



RESEARCH ARTICLE

Temporal dynamics of soil potassium fractions as influenced by potassium-enriched rice husk biochar and farmyard manure

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Abstract

Understanding the transformation of potassium (K) among different soil pools is essential for improving its availability and use efficiency in cropping systems. An incubation study was conducted during 2024 at the College of Agriculture, V C Farm, Mandya, Karnataka, India to evaluate the effect of K-enriched rice husk biochar (BC) and farmyard manure (FYM) on soil chemical properties and K fractions over time. The experiment was laid out in a factorial completely randomized design (FCRD) with two main factors - soil alone and soil + FYM combined with five levels of K supplied through K-enriched biochar (KBC) (0, 25, 50, 75 and 100 % recommended dose of K (RDK)), along with a conventional fertiliser treatment for comparison. Soil samples were incubated for 90 days with periodic destructive sampling. Results revealed that the combined application of FYM and 100 % RDK-KBC significantly increased electrical conductivity (EC) from 0.32–0.49 dS m⁻¹ and soil organic carbon (OC) increased to 6.66 g kg⁻¹ at 21 days after incubation (DAI) and remained higher at 90 DAI than the 3.97 g kg⁻¹ observed in soil alone. Exchangeable calcium (Ca) and magnesium (Mg) also increased to 7.40 and 3.40 cmol (p⁺) kg⁻¹ respectively. Potassium fractions showed clear trends, increasing up to 30 DAI and declining thereafter. Under 100 % RDK-KBC with FYM, water-soluble, exchangeable and available K increased from 34.39–84.35, 42.06–93.37 and 80.38–157.78 mg kg⁻¹ respectively. Non-exchangeable K decreased from 361.89–298.13 mg kg⁻¹, indicating transformation into plant-available forms. The KBC + FYM ensured sustained K release, retention and enhanced soil fertility, proving to be a viable alternative to conventional K fertilisers.

Keywords: exchangeable potassium; potassium dynamics; potassium-enriched biochar; soil fertility; water-soluble potassium

Introduction

Potassium (K) is an essential macronutrient required for optimal plant growth and development and is predominantly present in soil in association with clay minerals and other mineral fractions such as mica, feldspar and illite (1). It plays a vital role in regulating key physiological and biochemical processes such as enzyme activation, osmoregulation, photosynthesis, translocation of assimilates and stress tolerance, thereby significantly influencing crop productivity as well as quality attributes of produce (2). Despite its importance, K availability in soils is increasingly becoming a limiting factor due to continuous nutrient mining under intensive agricultural systems and inadequate replenishment (3, 4).

Globally, sustained crop production has led to progressive depletion of soil K reserves; however, the challenge is more acute in India due to economic and management constraints. A substantial proportion of potassic fertilisers used in the country is imported, making them relatively costly compared to nitrogenous and phosphatic fertilisers. This economic factor, coupled with the perception that K fertilisers produce slower visible responses, has resulted in their comparatively lower application by farmers (5).

Over time, this imbalance in nutrient application has created a negative K budget, leading to a steady decline in soil K reserves. Soil test data across diverse agro-ecological regions indicate an emerging trend of K deficiency, particularly in intensively cultivated and inherently low-fertility soils (6, 7).

The situation is further aggravated in coarse-textured soils, which are characterised by low cation exchange capacity and poor nutrient retention. In such soils, K is highly prone to leaching losses, resulting in reduced availability to plants even after fertiliser application (8). This not only lowers K use efficiency but also disrupts the equilibrium among different K fractions, ultimately affecting nutrient supply to crops. Therefore, improving K retention and regulating its transformation among various soil pools is critical for ensuring sustained availability and efficient utilisation.

