Research Article

Role of Biochar and Potassium Fertilization in Improving Soil Fertility, Soil Chemical Properties, and Wheat Growth and Yield

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Abstract | A field experiment was carried out to study the effects of biochar application and potassium fertilizer levels on selected soil chemical properties and wheat growth and productivity, in a sandy loam soil texture, using Randomized Complete Block Design (R.C.B.D) with three replicates. The experiment included three levels of Biochar (0, 15 and 30) Mg ha^{-1}, and their symbols were BC0, BC1 and BC2 respectively, and three levels of Potassium fertilizer (0, 60 and 120) kg K ha^{-1}(K41.5 %), their symbols were K, K_1 and K_2 respectively. The obtained results revealed that level of Biochar 30 Mg ha^{-1} gave the lowest value for EC was 3.12 dS m^{-1}, and gave highest values for N, P and K available were 43.43, 20.46, 224.41 mg kg^{-1} respectively, and 2.31% for SOM, and recorded highest values for plant height, leaf area, dry matter weight, leaf chlorophyll content and weight of 1000 grain were 95.4 cm, 35.72 cm^2, 15.71 g plant^{-1}, 29.21 SPAD and 39.89 g plant^{-1}, respectively. Potassium fertilizer at 120 kg K ha^{-1} and resulted in the highest values of the measured nutrient properties (available N, P, and K, and SOM), while EC increased as expected with potassium addition. reaching 43.69, 20.75 and 221.70 mg kg^{-1} for available N, P, and K, respectively, EC (4.03 dS m^{-1}), and SOM (1.72%). It also gave the highest values for plant traits, with plant height, leaf area, dry matter weight, chlorophyll content and 1000 grain weight reached 97.2 cm, 34.83 cm^2, 16.28 g plant^{-1}, 27.74 spad and 39.28 g plant^{-1} respectively, On the other hand, the interactions between the levels of biochar and potassium at treatment 30 Mg ha^{-1} + 120 kg K ha^{-1} showed an effect on all the studied traits. In addition, presenting the relative changes (such as the percentage increase compared to the control treatment) makes the results more informative and strengthens their agronomic significance. These findings highlight the importance of enhancing fertilizer use efficiency as a key pathway to improving wheat productivity under sandy loam soil conditions.

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Introduction

Soil fertility is a core component in the assessment of soil quality, thus its importance cannot be overemphasized regarding sustainable agricultural development as it impacts greatly on the long-term maintenance of soil physical and chemical properties and efficient utilization of soil resources (Mulugeta and Karl, 2010). Precise diagnosis and combating these factors affecting agricultural production must be done with efficient management and use of modern technologies. These tools may provide significant aid on achieving higher yield of crop per unit area. The adequate supply of the required nutrients to the plants and effectively at their optimum time is also very important to avoid yield constraints (Hassan and Ati, 2021).

Climate change, soil depletion, environmental pollution and the depleting water resources are on top list among those factors that have an impact on carrying capacity of earth to produce food (AlKharabsheh *et al*., 2021). Application of biochar has become a potential agricultural practice to meet these challenges and it is becoming more popular, due to its unique qualities that can improve soil quality and capacity, such as: photocatalytic effect, high porosity & surface area, carbon storage power – sequester carbon but also act for nutrient loss control – nitrogen and others – improvements in soil acidity, climate changes relevant field (Pandian *et al*., 2024; Hamid *et al*., 2025).

Potassium (K) is an essential macronutrient, which, due to its important role in increasing crop yield and quality, is needed by plants in large quantities (Zamani *et al*., 2020). Moreover, Potassium has also been found to play a major role in alleviating the plant tolerance against abiotic stresses like salinity, drought, high temperature and biotic stresses such as pests and diseases (Ramzan *et al*., 2020). Osmotic regulation (which causes plants to absorb water) is one of its most important physiological effects. Therefore, with a potassium deficiency the plant is not able to efficiently access available water and becomes more prone to water stress (Mahmoud *et al*., 2025).

Wheat (Triticum aestivum L.) is a cereal of monocotyledonous, belonging to the family of poaceae that used for food grain which consumed and produces all over the world, it is first crop in Iraq economically and cultivated area wise.

Wheat production in Iraq was 4248 thousand tons per year with an area of 8420 thousands of dunums sown wheat during the same period (Ministry of Planning, 2023). Wheat is a major source of essential amino acids, vitamins, minerals, dietary fibers as well as beneficial phytochemicals (Dahham *et al*., 2025).

