Potassium Dynamic, Soil Chemical Properties, and Nutrients Uptake by Barley (*Hordeum vulgare L.*) in Loamy Sand Soil Amended with Banana Pseudostem Biochar

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ABSTRACT: In a pot experiment followed a randomized completely block design with three replications, the effect of banana pseudostem biochar on potassium quantity/intensity (Q/I) parameters, soil chemical properties, and barely growth and nutritional statue in loamy sand soil was investigated. The biochar was applied to soil at three levels included 0% (control treatment), 0.5% (B1), 1% (B2), and B3 (2%). Barely grains were planted, after harvest each soil treatment was analyzed for potassium forms, some chemical properties (pH, salinity, organic matter content, total nitrogen, available phosphorus) and potassium Q/I parameters. The plants were analyzed for nutrients (nitrogen, phosphorus, potassium) content and nutrients uptake was calculated. The results showed significant improvement in soil organic matter content, total nitrogen, and soil available phosphorus. The potassium forms (water soluble K, exchangeable K, HNO_3-extractable K, and non-exchangeable K) increased significantly with application of biochar compared to control soil. Also, significant increases resulted in the soil potential buffering capacity of K (PBC^k), potassium activity ratio in soil at equilibrium (AR_e^k), and the labile K pool ($-\Delta K^o$) with addition of biochar to the studied soil. Fresh and dry weights, NPK contents and uptakes by barely plants enhanced significantly with biochar application. Therefore, the biochar produced from banana tree waste is beneficial tool for long-term carbon sequestration, enhancing soil fertility and plant health. The banana pseudostem biochar application can be an effective way for enhancing soil potassium availability, replenishment and storage, which could lessen the demand for synthetic chemical K fertilizers and promote sustainable agriculture techniques.

Key words: Banana waste, Potassium buffering capacity, quantity/intensity ratio, Agricultural waste management, Sustainable agricultural production.

INTRODUCTION

Potassium (K) is one of the essential nutrients that plants need. In addition to being a component of plant structure, potassium also regulates a number of biochemical processes associated with enzyme activation, protein synthesis, stress tolerance, and glucose metabolism (Lu et al., 2024). K is essential for a number of physiological functions, including photosynthesis and stomatal regulation (Ladikou et al., 2025). Although most soils have substantial total K reserves, only a small amount of them are readily or gradually available for plant uptake (Azadi et al., 2022). Soil solution K is directly available for plant uptake and usually constitutes 0.1 to 2% of the total soil K. Exchangeable K is held on the surfaces of clay and organic matter by electrostatic forces, it is readily available to plants but only makes up around 1-2% of the total soil K (Bell et al., 2021). These two forms of K are readily available for plant. The non-exchangeable K is slowly available to plant, it is retained between clay layers and organic matter, it slowly transforms into more accessible forms of K over time. Non-exchangeable K also represents about 1-10% of the total soil potassium. The major portion of soil K (about 90–98%) is found in mineral formations like micas and feldspars, which are not readily available unless they have weathered over an extended period of time (Bell et al., 2021). Thus, the combination of intensive agriculture and insufficient soil K replenishment through conventional inorganic fertilization leads to the gradual exhaustion of various K reserves in soils (Das et al., 2022). The majority of the soils in Egypt that are suitable for agricultural growth are desert soils with a coarse texture that are poor in necessary nutrients for plants, especially potassium. The chemical fertilizers overuse and incorrect agricultural practices have a negative impact on health of soil, plants, animals and humans (Pahalvi et al., 2021). And one of the objectives of sustainable agriculture is to find an alternative method to lessen the need of chemical fertilizers in these soils (Negim et al., 2024). Utilizing agricultural waste to improve soil fertility and reduce the amount of added chemical fertilizers is sustainable tool improves soil quality and reduces the negative environmental impact resulting from the accumulation of this waste or burning it in the air (Lavagi et al., 2024). Recently, a lot of wastes have been produced by agricultural activities; to benefit from these wastes in various environmental and economic aspects, we had to recycle it (Sharma et al., 2019). Converting of the agricultural waste to plant nutrients rich-biochar enhances the soil's fertility and certain physical and chemical properties.

Biochar is a type of charcoal made from organic materials, like forestry and agricultural waste, by heating the biomass at high temperatures (400°C or more) in an oxygen-limited environment to produce stable carbon (Farrag, 2023). As a soil amendment, biochar's high cation exchange capacity (CEC) improves nutrients retention, minimizing leaching loss and increasing them availability for plant (Zubairu et al., 2023). Beneficial microbes can find their habitat in the porous structure of biochar, increasing microbial biomass and diversity and facilitating nutrient availability and cycling in the soil (Kapoor et al., 2022). Biochar addition increases the soil total and available content of nitrogen, phosphorus, and potassium, as well as soil organic matter percentage (Farrag, 2023). By increasing pore size and aggregate stability, biochar improves a soil's ability to hold water, especially in sandy or coarse-textured soils (Nepal et al., 2023). biochar can sequester carbon in soil for mitigation of the global warming and climate change. When applied to soil, biochar is highly durable, where it has the potential to last in soil hundreds of years (Ayman & Fawzy, 2023). The potassium in biochar made from organic waste is partially water-soluble and exchangeable, giving plants easy access to it while also supplying the soil with non-exchangeable potassium over an extended period of time (Xiu et al., 2023). Accordingly, biochar can directly provide crops with potassium nutrition.

Banana (*Musa sapientam* L.) trees produce a significant amount of waste, especially after the harvest of their fruit. This waste primarily consists of the stems and leaves, with studies indicating that approximately 60% of banana biomass is left as residual waste after processing. Around 114.08 million metric tons of banana waste are produced worldwide each year, contributing to environmental issues such as greenhouse gas emissions due to decomposition (Acevedo et al., 2021). Banana stems and leaves are particularly noted for their high levels of potassium and other nutrients such as nitrogen, calcium, phosphorus and magnesium (Zou et al., 2022). Banana tree waste is increasingly recognized as a cost-effective source for biochar (Liu, 2022). Converting this waste into biochar rich in nutrients and organic matter maximizes its economic and environmental benefits. Applying biochar as a soil amendment has been recognized as a method for integrated nutrient management; nevertheless, the impact of biochar application on soil K availability has not received much attention in research. To assess the potassium (K) status in soils and its effect on plant growth, the quantity/intensity (Q/I) ratio can be used to determine the characteristics related to soil K availability, such as the equilibrium activity ratio (AR_e^K), total labile K (K_L), and potential buffering capacity (PBC^K). These parameters can be affected by the addition of soil amendments, which can alter soil properties and potassium dynamics. Based on solid-solution exchange equilibria, the quantity-intensity (Q/I) equations, which were initially presented by Beckett (1964), can be used to evaluate the K providing capability of soil to plants (Lakkappa et al., 2024). These relationships explain how variations in K^+ concentration in the soil solution (or intensity factor) relate to variations in K^+ at the soil's exchange sites (or capacity or quantity factor). Therefore, the purpose of study is to produce banana pseudostem biochar and investigate its effect on (1) potassium status in loamy sand soil by using parameters of quantity/intensity (Q/I) relations; (2) some soil chemical characteristics, barley plant growth and nutrients uptake.

