Journal of Pure and Applied Agriculture (2025) 10(2): 56-66
ISSN (Print) 2617-8672, ISSN (Online) 2617-8680
http://jpaa.aiou.edu.pk/

Effect of biochar coated potassium fertilizer on yield and nutritional value of maize

Mafia Bashir[1], Noor Us Sabah[1]* and Mukkram Ali Tahir[1]

[1]Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha (40100), Pakistan

*Corresponding author: Noor Us Sabah (soilscientist.uca@gmail.com)

Abstract

Potassium (K) plays a critical function in the production of maize because it is essential to several physiological and biochemical processes that increase crop resilience and yield. A pot experiment on impact of biochar coated K on maize production was conducted in research area of university of Sargodha. The experiment was conducted in triplicate and comprised of 11 treatments. T1= control, T2= KCI @ 50 kg ha^{-1}, T3 = K_2SO_4 @ 50 kg ha^{-1}, T4 = KCI @ 50 kg ha^{-1} + 1 % BCM, T5 = KCI @ 50 kg ha^{-1} + 2 % BCM, T6 = K_2SO_4 @ 50 kg ha^{-1} + 1 % BCM, T7= K_2SO_4 @ 50 kg ha^{-1}+ 2 % BCM, T8= KCI @ 25 kg ha^{-1} + 1 % BCM, T9= KCI @ 25 kg ha^{-1} + 2 % BCM, T10 = K_2SO_4 @ 25 kg ha^{-1} + 1 % BCM, T11= K_2SO_4 @ 25 kg ha^{-1} + 2 % BCM respectively. All treatments were applied two weeks after sowing. Results indicated that maximum K concentration was found where K was applied as K_2SO_4 @ 50 kg ha^{-1} + 2 % BCM. Thus, the mode of soil application of K had beneficial effect on nutritional composition of maize and yield.

Keywords: Biochar, Controlled-released fertilizer, Maize, Nutrition, Potassium, Sustainable agriculture, Yield

To cite this article: Bashir, M., Sabah, N. U., & Tahir, M. A. (2025). Effect of biochar coated potassium fertilizer on yield and nutritional value of maize. *Journal of Pure and Applied Agriculture, 10*(2), 56-66.

Introduction

Potassium (K) is considered a vital macronutrient required for agricultural output and plant growth. Potassium is required for assimilate transfer, enzyme activation, and photosynthesis, all of which enhance plant health and productivity. It serves as more than just a source of nutrients because it is vital to several physiological processes that enhance crop quality and output (Hasanuzzaman et al., 2018). Potassium influences the structural integrity and metabolic processes of seeds by facilitating the synthesis of proteins, carbohydrates, and cellulose. Furthermore, K considerably improves water use efficiency in plants. It is essential for regulating stomatal functioning, which influences transpiration and water retention. Hence, K helps maintain plant turgor and minimizes water loss during abiotic stressors like drought, making its regulation especially crucial. It adds to plant resilience against pests and diseases by increasing their general vigor, which is crucial for sustainable farming methods. K accumulation in crops is affected by a variety of factors, including soil type, crop variety, and management practices. According to studies, potassium is frequently the most accumulated macronutrient in many crops, followed by nitrogen in terms of uptake (Araujo et al., 2024). The use of K fertilizers is still essential in agricultural practices. Despite its significance, potassium is frequently applied at a lower rate than nitrogen (N) and phosphorus (P), which causes nutrient imbalances in soils (Han, 2024).

Maize (*Zea mays* L.) is a vital cereal crop globally, serving as a staple food, animal feed (Zia et al., 2023; Kekere et al., 2024). It acts as raw material in various industries due to its high nutritional and economic value (Ahmad & Ahmad, 2018; Rubab et al., 2020; Azam et al., 2023). Maize is highly adaptable to diverse climatic conditions, making it a key crop in both temperate and tropical regions. It is rich in carbohydrates and provides essential nutrients, playing a significant role in global food security (Abbas et al., 2025; Abdullah et al., 2025). Potassium is an essential macronutrient for maize growth, influencing physiological processes such as photosynthesis, enzyme activation, and water-use efficiency (Mehmood et al., 2022; Jamilah et al., 2024). Recent studies have explored the use of biochar-coated potassium fertilizers to enhance nutrient use efficiency, reduce leaching losses, and improve soil health (Shakeel et al., 2023). The biochar coating acts as a slow-release mechanism, ensuring a sustained supply of potassium throughout the growing season, which can significantly improve both yield and the nutritional quality of maize grains (Abid & Latif, 2023). Literature indicates that such innovative fertilization strategies not only boost crop productivity but also contribute to sustainable soil and nutrient management practices under varying environmental conditions (Latif & Abbas, 2025).

To improve K availability and uptake by crops, innovative ways have been investigated, such as the use of slow-release fertilizers, coated K fertilizers and the use of potassium silicate (Bartog et al., 2022). K fertilization in agriculture presents a number of difficulties, such as the high solubility of conventional K fertilizers, which can result in substantial nutrient loss and leaching, especially in soils with low organic matter or in areas with heavy rainfall. The extremely soluble nature of potassium chloride (KCl), the most widely used potassium fertilizer, allows it to flow quickly across the soil profile (Grzebisz et al., 2020). This trait may cause leaching, in which potassium is removed from the root zone and made unavailable for plant absorption (Nogueira et al., 2021). Furthermore, excessive KCl rates can raise the electrical conductivity of the soil, which can harm plant growth by osmotically stressing the roots and preventing them from absorbing nutrients and water (Urrutia et al., 2018). Alternative methods of fertilization have been suggested in order to overcome these difficulties. For example, the quick leaching linked to standard potassium fertilizers has been investigated using controlled-release fertilizers (KCl). Because these fertilizers are made to release potassium gradually, they increase nutrient availability over time and lower the chance of leaching (Licker et al., 2010).

The development of coated fertilizer technologies has significantly transformed agricultural practices, particularly through the introduction of controlled-release fertilizers (CRFs). These fertilizers are designed to release nutrients gradually over time, which aligns nutrient availability with plant uptake requirements. This synchronization is crucial for enhancing nutrient use efficiency and minimizing environmental impacts associated with nutrient leaching and volatilization (Ciampitti et al., 2013, Lee at al., 2025). For instance, stabilized slow-release nitrogen fertilizers can effectively reduce nitrogen losses, primarily through ammonia volatilization, while steadily providing nitrogen to plants. This gradual release mechanism not only improves nutrient availability but also raises questions about the efficiency of traditional nitrogen fertilizers that lack such technology. Furthermore, the coating materials used in CRFs must possess specific characteristics, such as biodegradability and appropriate permeability, to ensure that nutrients are released in a manner conducive to plant uptake without causing significant variations in fertilizer volume (Feyissaet al., 2022).