This study addresses a critical research gap concerning the combined influence of biochar and potassium fertilization on improving soil health and enhancing nutrient availability in sandy loam soils. The integration of these amendments is essential for mitigating soil degradation and supporting sustainable wheat production. Therefore, the objective of this study is to evaluate the effects of biochar and potassium levels on soil chemical properties, nutrient availability, and the growth and yield of wheat grown under sandy loam soil conditions.

Materials and Methods

This research was executed in the 2023/2024 agricultural season, at the College of Agriculture in Al-Qasim Green University, located in Babylon Governorate, central Iraq. The goal of this research was to determine the effects of biochar and potassium fertilization on macronutrients and some chemical properties of the soil, as well as on the growth and yield of wheat in sandy loam soil. Prior to planting, multiple soil samples were collected from the 0-30 cm depth, air-dried, ground, and passed through a 2 mm diameter sieve. The samples were then analyzed for various chemical and physical properties using the method described by Page *et al*. (1982), as detailed in Table 1.

The soil for the experiment was prepared for cultivation by ploughing it twice in perpendicular directions. It was then levelled and divided into panels, each with an area of 6 m^2, containing 9 rows and with a length of 2 m. The distance between each row was 20 cm. The seeds, obtained from "Mabin al-Nahrain Company / Ministry of Agriculture", were manually planted on 11/26/2023 at a quantity of 120 kg ha^{-1}. Throughout the cultivation process, crop service operations, including weeding and irrigation, were performed as needed. The experiment was monitored immediately after planting, and irrigation was carried out according to field-moisture conditions.

The experiment was conducted using a randomized complete block design (R.C.B.D) with three replicates, consisted of three levels of Biochar used which were 0, 15 and 30 Mg ha^{-1} and their symbols (BC0, BC1 and BC2) applied to the soil in three split doses, The biochar used was prepared through the pyrolysis of corn residues at temperatures ranging between 450 and 700 °C under limited oxygen availability. Table 2 shows some properties of the biochar as determined by its production process.

Table 1: *Some chemical, physical and fertility properties of the soil before planting.*

Properties		Value	Unit
pH $_{(1:1)}$		7.8	—
EC $_{(1:1)}$		3.2	ds m^{-1}
CEC		23.93	Cmol $_+$kg^{-1} soil
SOM		1.02	g kg^{-1} soil
Carbonate minerals		252.64	
Gypsum		18.77	
Cations	Ca^{2+}	9.45	mmol L^{-1}
	Mg^{2+}	7.39	
	Na^{+}	5.81	
	K^{+}	1.64	
Anions	Cl^{-}	10.16	
	SO_4^{2-}	12.21	
	HCO_3^{-}	2.92	
	CO_3^{2-}	Nil	
Available nutrients	N	36.24	mg kg^{-1} soil
	P	14.83	
	K	192.87	
Bulk ensity		1.47	Mg m^{-3}
Particle size distribution	Sand	511.10	g kg^{-1} soil
	Silt	375.30	
	Clay	113.60	
Texture sandy loam			

Table 2: *Some properties of biochar used in the experiment.*

Property	Value	Unit
$EC_{1:5}$	3.09	dS m^{-1}
$pH_{1:5}$	7.83	%
N	1.28	%
P	0.93	%
K	1.84	%
O.C	24.3	%
O.M	41.29	%
C:N Ratio	18.98	%
Exchangeable Ca	5.11	cmol kg^{-1}
Exchangeable Mg	9.02	cmol kg^{-1}

The first factor consisted of three levels of Biochar used which were 0, 15 and 30 Mg ha^{-1} and their symbols (BC0, BC1 and BC2) added for soil in three batches, and the second factor involved three levels of Potassium fertilizer (0, 50% and 100%) of the recommended rate which were (0, 60 and 120 kg K ha^{-1}) and their symbols (K0, K1 and K2), added in one batch in the form of potassium sulfate K_2SO_4 (41.5% K) mixed with the soil before planting.

Nitrogen was added at a level of 240 kg N ha^{-1} in the form of urea fertilizer $(NH_2)_2CO$ (46% N) in two batches, half the amount in the first batch at planting, mixed with the soil, and the second batch of the remaining amount was added 45 days after adding the first batch. Additionally, triple superphosphate (21% P) was applied in one batch before planting at a rate of 80 kg P ha^{-1}.

