented by (Ding et al., 2022).

Table (1) Effect of cultivars differences on Wheat traits.

Cultivar	Plant height (cm)	Tillers plant ⁻¹	Flag leaf area (cm ²)	Spike length (cm)	No. grains spike ⁻¹	1000-grain weight (g)	Grain yield (g pot ⁻¹)	Biological yield (g pot ⁻¹)	Protein (%)
Khanaqin	45.50 a	1.72 a	14.39 a	10.61 a	25.83 a	43.61 a	12.61 a	36.44 a	11.20 a
Erbil	46.83 a	1.72 a	14.06 a	10.83 a	24.00 b	43.94 a	12.89 a	36.94 a	11.08 a

Means with the same letter are not significantly different at the 5% level (DMRT).

2. Effect of Varying Biochar Concentrations on Wheat Growth and Yield.

The data shown in Table (2) statistically significant differences observed the various biochar application rates concerning wheat growth and yield parameters. The treatment 500 g m⁻² consistently outperformed all other concentrations in every attribute measured, it shows a gradual decrease in effectiveness that corresponds to decreasing application rates, peaking at the lowest values recorded for the untreated control group.

Plant height was significantly affected; the average height of plants treated with 500 g m⁻² of biochar reached 66.83 cm. This represented a progressive and significant superiority over the lower application rates, whereas the control treatment yielded the lowest significant height value at 34.0 cm. This marked response can be attributed to improvements in the soil's physical and chemical properties resulting from the biochar addition factors that combine to promote vigorous plant growth.

Regarding the ability of the wheat plant to tillering out, the treatment 500 g m⁻² achieved a significant increase (2.67) compared the control (1.33) Tillers plant⁻¹. Similarly, the flag leaf area showed a progressive enhancement with increasing biochar levels, the highest concentration resulted in the mean area of flag leaf 17.67 cm², while the control recorded 12.33 cm. The use of sufficient quantities of biochar also had significantly and profound effect on the trait of the Spike length. The 500 g m⁻² treatment produced resulted in the production of longer spikes (15.17 cm), substantially exceeds the control (8.67 cm). This improvement in spike length was reflected in a similar increase in the number of grains per spike, wherein the highest biochar concentration (29.0) significantly outperformed all other treatments, while the control recorded the minimal value of (23.0) grains per spike.

The overall vigor of vegetative growth was further reflected in grain weight, with the 500 g m⁻² biochar treatment achieving a (48.0 g) in 1000 grain weight relative to the control (41.17 g). The remaining application rates showed a gradual decline in this trait, yielding values of (45.00, 43.00, 43.17, and 42.33 g), respectively, for the successively lower biochar concentrations.

Therefore, the improved growth parameters were reflected positively in the grain yield per pot. The 500 g m⁻² treatment produced the highest yield at (17.00 g) per pot. It shows a gradual significant decrease across low concentrations, with the lowest value in control which is (9.33 g). The improvement in vegetative growth, and grain yield was reflected in the biological yield. The application of 500 g m⁻² biochar resulted in a 44.09% increase the biological yield compared with the control. This overall improvement is likely attributed to the elevated availability of mineral elements within the soil, which subsequently led to improve growth traits of wheat plants. These results are largely consistent with the results previously reported by (De la Rosa et al., 2022) and (Abou-Zeid & Aly, 2023).

Table (2) Effect of different concentrations of biochar on Wheat traits

Biochar rate (g m ⁻²)	Plant height (cm)	Tillers plant ⁻¹	Flag leaf area (cm ²)	Spike length (cm)	No. grains spike ⁻¹	1000-grain weight (g)	Grain yield (g pot ⁻¹)	Biological yield (g pot ⁻¹)	Protein (%)
0 (Control)	34.00 e	1.33 b	12.33 d	8.67 e	23.00 d	41.17 e	9.33 e	32.50 d	10.83 a
100	35.67 e	1.33 b	12.67 d	8.50 e	24.00 c	42.33 d	11.00 d	34.67 c	11.13 a
200	40.50 d	1.67 b	13.50 c	9.50 d	25.17 b	43.17 c	12.50 c	34.67 c	11.20 a
300	47.00 c	1.83 b	14.17 c	10.67 c	25.67 b	43.00 cd	12.83 c	34.83 c	10.72 a
400	53.00 b	1.50 b	15.00 b	11.83 b	22.67 d	45.00 b	13.83 b	36.67 b	11.05 a
500	66.83 a	2.67 a	17.67 a	15.17 a	29.00 a	48.00 a	17.00 a	46.83 a	11.90 a