2. MATERIALS & METHODS

2.1. Banana pseudostem biochar preparation and analysis

Banana pseudostem wastes were collected from banana orchard after harvest, which located in Gerga, Sohag city, Egypt. The wastes chopped into small pieces and then, oven dried at 70°C. The dried wastes were compressed in an aluminum container and tightly closed with a fitted cap, and then pyrolyzed in a muffle furnace for 2 h at 400°C under limited oxygen conditions. When the muffle's temperature closed to the ambient temperature the aluminum container gated out and the charred material was ground and sieved using a 2-mm sieve, and then saved in glass jar for subsequent analyses.

Some measured properties of banana pseudostem biochar are shown in **Table (1)**. The biochar's pH was measured by using pH meter with galss electrode (Orion 420A, USA) in 1:10 (biochar:water) suspension after shaking for 30 minutes, while the EC measured in the filtrate of the suspension. A 0.5 g of biochar was digested using concentrated H_2SO_4 and H_2O_2 (analytical grade). The concentration of total N, P, and K in the digested samples was measured using the same method as in the soil samples (Jackson, 1973). The available K content in biochar was extracted by ammonium acetate solution (1N, pH=7) (Carson, 1980) and measured using Flamephotometer (CL378- ELICO, UK). Total carbon content (organic and inorganic C) of biochar was determined using loss-on-ignition method by heating biochar at 550˚C for 4h in a ceramic crucible (Møller et al., 2000), the residual after ignition is the ash. The ash content (%) in biochar was calculated according to the following formula:

Ash (%) = weight of ash (g)*100/ initial weight of biochar (g).

2.2. Pot experiment setup

A screen greenhouse pot experiment was conducted to assess the potential use of banana pseudostem biochar as a potassium fertilizer resource, and its effect on soil properties and barely growth. The soil was taken from the Agricultural Experimental Farm (El-Kawamel Farm), Faculty of Agriculture, Sohag University, Sohag Governorate, Egypt. The soil classified as loamy sand with sand, silt and clay amount of 801.40, 107.60, and 91.0 g kg^{-1}soil; and has $pH_{(1:2.5)}$ value of 7.79, $EC_{(1:1)}$ 3.06 dS cm^{-1}, SOM 6.60 g.kg^{-1} soil, total N 0.264 g kg^{-1}, available P and K of 5.14, and 126.8 mg kg^{-1} soil, respectively. Twelve plastic pots were filled with 3kg of air-dried soil for each. The biochar was applied with the soil in four levels as follows: B_0 (0% = 0 g biochar pot^{-1} as a control treatment), B_1 (0.5% = 15 g biochar pot^{-1}), B_2 (1% = 30 g biochar pot^{-1}), and B_3 (2% = 60 g biochar pot^{-1}). Each applied biochar level was mixed well and homogenized with the soil for each pot. Each treatment was repeated 3 times. Recommended phosphate fertilizer dose with level of (476 kg ha^{-1} of superphosphate fertilizer 15.5% P_2O_5) was applied before seedling (0.6 g pot^{-1}). Barely grains (*Hordeum vulgare* L) sourced from local variety (Giza 138) were planted on 1st December 2024 and thinned to 5 plants/pot after 10 days of germination. The soil moisture content was maintained at soil field capacity during the experiment period using distilled water for irrigation. Nitrogen fertilizer was added at a level of 300 kg N ha^{-1} in form of ammonium nitrate fertilizer (33.5 %N) (1.13 g ammonium nitrate pot^{-1}) in two doses, the first dose was added two weeks after cultivation, and the second one was applied three weeks later. After 60 days of planting, the plants were harvested completely and then washed with distilled water, left to dry naturally for two days, and then oven-dried at 70 °C for 48 hours. The oven-dried plants of each pot were ground using a stainless-steal grinder.

Table (1): Chemical analysis of the produced biochar.

Analysis	Unit	Result
pH (1:10)	-	8.41
EC (1:10)	dS m^{-1}	5.98
*Total C		792.30
Ash	g kg^{-1}	207.70
Total N		15.40
Total P		9.60
Total K		38.60
Available K		20.08

*Total C = biochar carbon content determined using loss-on-ignition method.

2.3. Plant analysis

Half gram of the ground plant biomass was digested by concentrated sulfuric acid and hydrogen peroxide according to Chapman & Pratt (1961). Total Nitrogen, phosphorus, and potassium content were determined in the digested plant samples. Kjeldhal equipment (Automatic distillation system Rapidstill II, Labconco, USA) was used for total N determination (Jackson, 1973), ascorbic acid-ammonium molybdate method was used for total P measuring using spectrophotometer (BK-UV1900, China), and total K was measured using Flamephotometer (CL378- ELICO, UK) as ascribed by Jackson. (1973).

2.4. Soil analysis

The pipette method was used for determining soil particle-size distribution before cultivation based on Rowell (1994). Following the barely harvest, soil samples were taken from each pot, allowed to air dry, and then sieved through a 2-mm sieve for analysis. Using a digital pH meter with glass electrode (Orion420A, USA), the soil pH was measured in a 1:2.5 soil:water suspension. Electrical conductivity (EC) was measured in in 1:1 (soil: water) extract using a digital electrical conductivity meter (Jenway 4520 Conductivity, UK). The modified Walkley & Black oxidation method was used to determine the content of organic matter in the soil (SOM) (Jackson, 1973). The micro Kjeldahl method (Automatic distillation system Rapidstill II, Labconco, USA) (Jackson, 1973) was used to calculate the total nitrogen in the soil. The available P in the soil was extracted by $NaHCO_3$ solution (0.5M, pH=8.5) (Olsen et al., 1954) and colorimetrically measured using Spectrophotometer (BK-UV1900, China) by ascorbic acid-ammonium molybdate method (Jackson, 1973).