The trial was terminated when the crop achieved maturity on 16/5/2024. Soil nitrogen was deter Phosphorus was analyzed by the method of ammonium molybdate and determined at 882 nm wave length with a spectrophotometer, according to Watanabe and Olsen, (1965). Potassium was measured on a flame photometer as described by Page *et al*. (1982). Soil texture was described using the Pipette method according to (Black, 1965). The electrical conductivity in the saturated paste extract was determined by means of an Ec-meter as described by (Richards, 1954) while pH of the soil in saturated paste extract was also determined using a pH-meter as stated for by (Page *et al*., 1982). Soil organic matter was estimated by the Black (1965) method described in. Plant traits, including plant height, chlorophyll content, 1000-grain weight (TGW), leaf area and dry matter weight were assessed. The figure was analyzed using ANOVA, while the least significant difference (L.S.D) at 0.05 probability level were used.

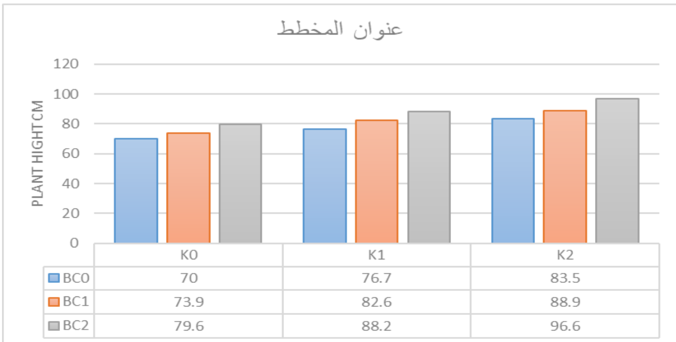

Figure 1: *Effect of adding biochar and potassium fertilization on plant height (cm)*

Results and Disscution

Effect of biochar and potassium fertilization on plant

Plant height

As shown in Figure 1, plant height had a significant positive response to biochar application, and the largest increases were observed under BC2 and

BC1treatments with improvements of 13.57% and 6.02%, respectively, when compared to the control treatment (BC_0) which registered the lowest value of 84 cm. Potassium fertilization also had a significant effect; compared with K0, K2 and K1 treatments resulted in a 18.9% and 9.29% increase of average plant height, respectively (81.8 cm). Moreover, Addbio and K levels interacted to a great extent. The average plant height was highest with the BC2K2 combined treatment (104.2 cm) and significantly greater than with BC0K0 (control), which had the shortest overall height of 77.3 cm (34.8%). This relationship presents strong evidence on a biochar and potassium synergy that leads to enhanced vegetative biomass accumulation in the favorable interplay.

Linear correlation analysis revealed that both biochar (BC) and potassium fertilization (K) had a significant effect on plant height, and a significant BC×K interaction was detected. A predictive equation for plant height was derived based on the experimental data, as follows:

Plant Height= 69.81+4.83*BC+6.71*K+0.88*(BC*K)

The model coefficients indicate that:

- Each one-level increase in BC results in a predicted 4.83 cm increase in plant height. Each one-level increase in K results in a 6.71 cm increase.
- The interaction between BC and K results in an additional 0.88 cm increase, reflecting a synergistic effect between the two factors.

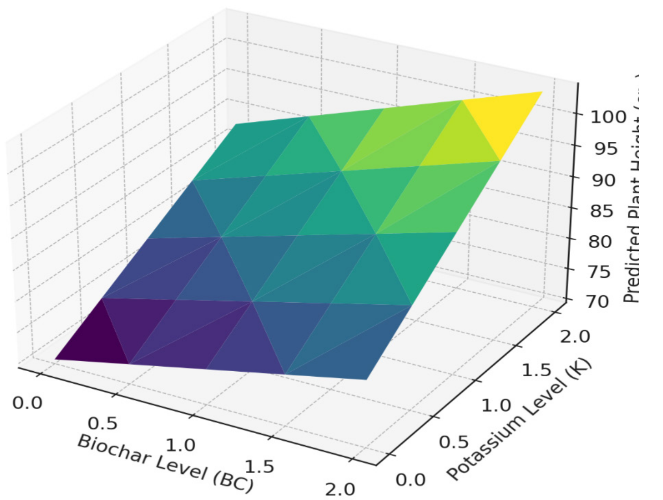

Figure 2: *3D Surface plot of predicted plant height under different biochar and potassium levels*

Leaf area

Leaf area was significantly influenced by application of levels of biochar, as presented in Figure 3. BC2 treatment showed the highest mean leaf area (35.72 cm^2), next to BC1 treatment, while control treatment (BC0) was similar to that obtained in control plant with the lowest value (28.69 cm^2).