The utilization of biochar as a coating material for fertilizer granules has garnered significant attention in recent agricultural research, primarily due to its potential to enhance nutrient release patterns and improve soil health. Biochar, a stable carbon-rich product derived from the pyrolysis of biomass, has been shown to interact positively with various soil components, thereby influencing the availability of nutrients to crops (Niu et al., 2021). The inclusion of biochar into soil not only improves physical qualities but also adds to enhanced soil organic carbon levels, which is crucial for maintaining soil health and fertility. In agriculture, biochar-coated fertilizers are a novel method of managing nutrients. In addition to the agronomic benefits, the environmental implications of coated fertilizer technologies are significant. The use of controlled-release fertilizers can lead to reduced nutrient leaching into water bodies, thereby mitigating the risk of eutrophication of a major environmental concern associated with conventional fertilizer application practices (Anjali et al., 2025). (Joshi et al., 2020) illustrated that fast-release fertilizers while providing immediate nutrient availability, can also lead to substantial nutrient leaching, particularly in horticultural settings. In contrast, the controlled release offered by CRFs allows for a more sustainable approach to nutrient management, as it minimizes the potential for nutrient runoff and enhances the overall efficiency of fertilizer application (Kandil et al., 2020). By applying biochar to potassium fertilizers, nutrient leaching can be greatly decreased, increasing the effectiveness of nutrient release (Fernandes et al., 2018, Ma et al., 2025). By ensuring that nutrients are available to plants for a longer length of time, biochar-coated fertilizers' slow-release properties minimize environmental effects related to nutrient runoff and decrease the frequency of fertilizer applications (Fernandes et al., 2018). Additionally, by comprehending the ways in which biochar interacts with soil and nutrients, future research and development initiatives helping to maximize its application in diverse agricultural contexts can be informed. Therefore, a pot study was carried out to check the impact of biochar coated K fertilizer on growth and yield quality of maize and to screen out the best source and optimize the best K levels for growth of hybrid maize crop production.

Materials and Methods

A pot experiment was conducted in 2024 at research area, College of Agriculture, University of Sargodha, Sargodha, Punjab, Pakistan to assess the impact of potassium coated fertilizer with biochar on soil organic carbon and maize yield. There were 11 treatments replicated thrice using CRD design of experiment. Treatments include T1= control, T2= KCI @ 50 kg ha^{-1}, T3 = K_2SO_4 @ 50 kg ha^{-1}, T4 = KCI @ 50 kg ha^{-1} + 1 % BCM, T5 = KCI @ 50 kg ha^{-1} + 2 % BCM, T6 = K_2SO_4 @ 50 kg ha^{-1} + 1 % BCM, T7= K_2SO_4 @ 50 kg ha^{-1}+ 2 % BCM, T8= KCI @ 25 kg ha^{-1} + 1 % BCM, T9= KCI @ 25 kg ha^{-1} + 2 % BCM, T10 = K_2SO_4 @ 25 kg ha^{-1} + 1 % BCM, T11= K_2SO_4 @ 25 kg ha^{-1} + 2 % BCM respectively. Biochar commercially available in the market was used. Pots were filled with soil @ 10 kg pot^{-1}. Various physio-chemical properties of soil are provided in Table 1. Three seeds of maize (pioneer) were sown in each pot. After 45 days of germination plants were selected for the study to examine the effects of biochar-coated potassium and organic carbon on maize crop yield and production. Furthermore, weed and plant diseases were managed throughout the study using all available agronomic methods. Total, a, and b chlorophyll concentrations (SPAD), plant fresh and dry biomass (g), plant height (cm), stem diameter (mm) were among the physiological parameters that were examined after the treatments were administered for 60 days. Standard techniques were used to determine these parameters.

Table 1 Characteristics of original soil used for study

Parameter	Values
Saturation percentage (%)	29
pH_s	8.15
EC_e (dS m^{-1})	1.28
Bicarbonates (HCO_3^-) m mol L^{-1}	4.95
Chlorides (Cl^{-1}) m mol L^{-1}	4.80
Sulphates (SO_4^{2-}) m mol L^{-1}	3.05
Calcium + Magnesium (Ca^{2+}+ Mg^{2+}) m mol L^{-1}	4.81
Sodium (Na^+) m mol L^{-1}	7.41
Sodium adsorption ratio (SAR) (m mol L^{-1})$^{1/2}$	4.77
Texture	Sandy clay loam
Organic matter (%)	0.49
Calcium carbonates (%)	6.1
Available phosphorus/ Olsen P (mg kg^{-1})	8.0
Soil total P (g kg^{-1})	1.6

Plant analysis

Physiological parameters during the plant growth period, including plant fresh and dry biomass (g), plant height (cm), stem diameter (mm) and chlorophyll concentration (SPAD) were recorded. Standard methods described in handbook 60 of USDA were used to evaluate yield contributing attributes such as number of rows per cob, number of grains per cob, cob diameter, cob length, 1000 grain yield, and available K concentration in plant sample. For the purpose of study, the following common methods used were used to estimate the data for these parameters. After harvest plants were packed into polythene bags and shifted into lab for further analysis. For measuring plant height using simple measuring tape was used to measure plant height. After removing the grains from each cob, length (mm) of cob was measured by using Guage and cob diameter (mm) was measured by using digital vernier caliper having least count value (0.01 mm). The filtrate was diluted using distilled water in accordance with the specifications for K determination. Method 27a of Handbook 60 of U.S Salinity Laboratory Staff (1954) was used for K estimation. There were established working standards for K. The Sherwood 410 Flame photometer was used to measure the values of unknown samples after standards were run to create a standard curve and then diluted potassium filtrates. K concentration from given plant sample was measured and then compared with the amount of K fertilizer was applied. After that K use efficiency was calculated by using the following formula:

$$\text{K use efficiency} = \frac{\text{Shoot dry weight + Root dry weight}}{\text{K content in root + shoot}}$$

Statistical analysis

All the data were evaluated using the statistical program Statistix 10, and the differences between the treatment means were examined using the least significant difference (LSD) test at 0.05 P (Steel et al., 1997).

Results and Discussion

Plant height (cm)

K nutrition in terms of different levels and application methods had significant ($p \leq 0.05$) effect on average plant height of maize crop. Although all levels and application methods of K increased average plant height of maize crop but highest improvement was found with higher level where K was applied as K_2SO_4 @ 50 kg + 2% BCM application with a value of 210 cm. The shortest plant height was observed in control where no K source was applied with recorded value of 150 cm. When comparing the individual effect of soil application, greater average plant stem was recorded (Fig. 1). Overall means of eleven treatments indicated that average plant available K improved by 33.0% with K_2SO_4 @ 50 kg + 2% BCM, as compared to the control.