Means with the same letter are not significantly different at the 5% level (DMRT).

3. Effect of the interaction between Wheat cultivar and Biochar application rate on plant growth and yield.

The results are summarized in Table (3) the result showed that the interaction between the two wheat cultivars and different biochar usage rates application rates exerted a statistically significant influence on the growth and yield attributes of bread wheat.

Regarding plant height, the use of biochar treatment a dose of 500 g m⁻² applied to both cultivars produced the significant tallest plants, recording mean heights of (66.67 cm and 67.00 cm) for the respective cultivars. In contrast, the untreated control plots yielded the shortest plants, with values of (34.33 cm and 33.67 cm) for the two cultivars, respectively.

Similarly, tillers number of per plant was significant improvement by the highest application of biochar concentration, which significantly outperformed all other processors in both cultivars, achieving an average rate of (2.67) tillers per plant, compared (1.33) tillers recorded in the control treatment for both cultivars.

The flag leaf area of the also responded positively to high application of biochar. The rate application 500 g m⁻² resulted in an area of flag leaf (17.67 cm²) for both cultivars, whereas the control treatment registered a distinctly lower value of (12.33 cm²) for both cultivars.

Spike length was influenced by increasing biochar quantities in both cultivars. The maximum lengths of spike were recorded at the 500 g m⁻² treatment, it reaching (14.67 cm) and (15.67 cm) for the two cultivars respectively, comparing with (8.67 cm) for both cultivars in control. This improvement in spike length was simultaneously reflected in grain number per spike, Where the highest concentration of biochar was obtained yielded (30.33 and 27.67 grains per spike) for the respective cultivars, whereas the control recorded (23.33 grains per spike) for both.

The enhanced availability of soil nutrients and the overall improvement in physicochemical properties attributable to biochar addition were clearly manifested in 1000-grain weight, which exhibited a progressive decline from the highest to the lowest application rates. The 500 g m⁻² treatment produced the heaviest grain weight value, with weights of (47.67 g and 48.33 g) for the two cultivars respectively, while the control recorded lower values of (40.67 g and 41.67 g), respectively.

Consequently, the cumulative improvements in growth attributes translated directly into enhanced individual plant grain yield. The 500 g m⁻² biochar rate yielded (16.33 g and 17.67 g) per pot for the two cultivars, respectively, compared with (9.67 and 9.00 g) in control treatment respectively.

Despite the marked improvements observed across nearly all vegetative and yield-related parameters, grain protein content remained statistically unaffected by either cultivar type or biochar application rate, with no significant differences detected among any of the experimental treatments.

Table (3) The interaction between cultivar differences and different concentrations of biochar on Wheat traits.