Similarly potassium fertilization had a significant effect. The greatest average leaf area was obtained with K2 treatment (34.83 cm^2), showing an increase of 18.75% compared to the control (K0). The K1 treatment also improved compared with the control, at 32.21 cm^2 on average.

Meanwhile, the combination effect of biochar and potassium addition also increased leaf area. The merged treatment of BC2K2 reached the highest result recorded (39.62 cm^2), and it was statistically similar to the obtained with BC2K1 (38.0 cm^2). However, the lowest mean leaf area (26.70 cm^2) was obtained under untreated control treatment (BC0K0), indicating a combination effect between biochar and potassium application.

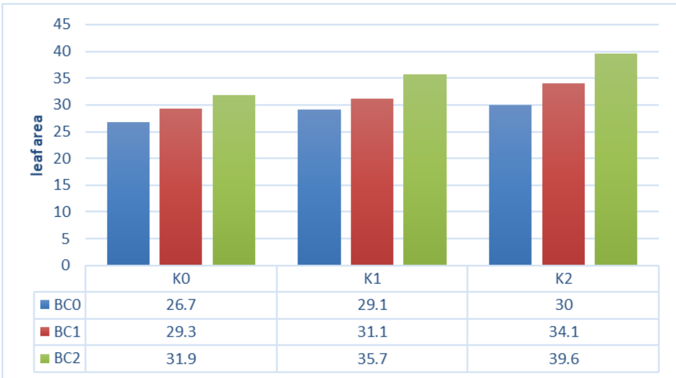

Figure 3: *Effect of biochar and levels of potassium fertilization on leaf area (cm^2) in wheat plants.*

Dry matter weight

The data shown in Figure 4 illustrated that the average dry matter weight of wheat, notably, was significantly improved by elevating the biochar application rates. Maximum average dry matter weight (15.6 g plant-^{1}) was observed under the treatment BC2 and the lowest from control treatment BC0 (10.95 g plant-^{1}).

Potassium fertilizer application too was found to exert a significant influence on this character. The average dry matter weight was highest in treatment K2 (16.28 g plant-^{1}) and lowest in the control treatment K0 (10.56 g plant-^{1}).

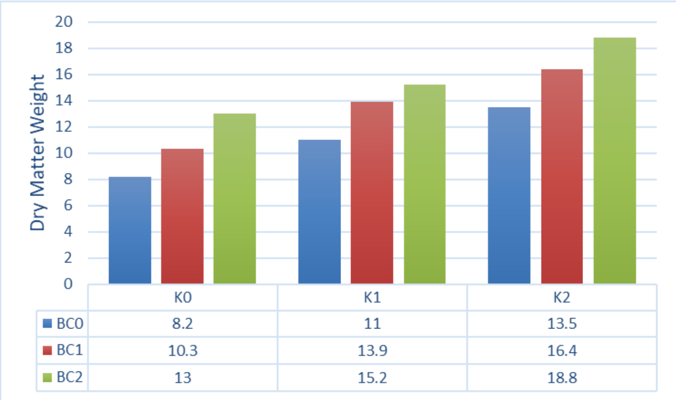

Figure 4: *Effect of biochar and potassium fertilization on dry matter weight (g plant^{-1}) in wheat plants.*

Statistically significant interactions were observed between biochar and potassium levels. The highest total dry matter weight was produced from the combination of BC2K2 treatment (18.87 g plant-^{1}) and the lowest could be found in BC0K0 treatment (8.26 g plant-^{1}), demonstrating that applied organic and inorganic nutrients are equally important to provide an increase on plant biomass production.

Chlorophyll content of leaves

According to Figure 5, the chlorophyll content of leaf was significantly increased with biochar amendment. The average chlorophyll content was highest under BC2 treatment (29.21 SPAD), which exhibited a 29.56% increment compared with the control (BC0: 22.00 SPAD). This indicates the beneficial effects of biochar application on increasing photosynthetic capacity.