2.5. Soil potassium forms

The extracted soil potassium (K) forms involved: 1) the soluble K which extracted by distilled water in a 1:5

(soil: water) extract; 2) available K (soluble + exchangeable K) was extracted by 1N ammonium acetate solution (NH_4OAc) (analytical grade, purity 98%, Loba Chemie Co., India) at pH 7 with ratio of 1:5 (soil: ammonium acetate solution) as ascribed by Carson (1980); 3) the difference between soluble K and available K gives the exchangeable K; the soluble K plus exchangeable and non-exchangeable K was extracted by boiling soil sample using 1M HNO_3 (analytical reagent grade, assay 69%) (1 soil:10 nitric acid) according to Knudsen et al. (1982), and 4) the difference between the NH_4OAc-extractable K and HNO_3-extractable K gives the non-exchangeable K or slowly available K.

All of the extracted K forms were determined using Flamephotometer (CL378- ELICO, UK) **(Jackson, 1973)** and calculated as mg K kg^{-1} soil.

2.6. Soil potassium dynamic assessment after barely harvest

The Q/I (quantity/intensity) ratio of soil potassium is the main parameter to access the soil potassium dynamic, 50 ml of 0.01 M calcium chloride ($CaCl_2$) (Sigma-Aldrich Co., anhydrous powder, purity ≥97%, Germany) solutions containing 0.0, 0.2, 0.4, 1.0, 2.0, and 4.0 mM potassium chloride (KCl) (Sigma-Aldrich Co., purity 99.5%, Germany) was added to five grams of each soil sample in glass bottles. After that, the soil suspensions in bottles were shaken for three hours, then left for equilibrium for twenty-four hours at room temperature. After filteration the supernatant of each sample, was analyzed for potassium, calcium, and magnesium. The flame photometer was used to determine potassium, while ethylene-diamine tetra acetic acid (EDTA) solution was used to titrate calcium and magnesium.

Potassium intensity (I) factor (AR^K) (or the activity ratio of K) was calculated using the K, calcium (Ca), and magnesium (Mg) concentrations in the filtrate after equilibrium using vangelou and Blevins (1988) equation as follows:

$$\mathbf{AR^K} = \frac{aK}{\sqrt{a(Ca+Mg)}}$$

where **a** is the ion activity and was calculated by the equation:

$$a_i = C_i \gamma_i$$

Ci = ion concentration after equilibrium.

γi = the ion activity coefficient, calculated using Davies equation (Sposito, 1989) as follow:

$$\text{Log } \gamma_i = -0.512 Z^2 [\sqrt{I} / (1+\sqrt{I}) - 0.31]$$

Z = the valence of the ionic species i and ***I*** = the ionic strength of the filtrate solution after equilibrium was estimated from the Griffin and Jurinak (1973) equation based on Lindsay (1979) as follows:

$$I = 0.013 \text{ EC}$$

EC = the filtrate's electrical conductivity (dS m^{-1}) after equilibrium.

The quantity factor (Q) or ±ΔK is the amount of potassium that the soil lost or gained after equilibrium. It is computed by subtracting the initial and after equilibrium potassium concentrations. The potassium potential buffering capacity (**PBC^K**) = the slope of the Q/I curve (Sparks, 1998).

2.7. Statistical analysis:

Using SPSS version 22, an analysis of variance (ANOVA) was performed on all obtained results. Duncan's Multiple Range test was used for post-hoc comparisons between the means of the treatments under investigation and their control treatment at a significance threshold of $p \leq 0.05$ (Gomez & Gomez, 1984).

3. RESULTS

3.1. Soil chemical properties:

Application of banana pseudostem biochar changed many chemical properties of the studied soil, as shown in **Table (2)**. The soil pH increased from 7.75 in control to 7.79, 7,85, and 7.88 in the 0.5, 1, and 2% biochar-treated soil, respectively. Regarding to soil salinity, amending soil with banana pseudostem biochar significantly increased soil EC from 3.16 dS m^{-1} in control to 3.86 and 4.56 dS m^{-1} in the treated soil with 1 and 2% of the studied biochar.

Comparing with control treatment, using of banana pseudostem biochar dramatically enhanced the soil organic matter (OM) content significantly **(Table 2)**. The soil OM content reached 0.67, 1.14, and 1.64 % for 0.5%, 1%, and 2%-treated soils, respectively, higher than control soil (0.47%).

Total nitrogen and available P in soil are critical indicators of soil fertility and quality. As regard to the results shown in **Table (2)**, it can be noticed that banana pseudostem biochar enhanced the total N content in soil after barely harvest from 0.397 g kg^{-1} in control soil to 0.467, 0.539, and 0.633 mg kg^{-1} under application levels of 0.5, 1, and 2%, respectively; by an increase of 17.63, 35.77, and 59.45 % more than the control treatment.

According to the results presented in **Table (2)**, applying banana pseudostem biochar enhanced the available phosphorus content in soil significantly from 7.21 mg kg^{-1} in control to 10.57, 15.40 and 17.95 mg kg^{-1} in B(0.5%), B(1%), and B(2%)-treated soil, respectively. Our findings matched with Kakar et al. (2021) and Farrag (2023).

Table (2): Impact of banana pseudostem biochar levels on soil chemical characteristics after barely harvest.

Treatment	pH (1:2.5 susp.)	EC (1:1 ext.) (dS m^{-1})	OM (%)	Total N(g kg^{-1})	Available P(mg kg^{-1})
Control	7.75 c±0.017	3.16 c±0.05	0.47 c±0.07	0.397 d±0.024	7.21 d±0.84
B1 (0.5%)	7.79 b±0.025	3.34 c±0.14	0.67 c±0.09	0.467 c±0.020	10.57 c±1.16
B2 (1.0%)	7.85 a±0.020	3.86 b±0.20	1.14 b±0.14	0.539 b±0.023	15.40 b±1.47
B3 (2.0%)	7.88 a±0.020	4.56 a±0.35	1.61 a±0.18	0.633 a±0.012	17.95 a±1.39

Each value in the table represents a mean of three replicates ± SD and the different lower-case letter besides values indicate a significant difference between treatments based on Duncan's Multiple Range test at P ≤0.05.

3.2. Potassium forms in soil

The presented results in **Table (3)** indicated that the different soil potassium forms increased significantly ($p \leq 0.05$) with increasing the biochar addition level. The application of banana pseudostem biochar improved the soluble K content from 34.58 mg kg^{-1} for the control soil to 56.31. 80.55, and 128.90 mg kg^{-1} for amended soils with 0.5, 1, and 2% biochar, respectively (by 62.84, 147.40, and 272.76% more than control). While, the B1, B2, and B3-treated soils recorded significant increases in the exchangeable K content to 141.99, 198.85, 331.20 mg kg^{-1} (by 66.62, 133.34, and 245.98%), respectively compared with control soil (85.22 mg kg^{-1}). Similar trend was observed in non-exchangeable K content which increased significantly from 306 mg kg^{-1} in control treatment to 336, 358, and 407 mg kg^{-1} after application of 0.5, 1, and 2% biochar levels, respectively.