Cultivar	Biochar rate (g m ⁻²)	Plant height (cm)	Tillers plant ⁻¹	Flag leaf area (cm ²)	Spike length (cm)	No. grains spike ⁻¹	1000-grain weight (g)	Grain yield (g pot ⁻¹)	Biological yield (g pot ⁻¹)	Protein (%)
Khanaqin	0 (Control)	34.33 f	1.33 b	12.33 e	8.67 ef	23.33 def	40.67 f	9.67 f	32.00 e	11.00 a
	100	36.33 ef	1.33 b	13.00 de	8.67 ef	24.67 d	42.00 e	11.00 e	34.33 cd	11.20 a
	200	38.33 def	1.67 ab	13.33 cde	9.67 de	26.00 c	42.67 de	12.00 de	34.67 bcd	11.20 a
	300	40.67 de	1.67 ab	14.33 c	11.00 c	27.33 b	43.33 d	12.67 cd	34.67 bcd	10.70 a
	400	56.67 b	1.67 ab	15.67 b	11.00 c	23.33 def	45.33 b	14.00 c	37.00 b	11.10 a
	500	66.67 a	2.67 a	17.67 a	14.67 a	30.33 a	47.67 a	16.33 b	46.00 a	12.00 a
Erbil	0 (Control)	33.67 f	1.33 b	12.33 e	8.67 ef	22.67 ef	41.67 ef	9.00 f	33.00 de	10.67 a
	100	35.00 ef	1.33 b	12.33 e	8.33 f	23.33 def	42.67 de	11.00 e	35.00 bcd	11.07 a
	200	42.67 d	1.67 ab	13.67 cd	9.33 def	24.33 d	43.67 cd	13.00 cd	34.67 bcd	11.20 a
	300	53.33 bc	2.00 ab	14.00 cd	10.3 cd	24.00 de	42.67 de	13.00 cd	35.00 bcd	10.73 a
	400	49.33 c	1.33 b	14.33 c	12.67 b	22.00 f	44.67 bc	13.67 c	36.33 bc	11.00 a
	500	67.00 a	2.67 ab	17.67 a	15.67 a	27.67 b	48.33 a	17.67 a	47.67 a	11.80 a

Means with the same letter are not significantly different at the 5% level (DMRT).

4. Effect of Wheat Cultivar Variation differences on chemical soil traits .

The data presented in Table (4) illustrate the influence of the two tested bread wheat cultivars (Khanaqin and Erbil) on selected post-harvest soil chemical attributes. Statistical analysis of the results revealed no significant differences between the two cultivars for the vast majority of the measured properties. The effects of soil electrical conductivity (EC), pH, sodium (Na⁺), calcium (Ca²⁺), magnesium (Mg²⁺), Cl⁻ bicarbonate (HCO₃⁻²), and sulfate (SO₄⁻²) concentrations, along with available nitrogen (N), available phosphorus (P), available potassium (K), lead (pb), calcium carbonate (CaCO₃), and soil organic matter (OM), all showed statistically similar mean values, as indicated by the common letter combinations. This homogeneity indicated that the variety was not a decisive factor in shaping these chemical properties of the soil after the harvest.

This lack of varietal effect on cultivars may be attributed primarily to the fact that the chemical properties of the soil are largely subject to the intrinsic properties of the soil, basic salinity levels, irrigation, fertilization practices, and the nature of applied amendments. The influence of cultivar selection on chemistry soil composition of the remains soils relatively limited over the course of a single growing season. In fact, genotypic differences are usually more evident in nutrient uptake efficiency and overall plant productivity than in fundamental changes in soil chemical composition. This observation is consistent with the conclusion he reported. (Moreno-Lora et al., 2023).

Furthermore, lack of significant differences in EC and pH values indicates The chemical balance of the soil after harvest remained primarily governed by ion exchange dynamics, In addition to the mechanisms of salt dissolution and precipitation, this depend primarily on the intrinsic properties of the soil rather than the genetic makeup of the cultivated variety. This aligns closely with the claims (Barrow & Hartemink, 2023) , this confirmed that the soil pH response and nutrient availability are more closely tied to soil characteristics and management regimes than to the planted genotype.

Similarly, there was no significant difference in the concentrations of sodium, calcium, magnesium, bicarbonate, and sulfate between the two cultivars. This indicates that both two cultivars possessed comparable capacities for absorbing these ions, and that their residual concentrations in the soil after harvest are more affected by soil properties and surrounding soluble salt stock than by genetic variation between cultivars. This is consistent with what he found (Kramer & Mau, 2023), who highlighted the predominance of chemical soil processes over varietal genetics in dictating the after-season behavior of soluble salts.