Potassium rate also had a significant effect on leaf chlorophyll content. The best outcome was observed with K2 treatment (27.74 SPAD) that resulted in 18.29% higher than the control (K0: 23.45 SPAD).

The regression analysis revealed a strong and statistically significant relationship between chlorophyll content and both biochar and Potassium fertilization levels. The derived predictive model is expressed by the following equation:

$$\text{Chlorophyll(SPAD)} = 19.04 + 1.81 \times BC + 2.30 \times K + 1.40 \times (BC \times K)$$

This model indicates that each incremental increase in biochar level contributes to a 1.81 unit rise in SPAD value, while Potassium fertilization adds 2.30 units an average. Furthermore, the interaction term suggests a synergistic effect, where the combined application enhances chlorophyll content by an additional 1.40 units.

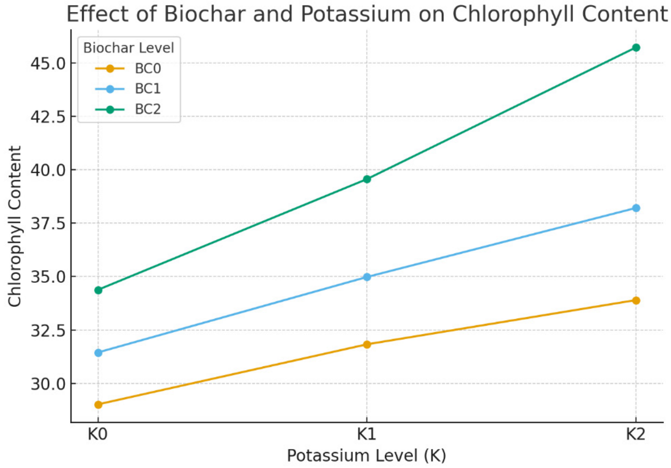

Figure 5: *Effect of biochar and potassium fertilization on chlorophyll content of leaves (Spad).*

To visualize this relationship, a 3D surface plot was constructed (Figure 5). The graph illustrates a consistent upward trend, demonstrating that the highest chlorophyll levels were achieved when both inputs were at their maximum tested levels (BC2 and K2). The surface's smooth gradient confirms the additive and interactional nature of the two factors. Notably, no diminishing returns were observed within the studied range, reinforcing the efficiency of integrated fertilization strategies.

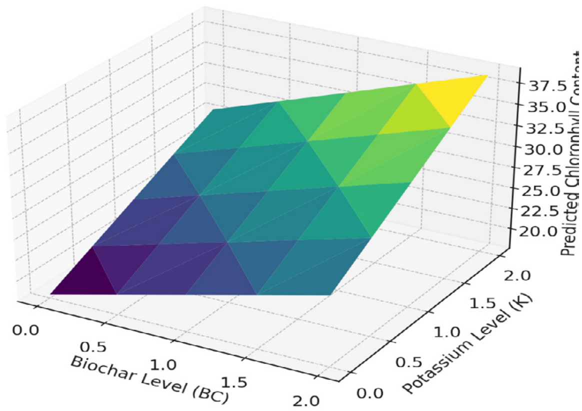

Figure 6: *3D effect of biochar and potassium fertilization on chlorophyll content of leaves (Spad).*

These findings suggest that coordinated use of organic (biochar) and inorganic (Potassium) sources can significantly enhance photosynthetic pigment concentration, which is closely associated with improved plant vigor and productivity.

Weight of 1000 grains

Figure 7 shows that increasing the levels of biochar application led to an increase in the weight of 1000 grains. Treatments BC2 and BC1 had significantly (p g plant- 1, respectively, while the lowest average of 31.58 g plant-1 was found for the control treatment BC0. The findings revealed that the higher potassium fertilizer, the heavier 1000-grain weight. The average maximum of treatment K2 was 39.28 g plant-1, significantly higher than that of the treatment K1 (34.88 g plant-1) and comparison treatment K0 (31.62 g plant-1), respectively.

Significant pots interaction between biochar and potassium fertilization was observed. The information clearly reveals that the 1000 grain weight was significantly increased. Treatment BC2K2 had a significant increment of 57.54%, and treatment BC2K1 showed an increase of 36.31% in comparison to the check treatment which produced the lowest mean of 29.02 g plant-1 for 1000-grain weight trait.