Table (3): Effect of banana pseudostem biochar on soil potassium forms after barely harvest.

Treatment	NH_4OAc-extractable K	Soluble K	Exchangeable K	HNO_3-K	Non-exchangeable K
			mg kg^{-1}		
Control	119.80 d±3.70	34.58 d±2.36	85.22 d±2.88	425.80 d±8.60	306.00 d±6.38
B (0.5%)	198.30 c±8.87	56.31 c±3.56	141.99 c±8.15	535.30 c±12.39	337.00 c±11.80
B (1.0%)	279.40 b±11.30	80.55 b±3.76	198.85b±7.59	637.40 b±15.60	358.00 b±13.11
B (2.0%)	460.10 a±9.51	128.90 a±4.15	331.20a±9.56	867.10 a±17.60	407.00 a±8.94

Each value in the table represents a mean of three replicates ± SD and the different lower-case letter besides values indicate a significant difference between treatments based on Duncan's Multiple Range test at P ≤0.05.

3.3. Parameters of potassium Q/I ratio

Potassium Q/I isotherms can reveal details about the availability of K in the studied soil (Bangroo et al., 2021). All treatments produced linear trends over the activity ratio's range **(Figure 1).** The values of Q/I parameters are presented in **Table (4)**. Generally, the addition of banana pseudostem biochar exhibited a remarkable impact on potassium Q/I parameters of the studied soil.

The potential buffering capacity of soil K (PBC^K) indicates its capacity to supply K to the soil solution (intensity) as a result of either plant uptake or soil loss of potassium, which is related to soil's CEC (Amin 2016; Emad El-dean et al., 2021). The potential buffering capacity of K (PBC^K) significantly increased with the presence of banana pseudostem biochar in addition to the studied loamy sand soil from 17.61 (cmol kg^{-1}/mol $L^{-1})^{0.5}$ in control to 19.89, 22.36, and 25.18 (cmol kg^{-1}/mol L^{-1})0$^{.5}$ under addition levels 0.5, 1, and 2% of biochar, the B(0.5%), B(1 %), and B(2%) treatment, respectively; by 13, 27, and 43% more than the original PBC^K of this soil.

The activity ratio of K in the soil solution at equilibrium (AR_e^K) is a measure of the intensity factor of labile K in the soil and is defined as the activity ratio of K to Ca or "Ca+Mg" when there is no net adsorption or desorption of K between soil solution and exchange phases. The AR_e^K value was found at the intersection of the linear part of the Q/I curve with the X-axis and when $\Delta K = 0$ **(Figure 1)**. Results in **Table (4)** showed significant increases in the AR_e^K were recorded with applying banana pseudostem biochar to the studied soil from 0.0085 (mol $L^{-1})^{0.5}$ in the control to 0.0122, 0.0160, and 0.0224 (mol $L^{-1})^{0.5}$ in B(0.5%), B(1 %), and B(2 %)-amended soils, respectively by 43.50, 88.23, and 163.53 % more than the initial AR_e^K of this soil. Sparks and Liebhardt (1981) found that the AR_e^K value ranged between 0.020 and 0.058 (mol $L^{-1})^{0.5}$ in the sandy loam soil. Usman & Gameh (2008) found that he potassium AR_e^K of the newly reclaimed sandy loam soil was 0.01 (mol $L^{-1})^{0.5}$ and increased to 0.020, 0.016, and 0.027 (mol $L^{-1})^{0.5}$ with the addition of wastes of sugar industry (vinasse, bagasee ash, and Takamolia, respectively). Hamed & Amin (2017) showed that the AR_e^K ranged from 0.0071 to 0.0320 in some soils of El-Dakhla Oasis, New Valley, Egypt.

The $-\Delta K^o$ value indicates the non-specifically adsorbed potassium in the soil and is a measure of the exchangeable K or labile pool of K in the soil (Zhu et al., 2020). The non-specific adsorption of potassium occurs onto the planar surfaces of the soil minerals (Tan, 2011). And the increase in $-\Delta K^o$ value indicates an increase in this type of adsorption. The Q/I curve's linear portion's intersection with y-axis yields the $-\Delta K^o$ value ($-\Delta K^o$ is the K quantity factor at equilibrium**)** **(Figure 1)**. Significant increases were found in the $-\Delta K$ value of the studied soil with banana pseudostem biochar applications **(Table 4)**; the $-\Delta K^o$ value from 0.1497 cmole kg^{-1} in the control soil to 0.2414, 0.3581, and 0.5624 cmole kg^{-1} under addition level 0.5, 1, and 2% of biochar which representing 61.26, 139.21, and 275.68 % more than the original $-\Delta K^o$ value of the studied soil.

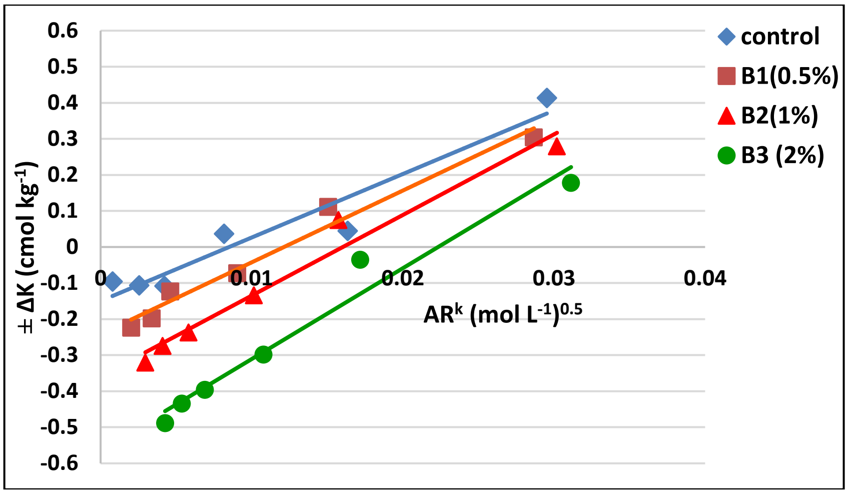

Fig. (1): Quantity-Intensity (Q/I) curves of soil K affected by banana pseudostem biochar levels application.

Table (4): Effect of banana pseudostem biochar levels on Quantity/Intensity (Q/I) parameters of soil potassium.