In contrast, the results showed a significant difference in the concentration of chloride ion (Cl⁻). The Khanaqin variety recorded the highest value (2.40) compared to the Erbil variety (2.33) These variations may be attributed to genetic differences between the two species in chloride uptake efficiency, exclusion, and regulation of internal ion transport. Wheat cultivars are characterized by having unique physiological mechanisms for managing the absorption and transport of sodium and chloride ions, especially under conditions of salt stress, which consequently leads to different levels of chloride remaining in the soil after harvest. This interpretation confirmed (Lindberg & Premkumar, 2023), They pointed out that it led to the regulation of chloride and sodium ion transport, which is one of the most important physiological features that characterize salt-tolerant genotypes.

The larger major nutrients (N, P, and K), The lack of significant differences between the two cultivars indicates similar nutritional requirements and comparable nutrient absorption efficiency., which consequently resulted in analogous residual concentrations in the soil after harvest. This result consistent with the conclusions by(Moreno-Lora et al., 2023), who ascertained

that residual soil nutrient concentrations are primarily governed by soil management practices and organic amendment applications rather than by cultivar choice.

The soil organic matter and calcium carbonate contents remained statistically unaffected by difference variety. This is attributed to the stable nature of the soil due to these two soil properties.; this are not subject to undergo substantial alterations within a single cropping season. Instead, these materials are gradually affected by the addition of organic waste, parent material composition, and prevailing environmental conditions over extended periods. This perspective is consistent with the findings of (Moreno-Lora et al., 2023).

Table (4) Effect of cultivar on chemical soil traits.

Cultivar	EC ($\mu\text{S cm}^{-1}$)	pH	Na ⁺	Ca ⁺²	Mg ⁺²	Cl ⁻	HCO ₃ ⁻²
Khanaqin	707.61 a	7.53 a	1.11 a	4.01 a	2.66 a	2.40 a	2.94 a
Erbil	709.00 a	7.52 a	1.05 a	3.95 a	2.55 a	2.33 b	2.92 a
	SO ₄ ⁻²	N	P	K ⁺	pb	CaCO ₃	O.M
Khanaqin	4.68 a	65.72 a	53.22 a	186 a	1.28 a	137.94 a	1.374 a
Erbil	4.66 a	64.28 a	52.11 a	181 a	1.29 a	135.50 a	1.357 a

Means with the same letter are not significantly different at the 5% level (DMRT).

5. Effect of Varying Biochar Application Rates on chemical soil traits.

Table (5) showed the findings presented in about the impact of differing biochar levels on the chemical attributes of the soil following crop harvest. Statistical analysis appears revealed significant differences among the various application rates across the majority of the measured parameters. The biochar treatment 500 g m⁻² consistently produced the highest mean values for most chemical properties relative to the control; this indicates that the increased addition of biochar had a clear improving effect on the chemical properties of the soil.

The use of biochar led to a significant increase in electrical conductivity (EC), which originated from 655.00 $\mu\text{S cm}^{-1}$ in the control treatment to 798.33 $\mu\text{S cm}^{-1}$ at the 500 g m⁻² rate. This increase is attributed to the presence of soluble salts and mineral elements within the biochar matrix, which are gradually released into the soil solution, In addition to increasing the cation exchange capacity and enhancing the ion retention capacity of the amended soil. These results are consistent with (Lehmann & Joseph, 2015). Furthermore, a comprehensive meta-analysis was conducted by (Wu et al., 2024) confirmed that increases in electrical conductivity following biochar addition represent a commonly observed response in salt-affected soils, with the magnitude of change dependent upon biochar feedstock type and the rate of application.

The soil pH values showed a significant upward trend, increase from (7.48) in the control to (7.65) at the highest biochar concentration. Which transformation is attributable to the inherent alkalinity to biochar, which contains carbonates, oxides, and base rich ash components that effectively neutralize hydrogen ions and enhance soil alkalinity. This observation was consistent with the reports (Hossain et al., 2020) and (Lehmann & Joseph, 2015).