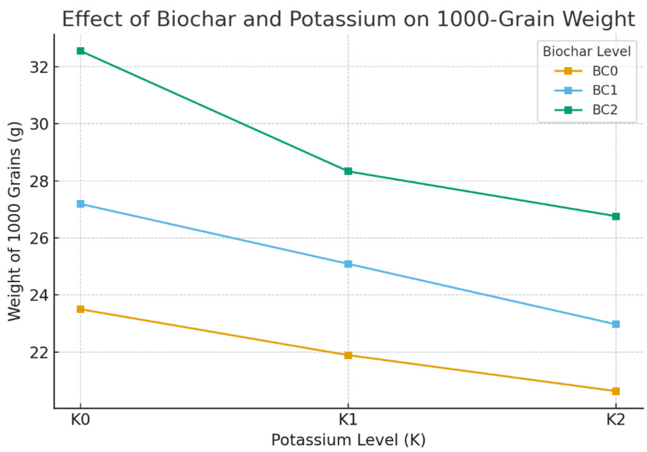

Figure 7: *Effect of biochar and potassium fertilization on weight of 1000 grains (g plant^{-1}).*

The Figures (1,3,4,5 and 7) show a significant increase in all studied plant traits: including plant height, leaf area, dry matter weight, chlorophyll content, and 1000-grain weight. The results clearly showed a significant response to the levels of biochar as organic fertilizer. This study's findings align with several recent studies (Adekiya *et al*., 2022; Pandit *et al*., 2018), which have indicated that the use of biochar can improve most crop characteristics, The role of biochar is to enhance the physical, chemical and biological properties of the soil, as well as to provide essential nutrients in plant-available forms, improve the plant's ability to absorb nutrients and promote vegetative growth (Jafaar and Abdulrasool, 2023; Jafaar *et al*., 2023).

The observed enhancements emphasize potassiums multiple roles in plant system physiology Besides enhancing enzymatic activities, and involved in metabolic pathways governing leaf initiation and expansion, it also helps to transport nutrients efficiently from roots to aboveground parts of the plants. This dual pathway provides increased photosynthetic capacity, partially through its contribution to raise leaf magnesium levels which along with nitrogen are essential for the synthesis of chlorophyll, Simultaneously, potassium enhances differentiation of chlorenchyma cells giving thicker and firmer stems that can sustain more biomass accumulation, At the reproductive stage higher availability of potassium leads to stronger partitioning into grains where it stimulates amino acid synthesis building block for proteins and thus improving nutritional quality of grain. These combined actions of potassium are in agreement with those reported from previous works (Singh, 2018; Al-Janabi *et al*., 2019; Pepo and Karancsi, 2017), highlighting its utmost importance in vegetative growth as well as quality of yield.

Table 3: *Effect of biochar and potassium fertilization on the available N, P and K in soil.*

	N			
Biochar (BC)	K0	K1	K2	Mean
BC0	35.28	37.46	39.93	37.55
BC1	36.83	39.79	42.23	39.61
BC2	38.05	43.34	48.92	43.43
K Mean	36.72	40.19	43.69	—
	P			
Biochar (BC)	K0	K1	K2	Mean
BC0	14.3	15.95	17.54	19.53
BC1	15.99	17.31	20.22	17.84
BC2	17.43	20.67	24.49	20.86
K Mean	15.9	17.97	20.75	—
	K			
Biochar (BC)	K0	K1	K2	Mean
BC0	188.09	193.12	200.57	193.92
BC1	194.11	210.48	221.97	208.85
BC2	204.21	226.44	242.58	224.41
K Mean	195.47	210.01	221.7	—

Effect of biochar and potassium fertilization on the available N, P and K in soil.

The results in Table 3 showed the effect of adding different levels of biochar and potassium fertilization on the concentration of macronutrients in the soil, It was found that there were significant differences between study treatments and an increase occurred in the concentrations of NPK in the soil, The concentration of 30 Mg ha^{-1} of biochar and potassium fertilization at the level of 120 kg ha^{-1} K fertilizer achieved the highest values of (48.92), (24.49) and (242.58) mg kg^{-1} for the concentration of nitrogen, phosphorus and potassium in the soil, respectively, Compared to the absence of addition, which recorded the lowest values for nutrient concentration, which was (35.28), (14.30) and (188.09) mg kg^{-1} for the concentration of nitrogen, phosphorus and potassium in the soil, respectively.