Treat.	Linear equation	R^2	AR_e^k $(mol\ L^{-1})^{0.5}$	$-\Delta K^o$ $(cmol\ kg^{-1})$	PBC^k $[(cmol\ kg^{-1}/mol\ L^{-1})^{0.5}]$
Control	Y = 17.609X - 0.1497	0.9250	0.0085 d±0.0010	0.1497 d±0.009	17.609 d±1.34
B (0.5%)	Y = 19.894X - 0.2414	0.9740	0.0122 c±0.0011	0.2414 c±0.014	19.894 c±0.64
B (1.0 %)	Y = 22.360X - 0.3581	0.9670	0.0160 b±0.0006	0.3581 b±0.011	22.360 b±1.28
B (2.0 %)	Y = 25.180X - 0.5624	0.9648	0.0224 a±0.0017	0.5624 a±0.026	25.180 a±0.98

Each value in the table represents a mean of three replicates ± SD and the different lower-case letter besides values indicate a significant difference between treatments based on Duncan's Multiple Range test at P ≤0.05.

3.4. Barely plants growth, nutrients contents and uptake

Data in **Fig. (2)** indicated that application of banana pseudostem biochar significantly improved the barley plants fresh weight (FW) from 19.56 g pot^{-1} in control to 26.77, 35.79, and 42.68 g pot^{-1} in the soil treated with B(0.5%), B(1%), and B(2%), respectively (by 36.86, 83.90, and 118.20 % more than control) and significantly increased the dry weight (DW) from 7.63 g pot^{-1} in control to 9.77, 11.33, and 12.17 g pot^{-1} in the soil treated with B(0.5%), B(1%), and B(2%), respectively (by 28.10, 48.50, 59.50 % more than control).

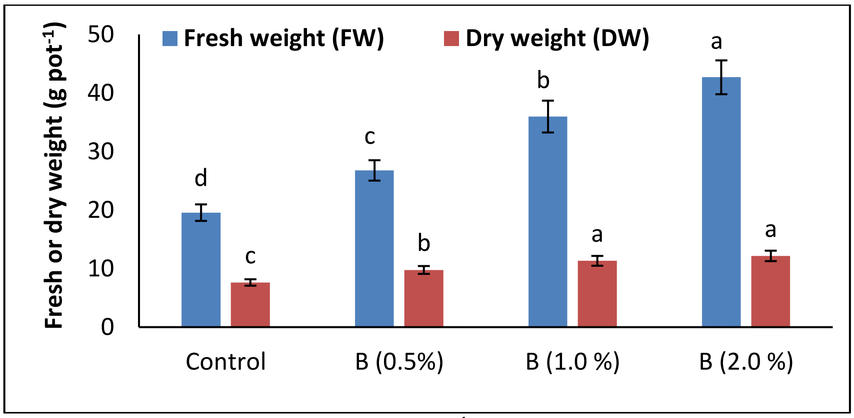

Fig. (2): Fresh (FW) and dry (DW) weights of barely plants (g pot^{-1}) affected by banana pseudostem biochar levels application
(Each column's value is a mean of three replicates ± SD and the different lower-case letter above each column indicate a significant difference between treatments based on Duncan's Multiple Range test at P ≤0.05).

As illustrated in **Figure (3)** and **Table (6)**, the studied biochar resulted in significant increase in N concentration and uptake in barley plants from 2.38 % and 181.35 mg pot^{-1} in control treatment to 2.61, 280, and 2.71 % and to 254.72, 315.75, and 328.56 mg pot^{-1} in B(0.5%)-, B(1%), and B(2%)-treated plants, respectively. Similar findings were obtained by **Farrag (2023)** who demonstrated that N uptake in barely plant increased by 12 and 58 % in the soil amended with banana waste biochar at levels of 0.5 and 1% comparing with control.

As shown in Figure (3) and Table (6), the phosphorus concentration and uptake in plant improved significantly from 0.35 % and 26.34 mg pot-1 in control plants to 0.51, 0.62, and 0.60 % and to 49.14, 70.91, and 73.67

mg pot-1 in plants that treated with banana pseudostem biochar at rates of 0.5, 1, and 2%, respectively.
Amending the studied soil with banana pseudostem biochar significantly increased the K concentration and uptake in barely plants (Figure 3 and Table 6). The K concentration improved from 1.40 % in the control plants to 1.78, 1.97, and 2.13 % in B(0.5%)-, B(1%), and B(2%)-treated plants; while the K uptake increased to 173.57, 222.70, and 258.60 mg pot^{-1}, respectively compared to control (106.62 mg pot^{-1}).