Biochar (BC) has emerged as a promising soil amendment with multifunctional benefits for soil fertility and nutrient management. It is a carbonaceous material produced through thermochemical conversion of biomass under oxygen-limited conditions, resulting in a stable, porous structure enriched with

mineral constituents (9, 10). Biochar typically contains appreciable amounts of K, ranging from 4–91 g kg⁻¹ depending on the feedstock type and pyrolysis conditions, with a considerable proportion present in water-soluble and exchangeable forms, thereby acting as both an immediate and a potential slow-release source of K (11–14). The incorporation of BC into soil can therefore alter the equilibrium of K fractions by enhancing the labile pools. Beyond its role as a nutrient source, BC significantly influences K dynamics through its physicochemical properties. Its high surface area, porous architecture and variable charge characteristics contribute to increased cation exchange capacity, facilitating greater adsorption and retention of K⁺ ions. This reduces leaching losses, particularly in light-textured soils and moderates K fixation and release processes (15). In addition, BC-induced modifications in soil pH, moisture regime and microbial activity further regulate K transformations among different pools, including exchangeable and non-exchangeable forms.

The functional efficiency of BC is further enhanced when it is enriched with K. Potassium-enriched BC serves a dual role as a direct nutrient source and a controlled-release reservoir, thereby improving K use efficiency and reducing dependence on costly mineral fertilisers. Its polycondensed aromatic structure ensures stability and resistance to microbial decomposition, while the presence of alkaline ash constituents contributes to improved soil chemical properties and buffering capacity (16).

Potassium in soils exists in multiple forms, including water-soluble, exchangeable, non-exchangeable and mineral-bound fractions, which are in dynamic equilibrium. Among these, water-soluble and exchangeable forms constitute the readily available pool, whereas non-exchangeable K acts as a reserve that replenishes the available forms over time (17). The transformation among these pools is a continuous and dynamic process governed by soil properties, external inputs and environmental conditions. Therefore, understanding the transformation and redistribution of K among these fractions is fundamental to predicting its availability to plants (18).

A comprehensive understanding of K dynamics is particularly important because crop uptake is primarily dependent on the maintenance of equilibrium between these pools. Rapid depletion of water-soluble K during crop uptake must be compensated by release from exchangeable and non-exchangeable forms to sustain plant growth. Any disruption in this equilibrium can lead to transient deficiencies, affecting physiological processes, biomass accumulation and ultimately crop yield and quality. Moreover, K plays a critical role in improving produce quality parameters such as grain filling, starch synthesis, fruit size and resistance to biotic and abiotic stresses (19). Hence, efficient management of K requires not only adequate supply but also a clear understanding of its temporal availability and transformation behaviour in soil.

In this context, studying the temporal dynamics of K fractions becomes highly significant. The rate and pattern of transformation of K from non-available to available forms over time determine its synchronisation with crop demand. Amendments such as K-enriched biochar (KBC) and organic manures can influence these dynamics by modifying soil chemical and physical properties, thereby affecting nutrient release patterns. A time-based evaluation helps in identifying critical phases of K release, retention and transformation, which is essential for designing efficient nutrient management strategies.

Despite the recognised importance of BC in nutrient management, limited information is available on the time-dependent behaviour of K fractions following the application of KBC under controlled conditions. In particular, there is a need to understand how such amendments influence the transformation of K among different pools and their ability to sustain plant-available forms over time.

Therefore, the present study was undertaken to evaluate the effect of KBC with and without farmyard manure (FYM) on soil chemical properties and K dynamics under incubation conditions. The study was specifically designed to assess the temporal transformation and distribution of K fractions, including water-soluble, exchangeable, available and non-exchangeable forms, at different intervals. This approach provides insights into the mechanisms governing K availability and helps in developing strategies for improving K use efficiency, sustaining soil fertility and enhancing crop productivity and quality.

Materials and Methods

In view of the need to understand the temporal dynamics of K transformation and the role of KBC in regulating K availability, a controlled laboratory incubation experiment was undertaken. The study aimed to evaluate the influence of K-enriched rice husk BC, with and without FYM on soil chemical properties and the distribution of K fractions over time.