Number of rows per cob

Overall treatments indicated that average number of cobs improved by 20.0 % with K_2SO_4 @ 50 kg + 2 % BCM, as compared to the control. The effect of K nutrition was found statistically significant ($p \leq 0.05$) with respect to average number of cobs of maize crop. Average numbers of rows per cob of maize crop increased significantly in all treatments compared to control but highest improvement was found with higher level in where K was applied as K_2SO_4 @ 50 kg + 2 % BCM application (Fig. 2).

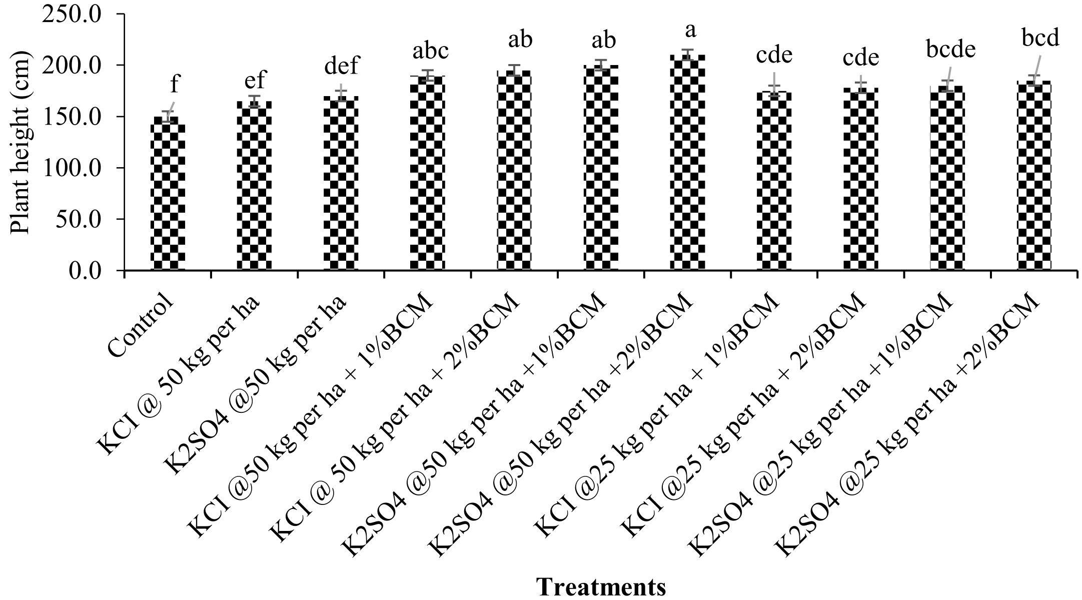

Fig. 1 Plant height (cm) of maize grown in pot experiment by supplying different levels of biochar coated potassium

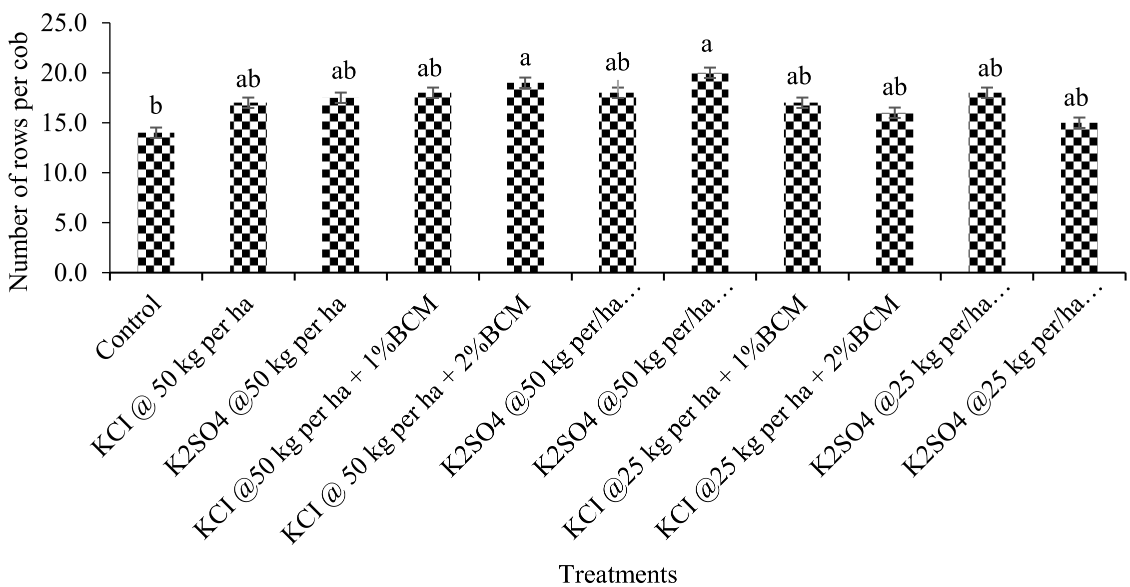

Fig. 2 Number of rows per cob of maize grown in pot experiment by supplying different levels of biochar coated potassium

Numbers of grains per row per cobs

Effect of different K nutrition sources, levels and application methods on number of grains per cob is depicted in Fig. 3. Data reflected that both K nutrition sources had significant ($p \leq 0.05$) effect on average number of grains of maize crop. Although, all levels and application methods of K increased average numbers of grains of maize crop but highest improvement was found with higher level in where K was applied @ K_2SO_4 @ 50 kg + 2 % BCM application pattern. Regarding the individual effect of soil application, greater average numbers of grains per row were recorded in case of soil application (Fig. 3). Overall means of eleven treatments indicated that average number of grains was improved by 35 with K_2SO_4 @ 50 kg + 2 % BCM, as compared to the control.