It was found that the difference in concentrations led to differences in the concentrations of elements, as the concentrations of sodium (Na⁺), calcium (Ca²⁺), magnesium (Mg²⁺), chloride (Cl⁻), and bicarbonate (HCO₃⁻) ions recorded significant increases corresponding to higher levels of biochar. This improvement is largely attributed to the inherent mineral composition of biochar, in addition to its proven role in improving the soil's ability to retain ions and reducing losses resulting from leaching, this increases the residual concentrations of these ions in the soil after harvest. This interpretation is supported by (Agegnehu et al., 2017). Moreover,(Blanco-Canqui, 2021) elucidated that biochar improves the retention of nutrients and ions due to its extensive specific surface area and heightened cation exchange capacity.

On the other hand, sulfate (SO₄²⁻) concentrations showed a marked downward trend with increasing biochar application rates, decreasing from 5.59 to 3.58 mg/L when treated with 500 g m⁻². This decrease can reasonably be explained by increased precipitation of sulfates with calcium, or their absorption on porous biochar surfaces, or increased plant utilization of them during the growing season. These results were consistent with what was found (Hossain et al., 2020) concerning the influence of biochar on the dynamics of elements and ions within the soil environment.

With regard to the available macronutrients, the results showed significant increases in nitrogen, phosphorus and potassium concentrations, consistent with the rise of the biochar levels. The 500 g m⁻² treatment recorded the highest mean values at (84.17, 81.67, and 212 ppm), respectively. This improvement is attributed to the direct nutrient content of the biochar itself, in addition to its role in increasing cation exchange capacity, reducing nutrient loss through leaching, and stimulating microbial activity responsible for mineralizing organic matter and the resulting release of nutrients in forms available to plants. These findings are strongly corroborated by the results of (Glaser et al., 2002) and (Joseph et al., 2021).

Furthermore, the results revealed a significant decrease in calcium carbonate (CaCO₃) content, this decreased from 147.50 to 119.50 g kg⁻¹ with increasing rate of biochar application. This reduction may be attributed to increase biological activity in the

soil, leading to increased production of organic acids and carbon dioxide within the rhizosphere, which in turn promotes the dissolution of calcium carbonate into more soluble forms, as elucidated by (Brady & Weil, 2017).

Similarly, soil organic matter (OM) content in the soil showed significant increase with rising biochar levels, from (1.144 to 1.554 %) at the highest application rate. This is among the most beneficial effects of biochar, it act as a stable source of organic carbon, which enhances carbon sequestration in the soil while simultaneously improving its chemical properties, physical, and biological attributes of the soil. This finding is consistent with the conclusions of (Lehmann & Joseph, 2015) (Singh et al., 2022).

The combined results of these study findings substantiate that increasing biochar application rates particularly at the 500 g m⁻² level led to pronounced improvements in the majority of post-harvest soil chemical properties. These improvements were evident in the increased availability of nutrients, high organic matter content, and improved soil ionic retention capacity, all of which contribute significantly to enhanced soil fertility and sustained agricultural productivity. Despite the observed increase in electrical conductivity resulting from the release of soluble salts from the biochar, this elevation is considered a natural and expected outcome associated with the application of mineral-rich organic amendments (Wu et al., 2024).