Experimental site and incubation conditions

The laboratory incubation experiment was conducted at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vishweshwaraiah Canal Farm, Mandya, Karnataka, India, which falls under Region III and Agro-Climatic Zone VI (Southern dry zone). The experimental site is located at 12°57' N latitude and 76°83' E longitude, at an altitude of 705 m above mean sea level. The experiment was carried out under controlled conditions to simulate soil processes governing K transformation and availability.

Standardised protocol for preparation of potassium-enriched rice husk biochar

Extraction of potassium from banana pseudostem

Banana pseudostem, an agro-residue rich in K, was used as the source material for K extraction (20). The initial K concentration in the pseudostem was 5.8 %. The pseudostem was chopped and subjected to sequential extraction procedure involving biological extraction using microbial cultures of *Bacillus subtilis*, *Pseudomonas putida*, *Aspergillus niger* and their combinations, followed by aqueous extraction with distilled water and organic acid extraction using citric acid, oxalic acid and tartaric acid. This procedure achieved a cumulative K recovery of 86.03 % (corresponding to a total extractable K content of 4.99 %), thereby demonstrating its efficiency in maximising K recovery from the biomass. The resulting mixture was filtered to remove solid residues, producing a K-rich solution that was subsequently used as the enrichment medium for BC impregnation.

Preparation of rice husk biochar

Rice husk BC was prepared through controlled pyrolysis under oxygen-limited conditions. The biomass was subjected to a temperature of 400 °C, with a heating rate of 10 °C min⁻¹ and a residence time of 2 hr. This process resulted in the formation of a stable carbonaceous material characterised by high porosity, large

surface area and retention of mineral ash constituents (21). The produced BC was allowed to cool under inert conditions, ground and sieved to obtain a uniform particle size suitable for soil application (Fig. 1).

Impregnation of potassium onto rice husk biochar

Potassium enrichment of rice husk BC was carried out using an ultrasonication-assisted impregnation technique, wherein a laboratory ultrasonic bath operating at 40 kHz and 150–200 W was used for 60 min to facilitate effective K impregnation. The prepared BC was mixed with the K-rich extract obtained from banana pseudostem under optimised conditions of $25 \pm 2^\circ\text{C}$ and a contact time of 60 min. Ultrasonication facilitated uniform adsorption and penetration of K ions into the porous structure of BC. The impregnated BC was subsequently air-dried to stabilise the adsorbed K and designated as KBC.

Characterisation of potassium-enriched biochar

The prepared KBC was analysed for its physicochemical properties, including pH, electrical conductivity (EC), total nitrogen (N), total phosphorus (P) and total K, using standard analytical procedures and the results are presented in Table 1 as the mean of 3 replicates. The KBC exhibited low bulk density, high porosity and good water-holding capacity, indicating its suitability as a soil amendment. It was mildly alkaline in nature (pH 8.21) with a high cation exchange capacity of $42.79 \text{ cmol (p}^+) \text{ kg}^{-1}$ and was enriched with K (4.95 %), calcium (Ca) (2.45 %) and magnesium (Mg) (1.38 %), indicating its suitability as a nutrient-enriched soil

amendment.

Initial soil characteristics

Surface soil samples (0–15 cm depth) were collected randomly from the experimental field and composited to obtain a representative sample. The soil was air-dried, ground and passed through a 2 mm sieve prior to use. The initial physicochemical properties of the soil were determined using standard methods. The soil at the experimental site was loamy sand in texture. It was neutral in reaction (pH 7.43) and had low organic carbon (OC) content (4.30 g kg^{-1}). Other initial physicochemical properties of the soil are presented in Table 2. The soil was also analysed for different K fractions to establish baseline values. The initial water-soluble, exchangeable, available, nitric acid-soluble and non-exchangeable K contents were 22.57, 55.96, 78.53, 389.85 and $311.32 \text{ mg kg}^{-1}$ respectively, indicating the distribution of K among various pools prior to incubation.