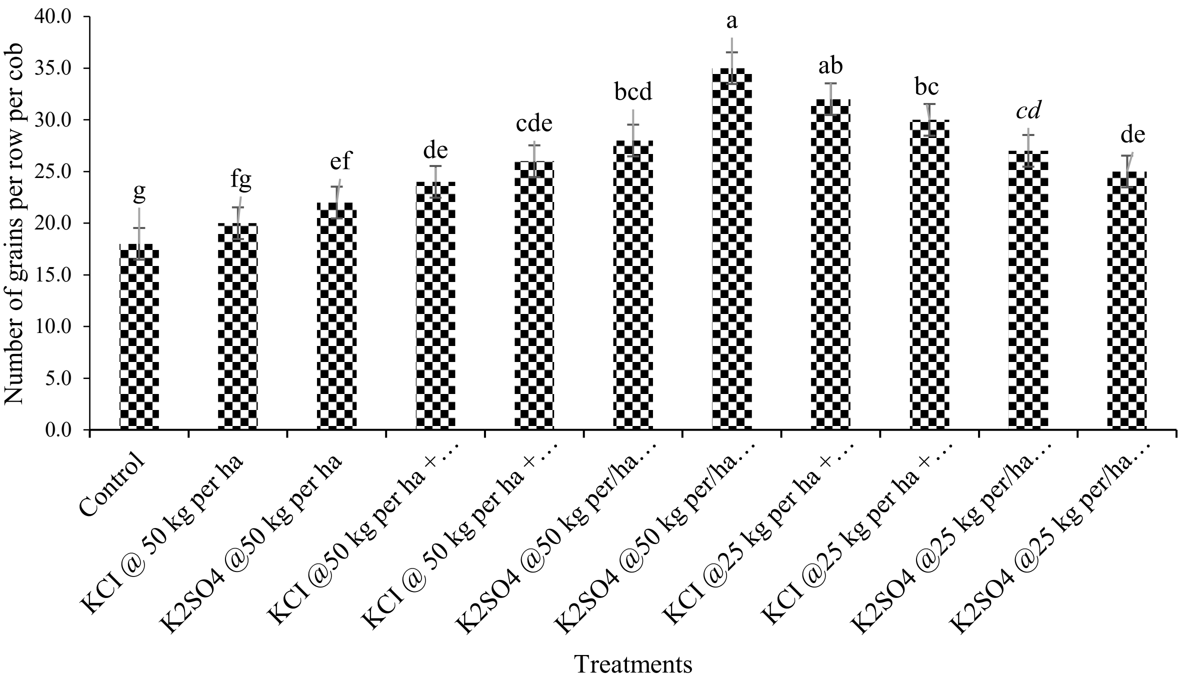

Fig. 3 Number of grains per row per cob of maize grown in pot experiment by supplying different levels of biochar coated potassium

Cob length (cm)

Data regarding average cob length as affected by different nutrition sources of potassium with different levels and application methods presented in Fig. 4. It was noticed that average cob length was improved by 21.0 % with K_2SO_4 @ 50 kg + 2 % BCM, as compared to the control. K nutrition in terms of different levels and application methods had significant ($p \leq 0.05$) effect on average cobs length of maize crop. All treatments with K nutrition sources improved the average cob length compared to control, but maximum improvement was obtained where K was applied as K_2SO_4 @ 50 kg + 2 % BCM. When comparing the individual effect of soil application, increased average cobs length was recorded significantly (Fig. 4).

Plant available K (ppm)

Impact of different sources of potassium (K_2SO_4 and KCl) with and without BCM and at different levels significantly affected the average plant available K content. Different levels and application methods of all sources of potassium had significant ($p \leq 0.05$) effect on average plant available K of maize crop. Minimum plant available K content was achieved in control that was improved by 0.9 % with the application of K_2SO_4 @ 50 kg + 2 % BCM. Comparing sources of potassium, sulphate of potash (K_2SO_4) performed better than muriate of potash (KCl) with regard to improvement in plant available K content in soil (Fig. 5).

Average shoot K (ppm)

Data pertaining to average potassium concentration in shoot of maize as affected by different nutrition sources of potassium with different levels and application methods in presented in Fig. 6. It was noticed that K nutritional sources applied at different levels and application methods had significant ($p \leq 0.05$) effect on average shoot K of maize crop. All sources, doses and application methods enhanced the average shoot K of maize crop but highest improvement was found with higher level where K was applied as K_2SO_4 @ 50 kg + 2 % BCM application. Highest noted average shoot K was improved by 1.2 % with the application of K_2SO_4 @ 50 kg + 2 % BCM, as compared to the control.

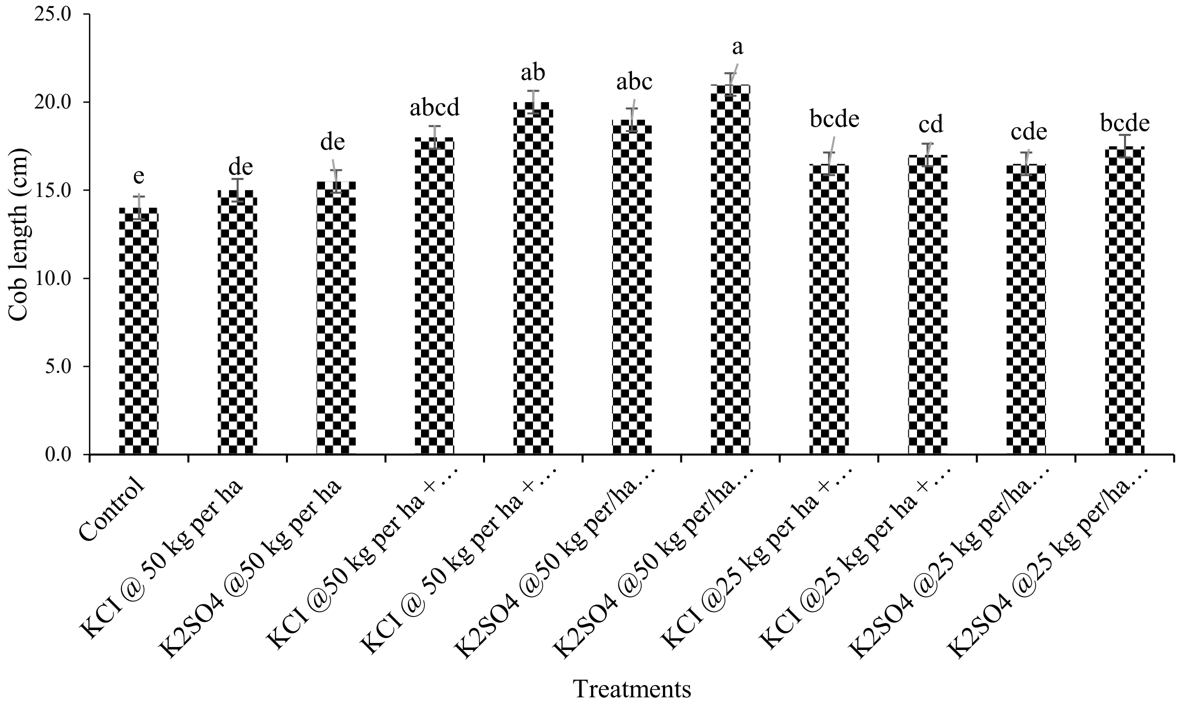

Fig. 4 Average cob length of maize grown in pot experiment by supplying different levels of biochar coated potassium