This increase is attributed to the significant effect of adding biochar, which agrees with Zhang *et al.* (2012), who reported that the application of biochar at rates of 20 and 40 tons per hectare significantly increased nitrogen concentration, According to Haider *et al.* (2017), biochar application enhanced mineral nitrogen concentration in the 0–15 cm soil layer, with no detectable effect at 15–30 cm, indicating that its large surface area and porosity contribute to improved nitrogen retention in the topsoil. Mahmoud *et al.* (2017) reported that biochar application increased phosphorus availability in soils, likely due to its role as a nutrient source and its capacity to reduce nutrient losses, although the effect may vary with soil type and environmental conditions.

The application of biochar affected available potassium The results are in accordance with El-Naggar *et al.* (2015), where available soil K was increased, and with long-term investigations by Major *et al.* (2010) and Khorram *et al.* (2019). The increase in available potassium may be due to the porous structure of biochar and its cation exchange capacity, thus increase nutrient retention and reduce leaching Akande *et al.*, (2025). Soil K responses to biochar in previous studies (Lentz and Ippolito, 2012) have varied; variability in soil K response likely would depend on feedstock source, pyrolysis conditions and other factors including soil properties as well as the context-dependent effect that biochar has on potassium availability. Biochar possesses a great capacity for adsorption, As well as the potential to decrease nutrients loss and enhance soil fertility (Gul *et al.* 2015).

The application of potassium fertilizer, particularly in the presence of nitrogen, contributed to rhizosphere acidification and subsequent changes in soil pH, thereby enhancing nutrient availability This agrees with the findings of (Jafaar and Abdulrasool, 2025). Increased potassium levels were associated with higher concentrations of phosphorus and potassium in the soil, while fertilization overall improved post-harvest N, P, and K availability by promoting greater nutrient uptake efficiency in plant roots (Al-Dulaimi, 2021; Al-Bayati *et al.*, 2021).

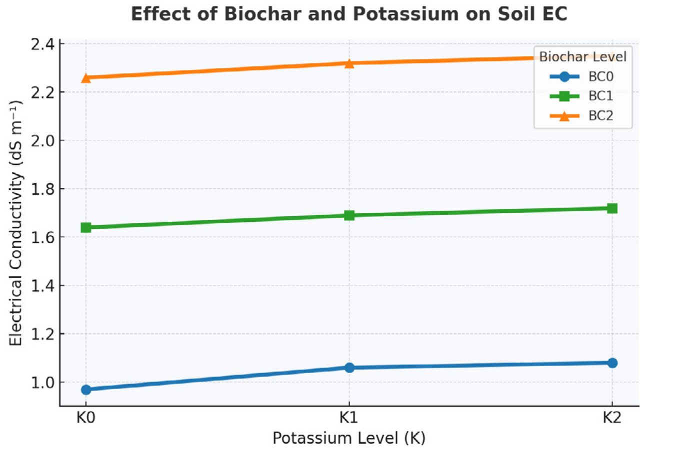

Figure 8: *Effect of biochar and potassium fertilization on EC in soil.*

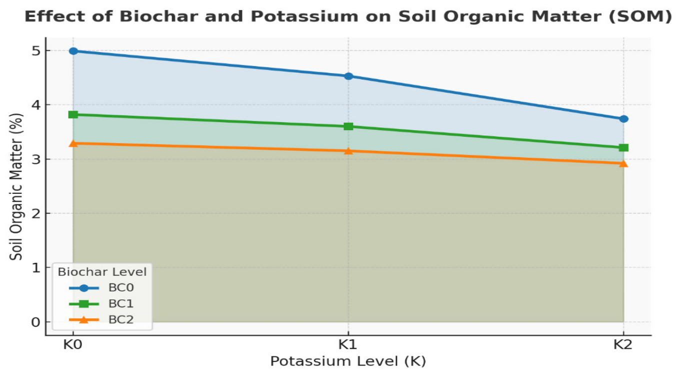

Figure 9: *Effect of biochar and potassium fertilization on SOM in soil.*

Effect of biochar and potassium fertilization on EC and OM in soil.