Table (5) Effect of different concentrations of biochar on chemical soil traits

Biochar rate (g m ⁻²)	EC (μS cm ⁻¹)	pH	Na ⁺	Ca ⁺²	Mg ⁺²	Cl ⁻	HCO ₃ ⁻²
0 (Control)	655.00 d	7.48 b	0.98 b	3.78 c	2.09 d	2.02 d	2.73 d
100	679.17 cd	7.50 b	1.08 b	3.92 b	2.37 c	2.18 c	2.82 c
200	680.00 cd	7.47 b	1.01 b	3.86 bc	2.46 bc	2.28 c	2.93 b
300	713.33 bc	7.52 b	1.05 b	3.89 bc	2.67 b	2.28 c	2.88 bc
400	724.00 b	7.53 ab	1.07 b	3.92 b	2.93 a	2.56 b	2.94 b
500	798.33 a	7.65 a	1.29 a	4.53 a	3.10 a	2.86 a	3.27 a
Biochar rate (g m ⁻²)	SO ₄ ⁻²	N	P	K ⁺	pb	CaCO ₃	O.M
0 (Control)	5.59 a	51.33 e	39.33 d	155 d	1.27 ab	147.50 a	1.144 e
100	5.41 a	56.67 d	34.33 d	173 c	1.32 a	147.50 a	1.194 d
200	4.90 b	62.83 c	45.50 c	188 b	1.27 ab	141.67 b	1.315 c
300	4.48 c	67.67 b	59.00 b	184 bc	1.31 ab	136.33 c	1.480 b
400	4.05 d	67.33 b	56.17 b	188 b	1.26 b	127.83 d	1.505 b
500	3.58 e	84.17 a	81.67 a	212 a	1.30 ab	119.50 e	1.554 a

Means with the same letter are not significantly different at the 5% level (DMRT).

6. Effect of interaction between Biochar rates and Wheat cultivars on soil traits.

Table (6) findings presented in reveal that biochar addition elicited a significant increase in electrical conductivity (EC), with rising values from (654.00 and 656.00 μS cm⁻¹) in the control treatment to (795.67 and 801.00 μS cm⁻¹) at the 500 g m⁻² application rate for the Erbil and Khanaqin cultivars, respectively. This increase reflects arise in the concentration of soluble salts resulting from the liberation of basic cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) along with their accompanying anions from the biochar ash into the soil solution. Additionally, the enhanced cation exchange capacity (CEC) reduces nutrient leaching losses and promotes their retention within the rhizosphere. It should be noted that previous studies indicate that EC increases following biochar application do not necessarily signify a deterioration in soil salinity, but rather often correspond to elevated concentrations of dissolved nutrients and enhanced soil fertility, particularly at moderate application rates (Agegnehu et al., 2017) ;(Lehmann & Joseph, 2024).

This also explain modest increase in soil pH, from (7.47–7.49) in the control plots to (7.65) at the highest biochar level (500 g m⁻²). This transformation is mainly attributable to the inherent alkalinity of biochar, derived from its content of carbonates and mineral oxides particularly calcium and magnesium carbonates and oxides, which act to consume hydrogen ions and enhance the soil's buffering capacity. This stable soil reaction contributes to improved availability of many essential nutrients, especially phosphorus (Zhang et al., 2025);(Pandian et al., 2024).

The results obtained indicate significant increases in concentrations (Ca²⁺, Mg²⁺, K⁺, Na⁺, Cl⁻, and HCO₃⁻) In line with the high levels of biochar. When, the concentrations of calcium increased from (3.70-3.85 to 4.45- 4.60 mg L⁻¹), while magnesium increased from (1.95-2.23 to 3.03-3.17 mg L⁻¹) at the 500 g m⁻² treatment. This improvement is attributed to the inherent reservoir of these cations within the biochar matrix, derived from its base rich ash content. The high cation exchange capacity facilitates the adsorption of these reduces their loss through filtration, thereby raising their concentrations in the soil solution and improving the ionic equilibrium surrounding plant roots (Ye et al., 2020) ;(Lehmann & Joseph, 2024). In contrast, concentrations of sulfate (SO₄²⁻)

exhibited a decline from (5.53-5.64 to 3.47-3.70 mg L⁻¹). This reduction is plausibly ascribed to enhanced precipitation with calcium or increased plant uptake facilitated by improved growth and nutrient utilization efficiency, a pattern that corroborates the observations of (Hoque et al., 2025).

The results in Table (6) also indicate that the use of biochar has led to a significant improvement in nutrient availability. The concentrations of nitrogen increased from 51.00-51.67 ppm in the control to (83.33-85.00 ppm) at the 500 g m⁻² level. This improvement is attributed to the ability of biochar to retain ammonium and nitrate ions within its microporous structure, alongside its stimulation of microbial activity responsible for organic matter mineralization, thereby accelerating nitrogen release rates while reducing losses through leaching or volatilization (Joseph et al., 2021) ;(Lehmann & Joseph, 2024).