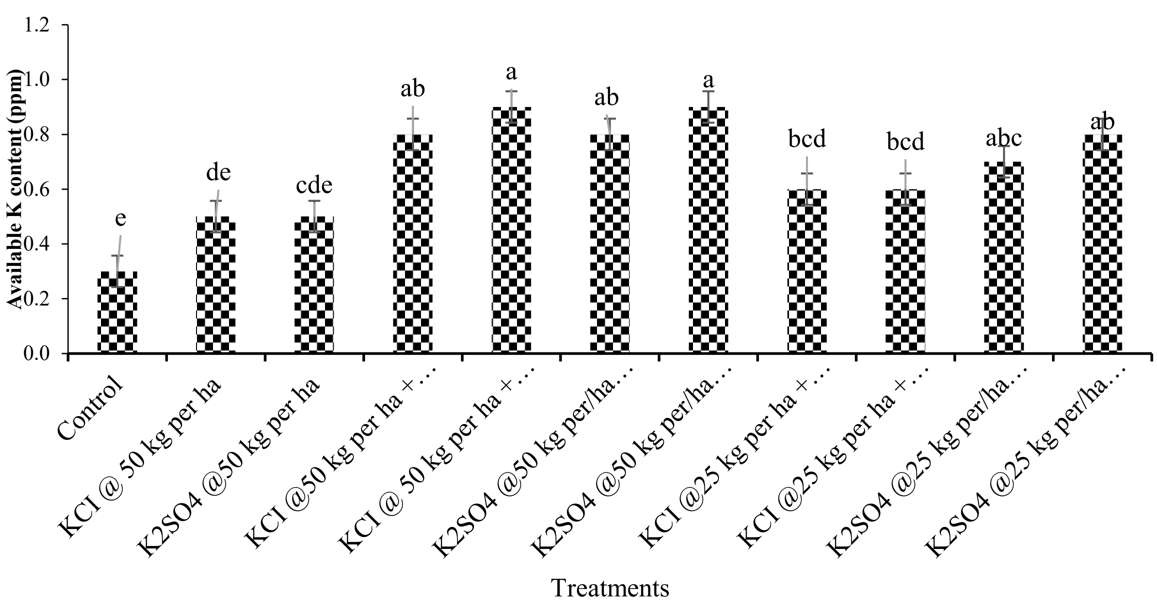

Fig. 5 Plant available K of maize grown in pot experiment by supplying different levels of biochar coated potassium

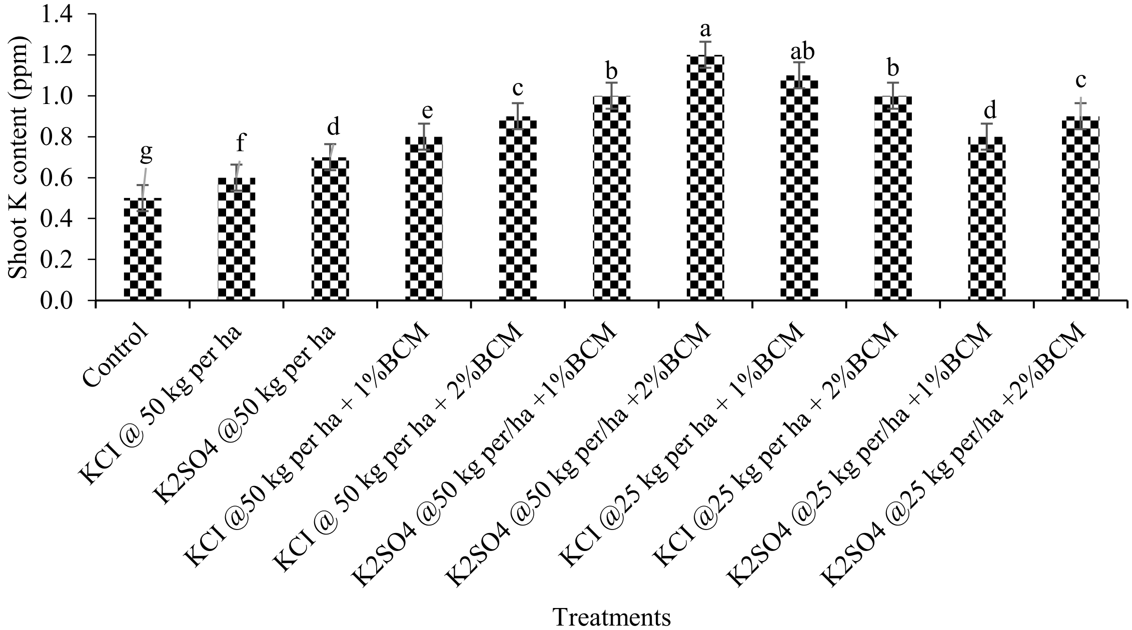

Fig. 6 Shoot available K of maize grown in pot experiment by supplying different levels of biochar coated potassium

Average root K (ppm)

Fig. 7 indicated the effect of different sources of potassium (K_2SO_4 and KCl), with and without biochar coating applied at different rates (1 and 2 %), on average K content of roots in maize. It was found that different levels and application methods had significant ($p \leq 0.05$) effect on average plant available root K of maize crop. All levels and application methods of K increased average plant root K of maize crop but highest improvement was found with higher level in where K was applied as K_2SO_4 @ 50 kg + 2% BCM application. Maximum average root K content was improved by 1.1 % in pots receiving K_2SO_4 @ 50 kg along with 2% BCM, as compared to all other treatments indicated the superiority of potassium sulphate compared to muriate of potash (KCl).

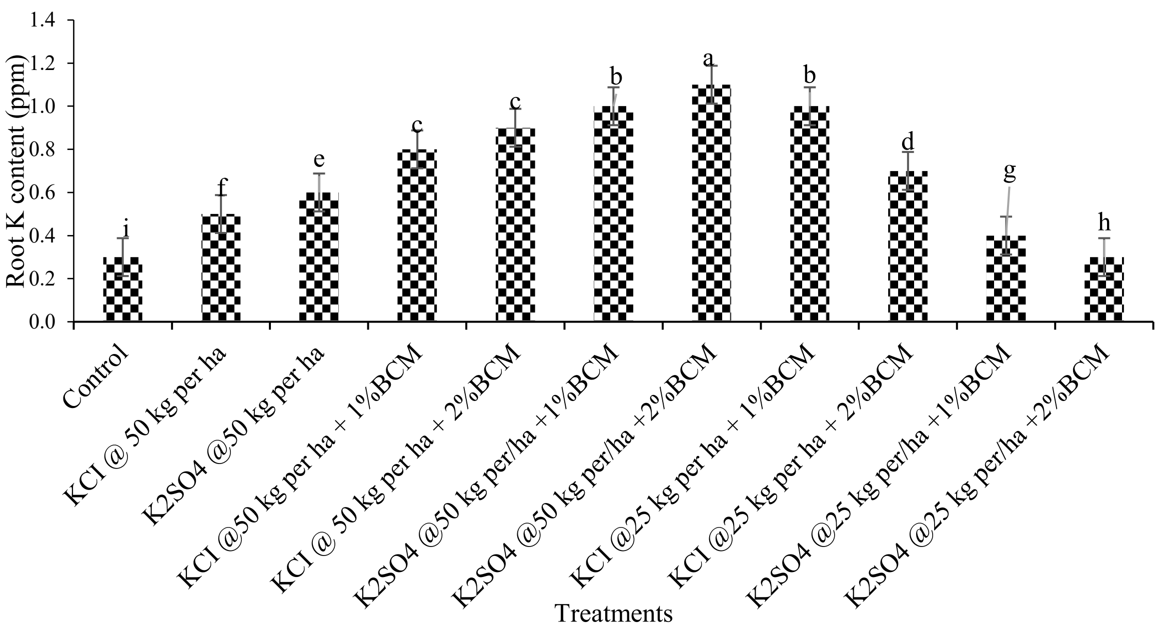

Fig. 7 Root available K of maize grown in pot experiment by supplying different levels of biochar coated potassium