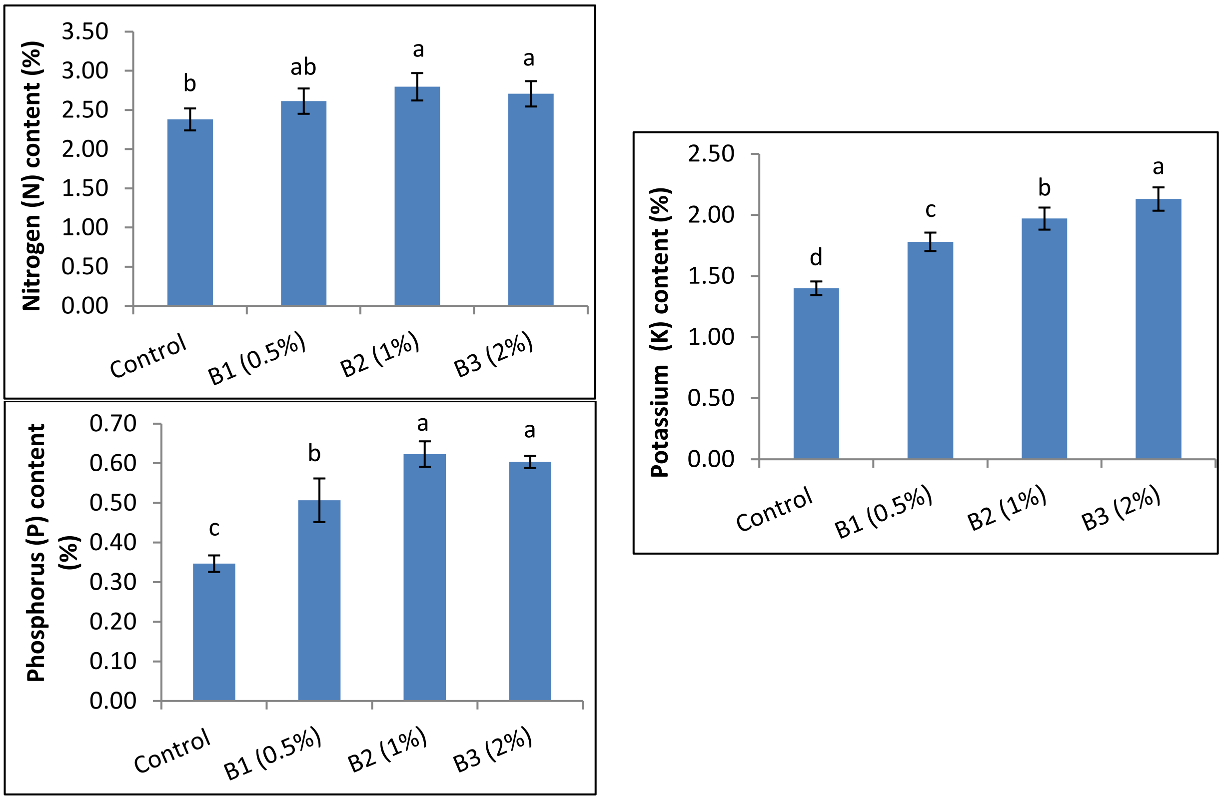

Fig. (3):Macronutrients (N,P,K) concentrations(%)in barely plants affected by banana pseudostem biochar levels application (Each column's value represents a mean of three replicates ± SD and the different lower-case letter above each column indicate a significant difference between treatments based on Duncan's Multiple Range test at P≤0.05).

Table (6): Effect of banana pseudostem biochar levels on macronutrients (N, P, K) uptake by barely plants.

Treatment	N Uptake	P Uptake	K uptake
	(mg pot^{-1})		
Control	181.35 c ±7.44	26.34 c ±1.94	106.62 d ±3.52
B (0.5%)	254.72 b ±9.61	49.14 b ±1.87	173.57 c ±4.55
B (1.0 %)	315.75 a ±5.82	70.91 a ±3.51	222.70 b ±6.37
B (2.0 %)	328.56 a ±7.90	73.67 a ±5.13	258.60 a ±7.43

Each value in the table represents a mean of three replicates ± SD and the different lower-case letter besides values indicate a significant difference between treatments based on Duncan's Multiple Range test at P ≤0.05.

3.5. Pearson correlation between Q/I parameters, soil K forms, K concentration and uptake in barely plants

Depending on the results of person correlation between Q/I parameters, soil K forms, K concentration and uptake in barely plants **(Table 7)**, there was positive correlations between all of these parameters. There was

highly significant correlation between soil K forms (soluble, exchangeable, and non-exchangeable K) and potassium Q/I parameters (AR_e^k, -ΔK, and PBC^k). Additionally, the Q/I parameters showed high significant correlations with each other. Furthermore, the K concentration and uptake in plant highly correlated with soil K forms and highly significant correlated with potassium Q/I parameters.

Table (7): Pearson correlation between Q/I parameters, soil K forms, K concentration and uptake in barely plants

	Soluble K	Exch. K	Non-exch. K	K conc.(%) in plant	K uptake (mg pot^{-1})	AR_e^K	$-\Delta K^o$	PBC^K
Soluble K	-							
Exch. K	1.00**	-						
Non-exch. K	0.99**	0.99**	-					
K conc. (%)	0.92	0.91	0.94	-				
K uptake	0.94	0.93	0.96*	0.99**	-			
AR_e^K	0.99**	0.99**	0.99**	0.94	0.96*	-		
$-\Delta K^o$	1.00**	0.99**	0.99**	0.92	0.95	0.99**	-	
PBC^K	0.98**	0.98*	0.99**	0.96*	0.98*	0.99**	0.99*	-

**Highly significant correlation.
*Significant correlation.

4. DISCUSSION

4.1. Soil chemical properties after barely harvest

From the obtained results in our study, it can be said that amending loamy sand soil with banana pseudostem biochar altered its chemical properties. The resulted rise in soil pH may be related to the alkaline nature of the biochar, and its constituents such as carbonates, oxides, alkali, and alkaline earth metals (Juriga & Šimanský, 2019). Similar results were obtained by Kalemelawa et al. (2014) and Farrag (2023) after banana wastes biochar addition to soil. The noticed increase in soil EC might be attributed to the content of soluble salts in biochar and the amount of dissolved soil salts increases as the labile organic fraction of biochar degrades over time (Farrag and Bakr, 2021). Our findings were matched with Farrag (2023) who found that amending sandy soil with banana residues biochar at levels of 2 and 5% increased soil EC to 1.83 and 2.13 dS m^{-1} compared to 0.95 dS m^{-1} in control. Our results showed an improvement in soil OM content, this increase may due to the biochar's stable carbon structure, which lasts for hundreds to thousands of years and helps to sequester carbon in soil for an extended period of time. It also increases the SOC content by encouraging the stability of microbial products and rhizodeposits (Khan et al., 2024). Also, biochar enhances soil humification and increases humic acid concentrations, which are crucial components of soil organic matter (Yang et al., 2024). The aromatic structures in biochar contribute to its stability and resistance to microbial degradation, thereby retaining more carbon in the soil (Yang et al., 2024). For instance, in Farrag (2023)' study, soil organic matter increased from 0.25% (control) to 3.12% with a 5% banana wastes biochar application rate after the first season.

In this study, applying biochar significantly boosted the total N content of soil. Previous study showed that biochar increased soil total N by 27.4% in sandy soil (Liu et al., 2017). Biochar can increase the availability of nutrients in the soil by serving as an organic storage for nitrogen, phosphorous, and potassium (Khan et al., 2022). The physiochemical characteristics and enzymatic activities of soil are improved by biochar, which promotes nitrification and nitrogen mineralization. Additionally, it can improve soil retention capacity, enhance soil water holding ability, which can decrease nitrogen leaching and increase the abundance of nitrogen-fixing bacteria (Zhang et al., 2021).

Because it contains phosphorus, biochar functions as a slow-release P fertilizer. When added to soil, it raises the overall P concentration. The obtained results of this study showed an improvement in soil available P content. It has been demonstrated that biochars made from particular feedstocks, like rice straw and banana waste, greatly raise the available P content in soils (Hong & Lu, 2018; Gao et al., 2019). By releasing dissolved organic carbon substances, biochar modifies the sorption properties of soil. These compounds decrease P fixation and increase its availability by competing with phosphate for sorption sites (Wu et al., 2022). Moreover, alkaline phosphatase activity in soils is increased by biochar. For instance, one study discovered that applying biochar increased alkaline phosphatase activity by 2.8% while decreasing acid phosphatase activity by 17.8% (Zhan et al., 2020). Additionally, applying biochar greatly increases the amount of P that is available in the soil. According to a meta-analysis, soil available P increased by an average of 57.6%, with biochars produced from manure or at low pyrolysis temperatures (Zhan et al., 2020).