Experimental design and treatment details

The experiment was laid out in a factorial completely randomized design (FCRD) with 3 replications. A subsample of 100 g soil was placed in plastic incubation containers and treatments were imposed and mixed thoroughly. The incubation study was conducted under controlled laboratory conditions at a temperature of $25 \pm 2^\circ\text{C}$. The combination of these factors resulted in ten factorial treatments (Table 3). In addition to the factorial treatments, a separate overall control consisting of soil + FYM + 100 % recommended dose of potassium (RDK) applied through

Table 1. Physicochemical properties of potassium (K) enriched biochar (BC) used for the study

Parameter	Value	Method followed	References
Bulk density (g cm^{-3})	0.57	Keen rackzowski method	(22)
Particle density (g cm^{-3})	1.80	Pycnometer method	(22)
Porosity (%)	68.34	Keen rackzowski method	(22)
Maximum water holding capacity (%)	87.20	Keen's cup method	(23)
pH (1 : 5)	8.21	pH meter in 1 : 10 suspension (sample:water)	(24)
EC (1 : 5) (dS m^{-1})	2.70	Conductivity bridge in 1 : 10 suspension	(24)
CEC ($\text{cmol (p}^+) \text{ kg}^{-1}$)	42.79	Ammonium acetate method	(24)
C : N ratio	48.28	-	-
Carbon (%)	33.65	Dry combustion method	(24)
Nitrogen (%)	0.68	Kjeldahl digestion and distillation method	(25)
Phosphorus (%)	1.20	Diacid digestion and vanadomolybdate method	(25)
Potassium (%)	4.95	Diacid digestion and flame photometer method	(25)
Calcium (%)	2.45	Diacid digestion and Complexometric titration using EDTA method	(25)
Magnesium (%)	1.38		

EC: electrical conductivity; CEC: cation exchange capacity; C: carbon; N: nitrogen.