Phosphorus concentrations rose significantly from (38.67-40.00 to 81.33-82.00 ppm). This increase is due to a decrease in phosphorus fixation resulting from improved soil pH, in addition, there are soluble organic compounds that compete with phosphates for adsorption sites. Biochar itself contributes intrinsic phosphorus content that becomes progressively available, collectively resulting in a substantial enhancement of phosphorus bioavailability (Mukherjee & Lal, 2013). Correspondingly, potassium concentrations increased from (152-157 to 207-217 ppm), which is attributable to potassium being among the most abundant elements in biochar ash, combined with the elevated cation exchange capacity that minimizes leaching and preserves it in plant-available forms (Blanco-Canqui, 2021).

The results in Table (6) show a significant increase in the organic matter content of the soil, from (1.132-1.156 to 1.545-1.562 %) with increasing application of biochar, reaching its peak at the 500 g m⁻² level. This increment reflects the addition of substantial quantities of stable organic carbon characterized by high resistance to decomposition, which contributes to enhanced carbon sequestration, improved soil structural development, and elevated microbial activity all of which collectively enhance soil fertility and sustain agricultural productivity (Xu et al., 2024); (Lehmann & Joseph, 2024). Meanwhile, calcium carbonate (CaCO₃) The content showed a decrease from (145-150 to 119-120 g kg⁻¹) at the highest application rate of biochar. Which decrease may be attributed to increased dissolution of carbonate compounds resulting from heightened biological activity and the production of organic acids and carbon dioxide within the rhizosphere, which promotes the conversion of calcium into more plant-available forms (Agegnehu et al., 2017).

Meanwhile, bulk density values remained statistically similar across all treatments ranging from (1.25 to 1.33 Mg m⁻³), so there was no need to present them in the table. This suggests that the experimental duration and the specific application rates employed were insufficient to induce discernible modifications in this particular physical property. Nevertheless, given biochar's inherently low specific density and high porosity, prolonged and repeated application would plausibly contribute to improved soil structural attributes over extended timeframes (Lehmann & Joseph, 2024).

Table (6) interaction between cultivar differences and different concentrations of biochar on soil traits.

Cultivar	Biochar rate (g m ⁻²)	EC (μS cm ⁻¹)	pH	Na ⁺	Ca ⁺²	Mg ⁺²	Cl ⁻	HCO ₃ ⁻²
Khanaghi	0 (Control)	656.00 cd	7.49 ab	1.00 c	3.85 bc	2.23 fg	2.10 d	2.74 ef
	100	679.00 bcd	7.52 ab	1.12 bc	3.95 b	2.40 def	2.17 cd	2.84 cde
	200	680.00 bcd	7.50 ab	1.02 c	3.88 bc	2.50 def	2.33 c	2.94 bc
	300	710.00 bcd	7.53 ab	1.08 bc	3.90 bc	2.70 bcd	2.30 c	2.89 bcd
	400	719.67 bc	7.50 ab	1.11 bc	3.90 bc	2.93 abc	2.60 b	2.97 b
	500	801.00 a	7.65 a	1.33 a	4.60 a	3.17 a	2.88 a	3.27 a
Erbil	0 (Control)	654.00 d	7.47 ab	0.97 c	3.70c	1.95 g	1.93 e	2.72 f
	100	679.33 bcd	7.48 ab	1.05 c	3.89 bc	2.33 ef	2.20 cd	2.81 def
	200	680.00 bcd	7.44 b	1.00 c	3.84 bc	2.42 def	2.23 cd	2.92 bc
	300	716.67 bcd	7.50 ab	1.02 c	3.88 bc	2.64 cde	2.27 cd	2.88 bcd
	400	728.33 b	7.57 ab	1.04 c	3.94 b	2.92 abc	2.51 b	2.92 bc
	500	795.67 a	7.65 a	1.25 ab	4.45 a	3.03 ab	2.83 a	3.27 a
Cultivar	Biochar rate (g m ⁻²)	SO ₄ ⁻²	N	P	K ⁺	pb	CaCO ₃	O.M
Khanaghi	0 (Control)	5.64 a	51.67 e	40.00 cd	157 f	1.27 ab	150.00 a	1.156 ef
	100	5.42 a	57.67 d	34.67 d	174 de	1.30 ab	148.33 a	1.202 e
	200	4.95 b	64.00 bc	46.00 c	190 cd	1.27 ab	143.3 abc	1.322 d
	300	4.50 bcd	68.00 b	59.67 b	185 cde	1.30 ab	138.00 cd	1.482 bc
	400	4.10 de	68.00 b	57.00 b	193 bc	1.27 ab	129.00 ef	1.517 abc