K use efficiency

Data regarding impact of different sources of potassium (K_2SO_4 and KCl) with and without BC and at different levels on K use efficiency is plotted in Fig. 8. It was found that all treatments significantly affected the K use efficiency. Different levels and application methods of all sources of potassium had significant ($p \leq 0.05$) effect on K use efficiency. K use efficiency was improved by 122.6 % with the application of K_2SO_4 @ 50 kg + 2 % BCM. Comparing sources of potassium, sulphate of potash (K_2SO_4) performed better than muriate of potash (KCl) with regard to improvement in K use efficiency.

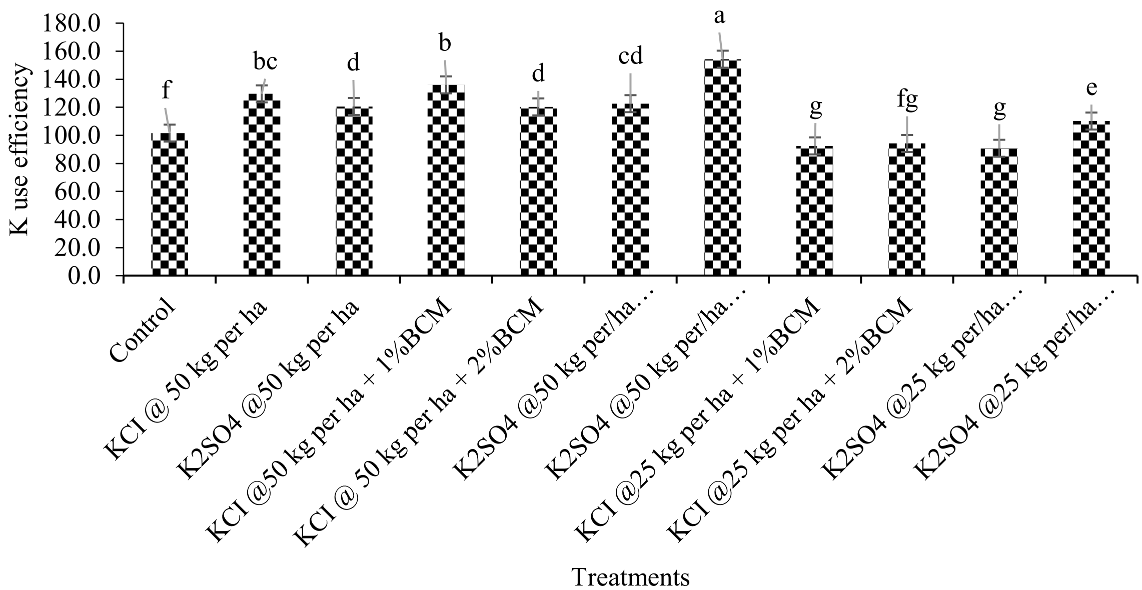

Fig. 8 Plant K use efficiency of maize grown in pot experiment by supplying different levels of biochar coated potassium

Discussion

For getting higher maize production, utilization of balanced NPK fertilizers in accordance with soil and crop demand along with progressive cultural techniques is essential. In order to achieve better growth and yield of maize, balanced nutrition is crucial. Plant growth and development depend on supply of nutrients (including K) in balanced forms. Chemical fertilizers application can boost crop yield by more than 50 % but there are several problems associated with their application like heavy cost, low use efficiency and environmental losses (Randhawa & Arora, 2000). Potassium is compulsory for achieving higher yields in crops. There is a widespread insufficiency of K prevailing in Pakistan now a day. Commercial application of K sources (K_2SO_4 and KCl) is applied to overcome this deficiency but due to severe losses these sources have low use efficiency. In order to improve plant available K content in growth medium, several coating agents are being used (Hafeez et al., 2024). One such material is biochar. Biochar (BC), a carbon-rich material, using pyrolysis in low oxygen conditions, is created from a variety of natural waste resources, such as municipal solid waste, industrial byproducts, agricultural waste, and forest waste (Ponnusamy et al., 2020).

By increasing crop yield, the low-cost technology product BC increases agricultural economic returns when applied to soil. Adding BC to soil enhances soil aeration and water retention, which improves the root growth environment for plants. Additionally, its porous structure facilitates greater drainage and root penetration (Hossain et al., 2020). Because of its high cation exchange capacity (CEC), BC increases agricultural productivity by reducing nutrient loss, retaining critical nutrients in the soil, and making them more available to plants. Similarly, BC alters microbial community structures, soil enzymatic activities, and most of the physio-chemical properties of the soil, all of which contribute to the improvement of soil health and quality (Jeffery et al., 2017). It has also been demonstrated that combining it with compost increases wheat crop production and growth. Furthermore, chlorophyll content, chlorophyll fluorescence, and photosynthetic activities have significantly boosted in plants when BC is combined with inorganic nitrogen fertilizer (Bebeley et al., 2021).

Results of present study revealed that maize growth (plant height, stem diameter, 1000 grain weight) and nutritional value in terms of K content (in plant roots and shoots) improved substantially when biochar coated K fertilizers were applied. Highest plant height, stem diameter, dry biomass, number of rows per cob and number of grains per rows were observed in pots where potassium sulphate was used 50 kg ha^{-1} along with 2 % biochar. Improvement in plant growth parameters could be due to application of biochar coated K fertilizers. Such an improvement in growth could be due to application of coating of K fertilizers with biochar at higher rates. Similar findings were reported by Hafeez at al. (2024) and Rahman et al. (2025) reflecting that application of biochar coated K fertilizers improved growth and yield of maize.

Numerous other studies have demonstrated that biochar application either applied alone or in conjunction with inorganic fertilizers, can greatly enhance crop growth or yield as well as the fertility of the soil (Zhao et al., 2025; Rodrigues et al., 2025). Such an improvement in growth and yield can be attributed to application of coated K. K, which is necessary for the growth and development of plants. The transport of photosynthetic products, ion balance, osmoregulation, and enzyme activation are only a few of the basic physiological functions in which K are involved. Crop quality and productivity are determined by adequate K supply and efficient K utilization, which also increases crop resistance to biotic and abiotic stressors. Enzyme stimulation, photosynthesis, osmotic pressure regulation, stomata movement, protein synthesis, phloem transport, energy transfer, cation-anion balance in soil, and enhanced stress resistance are all significantly impacted by potassium (Marschner, 2012). To improve K availability and uptake by crops, innovative ways have been investigated, such as the use of slow-release fertilizers, K coated material and use of potassium silicate. Coating of biochar on K fertilizer reduced the losses of K thereby improved the uptake by maize plants and subsequent K content of maize plant (Barłóg et al., 2022).