Our findings revealed that banana pseudostem biochar enhanced the readily available soil potassium and increased the soil soluble K content, this may be due to the biochar content of the free nutrient cations like potassium that does not volatilize after burning (Amin, 2016). In another previous study, the soil available K content increased by 55, 119, and 533 % compared to control after amending sandy soil with banana trees waste biochar (Farrag, 2023) in the first season of cultivation. Biochar produced from banana wastes is rich in potassium and has been shown to effectively increase soil potassium content, for instance, banana peel and peduncle waste biomass biochar contains a high concentration of potassium, ranging from 113.1 to 216.3 g/kg and it can be used as alternative source of K for sustainable soil enrichment with K, agriculture and plant productivity (Karim et al., 2017; Islam et al., 2019).

The obtained increase in the soil exchangeable K after application of banana pseudostem biochar may be due to that the exchangeable K is associated with the organic functional groups of biochar and can be exchanged with other cations in the soil solution, making it available to plants over time (Adhikari et al., 2024). Biochar's high cation exchange capacity (CEC) enhances its ability to retain and release exchangeable potassium (Bilias et al., 2023). The addition of biochar can enhance soil's potassium retention capacity, reducing leaching losses and improving overall soil fertility. Our results agreed with Ayman & Fawzy (2023) who found an increase in the soil available K content by 30, 34, and 42% compared to control in sandy soil and by 12, 17, and 32 % compared to control in calcareous soil as a result of applying olive stone biochar at levels of 1, 2, and 5%, respectively. According to Nie et al. (2016), applying biochar to volcanic soil increased the amount of soil exchangeable K and the K content of wheat plant. Additionally, Rasuli et al. (2022) studied the changes in the soil K fractions after applying biochar made from wheat and corn wastes to arid calcareous soils. They observed that using biochars raised the concentrations of all soil K forms, including HNO_3, soluble, exchangeable, and non-exchangeable. Furthermore, the ability of biochar to promote K solubilizing bacteria growth and can raise K availability in soils that are lacking in K. This was supported by a recent two-year study by Xia et al. (2022), which discovered that applying 2% peanut shell biochar to an acidic soil that was K-deficient encouraged the growth of K-dissolving bacteria and replaced 40% of the K fertilizer in terms of soil and plant K levels.

4.2. Soil potassium dynamic (Q/I) after barely harvest:

Results of this study indicated that banana pseudostem biochar application to the studied loamy sand soil enhanced the potassium quantity/intensity parameters included PBC^K, AR_e^K, and -Δ K°. The high soil's PBC^K value that obtained after biochar application indicate that there is a good supply and availability of K, whereas the low PBC^K in control soil indicates a need for K fertilization (Sparks and Liebhardt 1981). Previous studies claimed that biochar had high surface functional group content, CEC, exchangeable-K, and maintenance due its greater surface area and stronger negative surface charge (Ayman et al., 2020; Ayman & Fawzy, 2023; Bilias et al., 2023). Our results are in agreement with Amin (2016) who found that the PBC^K significantly increased by 59 % more than control with the corn cob biochar addition to the calcareous sandy soil at a level of 60 Mg ha^{-1}. Moreover, in sandy and calcareous soils, the addition of olive stone biochar at level of 5% considerably raised the PBC^K of the soils from 1.41 to 2.63 and 1.71 to 2.58 (cmol kg^{-1}/mol $L^{-1})^{0.5}$, respectively (Ayman & Fawzy, 2023).

Our obtained results showed that application of banana pseudostem biochar significantly improved AR_e^K values of the investigated soil to be higher than 0.01 mole/l, suggesting that the adsorbed K^+ was mostly retained as a non-specific adsorption on the mineral planar surfaces (Sparks and Liebhardt, 1981), implying a higher K^+ ionic strength in solution, a higher K^+ supply intensity, higher K^+ availability, and hence more K^+ being absorbed by plants more quickly (Beckett, 1964) after banana pseudostem biochar application. The obtained significant positive correlation between AR_e^K and K forms supports these interpretations. Similar results were obtained by Amin (2016) who found an increase in the AR_e^K values in corn cob biochar-amended calcareous sandy soil from 0.061 (mol $L^{-1})^{0.5}$ in control to 0.087 (mol $L^{-1})^{0.5}$ at the highest level of biochar (60 Mg ha^{-1}).

The obtained increases in the -ΔK° values in this study show potassium release to the soil solution, which may be due to the high potassium content of banana pseudostem biochar. Furthermore, Biochar may act as a reservoir for potassium, retaining it in its structure and releasing it slowly over time. This slow-release mechanism helps maintain a consistent level of available potassium in the soil, which is beneficial for plant growth with mitigation of K leaching loss (Premalatha et al., 2023). These findings indicate that the banana pseudostem biochar is considered a potassium alternative source in the loamy sand soil and it's application increases the labile K pool in soil. The obtained significant correlation coefficient between soluble K, exchangeable K, and -ΔK° shows that -ΔK is a good parameter for labile K. Our findings agreed with Ayman & Fawzy (2023) who found that applying olive stone biochar at levels of 1, 2, and 5% raised the -ΔK° values from 0.09 to 0.18, 0.23, and 0.28 cmole kg^{-1}, respectively for the sandy soil and from 0.15 to 0.23, 0.29, and 0.37 cmole kg^{-1}, respectively for the calcareous soil. Similar findings were obtained by Amin (2016), where he indicated that the -ΔK° value increased significantly from 0.103 cmole kg^{-1} in control to 0.151, 0.187, 0.234 cmol kg^{-1} in the calcareous sandy soil amended with 20, 40, and 60 Mg ha^{-1} of corn cob biochar, respectively.

4.3. Barely plants growth and nutrients uptake

The findings of the present study showed an improvement in barely growth, this may be related to the positive impacts of biochar on enhancing soil characteristics and nutrients availability especially K nutrition (El-Naggar et al., 2019; Bilias et al., 2021a), which hold critical roles in improvement of plant growth and sustaining soil health. When biochar is added to soil, it positively influences plant growth and soil fertility by increasing nutrient availability and reducing leaching of nutrients (Ding et al., 2016).

Plant absorbs N in form of ammonium (NH_4^+) or nitrate (NO_3^-) which are vital for plant growth. The obtained results showed an enhancement in nitrogen uptake by barely plants, which may be related to the role of biochar in increasing water holding ability of soil, decreasing N leaching loss, improving N retention and availability for plant (Khan et al., 2022; Li et al., 2022). Also, biochar supports microbial processes like nitrification and N fixation as well as soil enzymatic nitrogen cycling activities like urease activity. These processes improve nitrogen uptake and mineralization, which raises the content of nitrogen in plants (Zhang et al., 2021; Khan et., 2022). Previous studies indicated that the addition of biochar to nitrogen fertilizer enhanced the uptake of nitrogen by plants, as well as the total nitrogen accumulation and nitrogen utilization efficiency (NUE). In rapeseed systems, for instance, applying biochar raised the plant N content by up to 16% compared to the sole application of nitrogen fertilizer (Khan et al., 2022). Biochar and nitrogen fertilizer increased crop N uptake in maize, leading to increased grain yields (Li et al., 2022).