	500	3.47 f	85.00 a	82.00 a	217 a	1.30 ab	119.00 h	1.562 a
Erbil	0 (Control)	5.53 a	51.00 e	38.67 cd	152 f	1.27 ab	145.0 abc	1.132 f
	100	5.40 a	55.67 d	34.00 d	172 e	1.33 a	146.67 ab	1.186 ef
	200	4.86 bc	61.67 c	45.00 c	187 cde	1.28 ab	140.0bcd	1.308 d
	300	4.47 cd	67.33 b	58.33 b	182 cde	1.31 ab	134.67 de	1.478 c
	400	4.00 e	66.67 b	55.33 b	182 cde	1.25 b	126.67 fg	1.493 bc
	500	3.70 ef	83.33 a	81.33 a	207 ab	1.30 ab	120.0 gh	1.545 ab

Means with the same letter are not significantly different at the 5% level (DMRT).

CONCLUSION

Effect of cultivars on growth and yield traits: No significant differences were observed between the "Erbil" and "Khanaqin" cultivars regarding most of the studied traits (Plant height, No. of tillers, Flag leaf area, Spike length, Weight of 1000 grains, Grains yield.pot⁻¹, Biological yield.pot⁻¹, No. spike grains, Protein %) with the exception of the number of grains per spike, where the "Khanaqin" cultivar outperformed "Erbil" by 7.625%.

Effect of biochar on wheat growth and yield traits: Biochar application resulted in a significant improvement across all growth and yield traits. The 500 g m⁻² treatment yielded the best results, showing significant differences compared to the other treatments.

Specifically, plant height increased to 66.83 cm, the number of tillers increased to 2.67 tiller pot⁻¹, spike length reached 15.17 cm, the number of grains per spike rose to 29.00, and the 1000-grain weight reached 48.00 g. This translated to an increase in grains yield to (17.00 g pot⁻¹), compared to the control (9.33 g pot⁻¹). Grain protein content was not significantly affected by any of the treatments.

Effect of biochar on soil chemical characters: The application rate of 500 g m⁻² resulted in a significant Increase in soil properties after harvest compared with control. Electrical conductivity (EC) increased from (656–654 µS cm⁻¹) in control to (801–795 µS cm⁻¹) in 500 g m⁻², soil pH rose from (7.49–7.47) to (7.65). Content of Nitrogen increased from a range of (51.67–51.00 ppm) to (85.00–8.33 ppm); Content of Phosphorus increased from (40.00–38.67 ppm) to (82.00–81.33 ppm); and Content of Potassium increased from (157–152 ppm to 217–207 ppm) for the two cultivars respectively.

Additionally, Calcium Carbonate levels decreased from (150–145 g.kg⁻¹) to (119–120 g.kg⁻¹). Organic Matter content rose from (1.156 -1.132 %) to (1.562–1.545 %), while Overall, the results demonstrated that increasing biochar application rates, particularly at 500 g m⁻² led to a marked improvement in most soil chemical properties, as well as enhanced soil fertility and wheat productivity.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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