Conclusion

Based on findings of present study, it can be concluded that application of K improved the growth and yield of maize regardless of its source, dose and application method. However, application of K in form of K_2SO_4 performed better and improved K content in maize plant parts and soil. Best results were observed where K was applied @ K_2SO_4 @ 50 kg ha^{-1} along with 2 % BCM. Thus, biochar coated K_2SO_4 and KCl is better than sole use of these fertilizers for maize growth and nutritional status in soil. Regarding source, K_2SO_4 is better source of K than KCl in alkaline soil conditions.

References

Abbas, R., Hussain, I., Baloch, M. S., Saddozai, U. K., Khan, A. A., Khan, B., & Khan, R. (2025). Allelopathic effect of *Moringa oleifera* on germination and physiology of seedlings in maize (*Zea mays* L.). *Journal of Plant Production and Sustainability, 1*(1), 61–69.

Abdullah, Zia, M. A., Shoukat, S., Aziz, S., Khan, I. U., Khan, A., Maab, H., & Zaib, S. (2025). Co-expression of *ZmVPP1*, *ZmNAC111*, and *ZmTIP1* confers enhanced drought tolerance in maize (*Zea mays*). *Journal of Plant Production and Sustainability*, *1*(1), 12–19.

Abid, A. A., & Latif, A. (2023). Production and physico-chemical properties of biochar and its impact on phosphorous release for soil improvement: A review. *Advances in Agriculture and Biology, 6*(1), 17-27. https://doi.org/10.63072/aab.23003

Adekiya, A. O., Olaniran, A. F., Adenusi, T. T., Aremu, C., Ejue, W. S., Iranloye, Y. M., & Olayanju, A. (2020). Effects of cow dung and wood biochars and green manure on soil fertility and tiger nut (*Cyperus esculentus* L.) performance on a savanna Alfisol. *Scientific Reports*, *10*(1), 21021.

Ahmad, M., & Ahmad, S. (2018). Evaluation of insect pest infestation and yield losses in maize crop in Maina, district Malakand. *Advances in Agriculture and Biology, 1*(1), 34-39. https://doi.org/10.63072/aab.18005

Anjali, M. V., Jayadeva, H. M., Sannagoudar, M. S., Somashekharappa, P. R., Kurdekar, A. K., Rajanna, G. A., ... & Harish, M. N. (2025). Synthesis and characterization of nano potassium from green biomass and its impact on the growth, yield, and profitability of maize. *Discover Applied Sciences*, *7*(9), 1-16.

Araujo, N. M. P., Berni, P., Zandoná, L. R., de Toledo, N. M. V., da Silva, P. P. M., de Toledo, A. A., & Junior, M. R. M. (2024). Potential of Brazilian berries in developing innovative, healthy, and sustainable food products. *Sustainable Food Technology*, *2*(3), 506-530.

Azam, M., Saeed, B., Khan, S., & Zafar, D. (2023). Exploring the effect of nitrogen levels on yield and yield attributes of diverse open-pollinated varieties (OPVs) of maize (*Zea mays*). *Advances in Agriculture and Biology, 6*(1), 61-68. https://doi.org/10.63072/aab.23008

Barłóg, P., Grzebisz, W., & Łukowiak, R. (2022). Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. *Plants*, *11*(14), 1855.

Bebeley, H. A., Mabey, P. T., & Norman, P. E. (2021). Effects of biochar, plant density and spacing on growth and yield of rice in a tropical inland valley swamp. *International Journal of Applied Agricultural Sciences, 7*, 77-83.

Bin Yousaf, M. T., Nawaz, M. F., Yasin, G., Cheng, H., Ahmed, I., Gul, S., & Ur Rahman, S. (2022). Determining the appropriate level of farmyard manure biochar application in saline soils for three selected farm tree species. *Plos one*, *17*(4), e0265005.

Ciampitti, I. A., Murrell, S. T., Camberato, J. J., Tuinstra, M., Xia, Y., Friedemann, P., &Vyn, T. J. (2013). Physiological dynamics of maize nitrogen uptake and partitioning in response to plant density and N stress factors: I. Vegetative phase. *Crop Science*, *53*(5), 2105-2119.

Fernandes, J. D., Chaves, L. H. G., Mendes, J. D. S., Chaves, I. D. B., & Tito, G. A. (2018). Soil chemical amendments and the macronutrients mobility evaluation in Oxisol treated with biochar. *The Journal of Agricultural Science*, *10*(10), 238-247.

Feyissa, T., Zhao, S., Ma, H., Duan, Z., & Zhang, W. (2022). Optimizing plant density and balancing NPK inputs in combination with innovative fertilizer product for sustainable maize production in North China Plain. *Scientific Reports*, *12*(1), 10279.

Gao, L., Wang, R., Shen, G., Zhang, J., Meng, G., & Zhang, J. (2017). Effects of biochar on nutrients and the microbial community structure of tobacco-planting soils. *Journal of Soil Science and Plant Nutrition*, *17*(4), 884-896.

Grzebisz, W., Łukowiak, R., & Kotnis, K. (2020). Evaluation of nitrogen fertilization systems based on the in-season variability in the nitrogenous growth factor and soil fertility factors a case of winter oilseed rape (*Brassica napus* L.). *Agronomy*, *10*(11), 1701.

Guo, ZiFeng, G. Z., Chen DiJun, C. D., & Schnurbusch, T. (2018). Plant and floret growth at distinct developmental stages during the stem elongation phase in wheat. *Frontier in Plant Science*, *9*, 330. https://doi.org/10.3389/fpls.2018.00330

Hafeez, M., Tahir, M. A., Noorka, I. R., Sabah, N., Sarwar, G., & Gul, S. (2024). Carbon-sequestering fertilizers usage to boost potassium efficiency in wheat growth under saline conditions. *SABRAO Journal of Breeding and Genetics*, *56*(2), 628-640.

Han, G. Z., Fan, H. Z., Han, B. S., Huang, L. M., Cao, X. M., & Yang, F. (2024). Paddy management controls potassium release from minerals in purple soils after 40 years of cultivation. *European Journal of Soil Science*, *75*(3), e13492.

Hasanuzzaman, M., Bhuyan, M. H. M. B., Nahar, K., Hossain, M. S., Al Mahmud, J., Hossen, M. S., Masud, A. A. C., Moumita, & Fujita, M. (2018). Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy, 8*(3), 31. https://doi.org/10.3390/agronomy8030031

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., ... & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*, 379-420.