The data presented in Figures 8 and Figure 9 regarding the significant effect of two factors (biochar application and potassium fertilization), indicate that biochar alone significantly influenced soil electrical conductivity EC An increase in biochar level led to a decrease in soil EC values and recorded the lowest mean at 30 Mg ha^{-1} biochar (3.12 dS m^{-1}) compared with the control treatment which achieved (4.76 dS m^{-1}), Regarding soil organic matter (SOM), the 30 Mg ha^{-1} biochar treatment recorded 2.31 g kg^{-1} soil. In contrast, potassium fertilization alone did not affect soil organic matter but had a clear impact on soil EC, which increased EC at 120 kg ha^{-1} K fertilizer treatment reached (4.03 dS m^{-1}), compared with the control which was (2.94 dS m^{-1}). With respect to the interaction between biochar and potassium fertilization, the lowest mean EC value (2.92 dS m^{-1}) was recorded under 30 Mg ha^{-1} biochar + 0 kg ha^{-1} K fertilizer, while the treatment 0 Mg ha^{-1} biochar + 120 kg ha^{-1} K achieved the highest mean of soil EC values was (4.99 dS m^{-1}).

Relative to soil organic matter, the highest mean value (2.35 g kg^{-1} soil) was obtained from the treatment 30 Mg ha^{-1} biochar + 120 kg ha^{-1} K, which was not significantly different from 30 Mg ha^{-1} biochar + 60 kg ha^{-1} K (2.35 g kg^{-1} soil), In comparison, the control treatment exhibited the lowest soil organic matter content (0.97 g kg^{-1} soil).

Incremental additions of biochar have been shown to markedly decrease soil electrical conductivity EC through multiple mechanisms, including the enhancement of soil structural stability, improving of water-holding capacity, and the facilitation of excess salt leaching (Li *et al*., 2022). In addition, the rough microstructure of biochar with high porosity is also important for soil salinity mitigation through adsorption and fixing some amount of salts on the surface to reduce the ionic concentration in soil solution. This results in improving the physicochemical environment of soil. These findings are consistent with a previous study reported by El-Sayed *et al*. (2021) to validate that the favourable impact of biochar structure on its salinity stress mitigation could be positive. Also, Gu *et al*. (2023) also notice biochar's more significant role in addition to reduction of EC only – its impact on overall soil properties and potential future quality.

For SOM, the recorded increase is likely due to the favourable effect of biochar on specific physicochemical properties of soils and thus increasing their quality and functioning. This enhancement was consistent with the higher SOM concentration (Li *et al*., 2018). Similarly, Simarani *et al*. (2018) also concluded that the addition of biochar enhanced soil organic carbon content, showing a potential for long-term carbon storage. Additionally, the high organic matter included in biochar (41.29% OM, Table 2), may have also enhanced these values by stimulating microbial activity and accelerating organic matter decomposition (Li *et al*., 2021).

Conclusions and Recommendations

In the current investigation, biochar and K fertilizer application played a significant role in enhancing chemical properties of sandy loam soil leading to an increase in growth and yield performs wheat. Application of 30 Mg ha^{-1} biochar along with 120 kg K ha^{-1} significantly improved nutrient (N, P and K) availability, decreased soil salinity and increased soil organic matters which collectively led to increase in plant height, leaf area index, chlorophyll content, dry matter partitioning to ear head and 1000 grain weight. These results underline the scientific and practical significance of combined application of organic (biochar) and inorganic (potassium) amendments to improve soil fertility as well as a sustainable wheat production under sandy loam soil. Further experiments should further test the long-term effects of these amendments in different conditions and in varieties of soils, under various climatic conditions, as well as their potential commercialization for field-scale cultivation.

Novelty Statement

This study is novel in demonstrating the synergistic interaction between biochar and potassium fer-tilization in improving nutrient availability, reducing soil salinity, and enhancing wheat growth and yield in sandy loam soils under arid conditions.

Author's Contribution

Ameer Adnan Jafaar: Conceptualization, ex-perimental design, data analysis, and manuscript writing.
Zahraa Al-Mamouri: Field experimentation, data collection and laboratory analysis.
Ahmed F.M. Al-Enzy: Statistical analysis, interpretation of results, and manuscript revision.

Generative AI or AI assisted technology statement
The authors declare that no generative AI or AI-assisted technologies were used in the writing, analysis, or preparation of this manuscript.

Conflict of interest
The authors have no conflict of interest.

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