The noticed enhancement of P uptake in barely plants could be due to the impact of banana pseudostem biochar on improving P availability in the studied soil. Additionally, the high organic matter content can improve the microbial activity and enzymes, which supports nutrient mineralization and release phosphorus to the soil (Jing et al., 2020). Our results are in agreement with Sial et al. (2019) who indicated that banana peel biochar addition with chemical fertilization increased grain and root P content compared to the alone chemical fertilization in wheat plants.

Our findings indicated that biochar raised the content of K in plants. Unlike other elements that may volatilize (like N) or change into comparatively insoluble forms (like Mg) during pyrolysis, K is mostly retained which may enhance the K bioavailability for plants (Biederman and Harpole, 2013; Karim et al., 2017). According to previous research, applying biochar made from a biomass high in K, like banana peels, rapidly enhanced the K uptake by plant. Consequently, it may lead to a readily available K-supply pathway to plants as well as an alternate and eco-friendly soil K input (Islam et al., 2019). Studies showed that in comparison to control or conventional agriculture using K fertilizers, wheat and ryegrass seem to absorb more potassium from soils treated with biochar (Amin, 2016; Haddad et al., 2021). Furthermore, according to Oram et al. (2014), applying biochar along with inorganic fertilizers has a synergistic impact that raises crop yield and K content. According to Wu et al. (2019), biochar has the potential to improve crop yields and K consumption efficiency, which would decrease the demand for chemical K fertilizers and preserve soil health. When no fertilizer was used, applications of the biochar increased plant K uptake in Umbrisol by 27%, this supports the biochar's long-term K supply (Ippolito et al., 2015). Because the application of 30 Mg ha^{-1} of biochar added 136 kg ha^{-1} of total K in the soil, therefore, biochar could be an adequate carrier for enhancing plant K nutrition (Ippolito et al., 2015), which led to a notable increase in soil K availability in the early years (Tammeorg et al., 2014). In a soda salt alkali soil-maize crop long-term field experiment, Zhao et al. (2020) found that the rate of 20 tons ha^{-1} of corn straw biochar application gave the highest potassium concentrations in maize plants.

5. Conclusion

Banana trees waste such as pseudostems and leaves are one of the agricultural wastes that is produced annually in large quantities worldwide. These wastes are frequently dispersed or burned in the planting regions, which exacerbates pollution issues in the area. Converting these wastes into biochar is best strategy to reduce waste accumulation and produce a sustainable and natural soil amendments. According to the results of this study, the application of banana pseudostem biochar to the loamy sand soil increased the availability and the soil potential buffering capacity of potassium. Therefore, in an environmentally acceptable and sustainable method of managing potassium fertilization, biochar from banana pseudostem can be utilized as an alternative source of potassium fertilizers. Moreover, the present study found that application of banana pseudostem biochar to loamy sand soil improved carbon sequestration, soil chemical properties, and the growth of barely plants. This study gives banana farmers better way to handle their agricultural waste products to produce a cheap potassium rich amendment. This practice may save the cost of purchasing manufactured chemical fertilizers, support the sustainable agricultural production, protect the environment from contamination, and supports the cultivation of important export crops with high potassium requirements in Egypt.

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الملخص العربي

ديناميكية البوتاسيوم، والخصائص الكيميائية للتربة، وامتصاص العناصر الغذائية بواسطة الشعير في التربة الرملية الطينية المحسنة بالفحم الحيوي لساق الموز الكاذبة

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في تجربة أصص بتصميم كامل العشوائية وثلاثة مكررات لكل معاملة، تم دراسة تأثير الفحم الحيوي لساق الموز الكاذبة على معايير السعة/الشدة للبوتاسيوم(Q/I) ، والخصائص الكيميائية للتربة، والنمو والحالة الغذائية لنبات الشعير المنزرع في التربة الرملية الطينية .تم اضافة الفحم الحيوي للتربة بثلاثة مستويات تشمل 0٪ (الكنترول)، و 0.5٪ (B1)، و 1٪ (B2)، و 2٪ (B3) . تم زراعة حبوب الشعير، وبعد الحصاد تم تقدير صور البوتاسيوم وبعض الخصائص الكيميائية (الرقم الهيدروجيني، والملحية، ومحتوى المادة العضوية، والنيتروجين الكلي، والفوسفور الميسر) ومقاييس السعة/الشدة للبوتاسيوم فى التربة لكل معاملة . كما تم تحليل محتوى النباتات من العناصر الغذائية (النيتروجين والفوسفور والبوتاسيوم) وتم حساب الكمية الممتصة من هذه العناصر .أظهرت النتائج تحسنًا كبيرًا في محتوى المادة العضوية في التربة ومحتوى النيتروجين الكلي والفوسفور الميسر في التربة .ازداد بشكل ملحوظ تركيز صور البوتاسيوم المختلفة، بما في ذلك البوتاسيوم الذائب، والبوتاسيوم المتبادل، والبوتاسيوم المستخلص بحمض النيتريك، والبوتاسيوم الغير المتبادل مع إضافة الفحم الحيوي مقارنةً بالتربة الكنترول .كما أدت هذه الزيادات الكبيرة إلى زيادة في قدرة التربة الأمدادية بالبوتاسيوم (PBC^k)، عامل الشدة عند الاتزان (AR_e^k) ، و عامل السعة (ΔK^o) مع إضافة الفحم الحيوي إلى التربة .تحسن الوزن الطازج والجاف، ومحتوى النيتروجين والفوسفور والبوتاسيوم، وامتصاص النبات لهذه العناصر بشكل ملحوظ نتيجةً لاستخدام الفحم الحيوي .لذلك، يُعد الفحم الحيوي المُنتَج من مخلفات أشجار الموز أداةً مفيدةً لاحتجاز الكربون على المدى الطويل، مما يُعزز خصوبة التربة وصحة النبات .تطبيق الفحم الحيوي المُستخرَج من سيقان الموز الكاذبة يُمكن أن يكون طريقة فعّالةً لتعزيز توافر البوتاسيوم في التربة وتجديده وتخزينه، مما قد يُقلل من الطلب على أسمدة البوتاسيوم الكيماوية المصنعة ويُعزز تقنيات الزراعة المستدامة.

الكلمات المفتاحية: مخلفات الموز ، القدرة التنظيمية للبوتاسيوم، معدل السعة/الشدة، إدارة المخلفات الزراعية، الإنتاج الزراعي المستدام.