Jamilah, Suryani, I., Thesiwati, A. S., & Diyanti, A. (2024). Addition of urea fertilizer to crocober plus liquid organic fertilizer improves growth and yield of corn plants (*Zea mays* L.). *Advances in Agriculture and Biology, 7*(1), 1-7. https://doi.org/10.63072/aab.24001

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, *12*(5), 053001.

Joshi, N., Chandrashekara, C. P., & Potdar, M. P. (2020). Influence of precision nutrient management on yield and yield components and dry matter partitioning in maize hybrids. *Journal of Pharmacognosy and Phytochemistry, 9*, 1270-77.

Kandil, E. E., Abdelsalam, N. R., Mansour, M. A., Ali, H. M., & Siddiqui, M. H. (2020). Potentials of organic manure and potassium forms on maize (*Zea mays* L.) growth and production. *Scientific Reports*, *10*(1), 8752.

Kekere, O., Adeleke, G. P., Ajayi, O. M., Bulu, Y. I., Ekundayo, T. O., & Akinbuwa, O. (2024). Assessing the effect of carbide waste-contaminated soil on the growth and yield of maize (*Zea mays* L.). *Advances in Agriculture and Biology, 7*(1), 50-57. https://doi.org/10.63072/aab.24006

Kraska, P., Oleszczuk, P., Andruszczak, S., Kwiecińska-Poppe, E., Różyło, K., Pałys, E., & Michałojć, Z. (2016). Effect of various biochar rates on winter rye yield and the concentration of available nutrients in the soil. *Plant, Soil and Environment*, *62*(11), 483-489.

Latif, A., & Abbas, A. (2025). Soil management practices improve physical properties of soil, movement of water within the soil and yield of crops: A review. *Journal of Plant Production and Sustainability, 1*(2), 85–93.

Lee, J. H., & Ku, H. H. (2025). Optimizing nitrogen use efficiency and reducing nutrient losses in maize using controlled-release coated fertilizers. *Agrochemicals*, *4*(3), 10.

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., & Ramankutty, N. (2010). Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global Ecology and Biogeography*, *19*(6), 769-782.

Ma, S., Zhu, Q., Zhang, S., & Zhen, J. (2025). Biochar-composite methyl cellulose-coated slow-release materials for amelioration of soda saline soils. *Journal of Environmental Chemical Engineering, 13*(2), 116003.

Marschner, P. M. (2012). Mineral Nutrition of Higher Plants. 3rd ed. Academic Press; London, UK: 178–189.

Mehmood, K., Nasreen, S., Latif, A., & Shah, A. N. (2022). Growth of maize is improved by the combined use of natural and synthetic nutritional sources of potassium: A review. *Advances in Agriculture and Biology, 5*(1), 8-15. https://doi.org/10.63072/aab.22002

Niu, J., Zhang, W., Chen, X., Li, C., Zhang, F., Jiang, L., & Imas, P. (2011). Potassium fertilization on maize under different production practices in the North China Plain. *Agronomy, 103*(3), 822-829.

Nogueira, T. A. R., Miranda, B. G., Jalal, A., Lessa, L. G. F., Filho, M. C. M. T., Marcante, N. C., ... & Martins, É. D. S. (2021). Nepheline syenite and phonolite as alternative potassium sources for maize. *Agron.*, *11*(7), 1385.

Ponnusamy, V. K., Nagappan, S., Bhosale, R. R., Lay, C. H., Nguyen, D. D., Pugazhendhi, A & Kumar, G. (2020). Review on sustainable production of biochar through hydrothermal liquefaction: Physico-chemical properties and applications. *Bioresource Technology*, *310*, 123414.

Rahman, S. U., Han, J. C., Yasin, G., Imtiaz, M. T., Zhao, X., Alharbi, S. A., ... & Alarfaj, A. A. (2025). Synergetic effects of potassium and biochar on morphological, physiological, and biochemical attributes of maize crop grown under different levels of drought stress. *BMC Plant Biology*, *25*(1), 402.

Randhawa, P. S., & Arora, C. L. (2000). Phosphorus-sulphur interaction effects on dry matter yield and nutrient uptake by wheat. *Indian Journal of Soil Science*, *48*(3), 536-540.

Rodrigues, G. N. T. S., Silva, C. A., & Morais, E. G. D. (2025). Agronomic effectiveness of biochar–kcl composites for corn cultivation in tropical soils. *Soil Systems*, *9*(2), 45. https://doi.org/10.3390/soilsystems9020045

Rubab, S., Fayyaz, S., & Asmatullah. (2020). Plant parasitic nematodes associated with wheat and maize. *Advances in Agriculture and Biology, 3*(1), 8-17. https://doi.org/10.63072/aab.20002

Shakeel, M., Mehmood, K., Hayat, R., & Malik, K. (2023). Effect of biochar-based rhizobium biofertilizer on groundnut production. *Advances in Agriculture and Biology,* *6*(1), 47-53. https://doi.org/10.63072/aab.23006

Steel, R. G. D., Torrie, J. H., & Dickey, D. A. (1997). *Principles and procedures of statistics: A biometrical approach* (3rd ed.). New York, NY: McGraw-Hill.

U.S. Salinity Laboratory Staff. (1954). Diagnosis and Improvements of saline and alkali soils. Handbook No. 60. USDA. U.S. Govt. Printing Office, Washington, DC, USA.

Urrutia, O., Erro, J., Zabini, A., Hoshiba, K., Blandin, A. F., Baigorri, R., & García-Mina, J. M. (2018). New amphiphilic composite for preparing efficient coated potassium-fertilizers for top-dressing fertilization of annual crops. *Journal of Agricultural and Food Chemistry, 66*(19), 4787-4799.

Wu, M., Cheng, Y., Dong, C., Zhao, X., Wang, Z., Xiang, H., ... & Yu, B. (2025). Slow-release urea fertilizer with polymer and biochar-based organic coatings: Design, field trials and global economic implications. *Industrial Crops and Products*, *235*, 121738.

Zhao, X., Lu, J., Jiang, S., Fu, C., Li, Y., Xiang, H., ... & Yu, B. (2025). Enhancing slow-release performance of biochar-based fertilizers with kaolinite-infused polyvinyl alcohol/starch coating: From fertilizer development to field application. *International Journal of Biological Macromolecules*, *302*, 140665.

Zia, M. A., Shoukat, S., Arif, M., Ahmad, B., Nawaz, A. F., Bahadur, A., Zakria, M., Khan, H. S., Khan, S., Suleman, M., & Ali, S. (2023). A discussion on maize transformation during the last two decades (2002–2022): An update on present trends and future prospects. *Advances in Agriculture and Biology, 6*(1), 1-10. https://doi.org/10.63072/aab.23001