Table 2. Initial physicochemical properties of soil used for incubation study

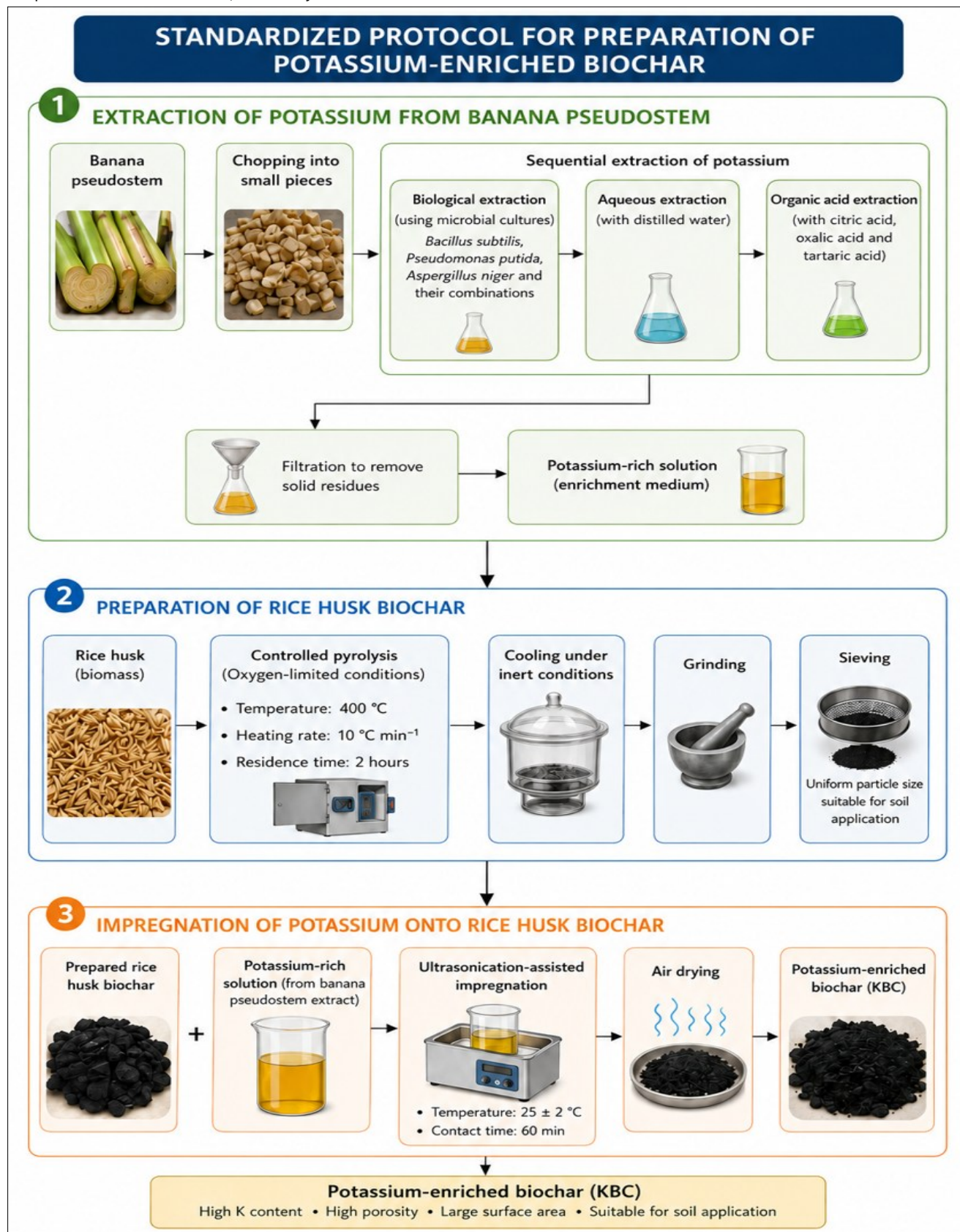
Sl. No	Parameter	Value
Physical properties		
1	Sand (%)	82.85
2	Silt (%)	4.62
3	Clay (%)	12.53
4	Textural class	Loamy sand
Chemical properties		
1	pH (1 : 2.5)	7.43
2	EC (dS m^{-1})	0.32
3	Organic carbon (g kg^{-1})	0.43
4	CEC ($\text{cmol (p}^+) \text{ kg}^{-1}$)	11.82
5	Available N (mg kg^{-1})	133.45
6	Available P_2O_5 (mg kg^{-1})	8.52
7	Available K_2O (mg kg^{-1})	76.96
8	Exchangeable Ca ($\text{cmol (p}^+) \text{ kg}^{-1}$)	6.05
9	Exchangeable Mg ($\text{cmol (p}^+) \text{ kg}^{-1}$)	2.09
10	Water soluble potassium (mg kg^{-1})	22.57
11	Exchangeable potassium (mg kg^{-1})	55.96
12	Non-exchangeable potassium (mg kg^{-1})	311.32
13	Available potassium (mg kg^{-1})	78.53
14	Nitric acid soluble potassium (mg kg^{-1})	389.85

EC: electrical conductivity; CEC: cation exchange capacity; C: carbon; N: nitrogen; Ca: calcium; Mg: magnesium.

Table 3. Experimental treatments and their descriptions

Factor type	Code	Description
Main factor	M1	Soil without amendment
	M2	Soil + FYM
Sub factor (K levels through KBC)	S1	Absolute control
	S2	25 % Recommended dose of K (RDK)
	S3	50 % RDK - KBC
	S4	75 % RDK - KBC
	S5	100 % RDK - KBC

KBC: potassium-enriched biochar; FYM: farmyard manure.

**Fig. 1.** Process flow diagram for the preparation of potassium-enriched rice husk biochar.

conventional fertiliser (muriate of potash) was maintained for

Table 3. Experimental treatments and their descriptions

Treatments	Description
T ₁ M1S1	Control (Only soil)
T ₂ M1S2	Soil at 25 % RDK through KBC
T ₃ M1S3	Soil at 50 % RDK through KBC
T ₄ M1S4	Soil at 75 % RDK through KBC
T ₅ M1S5	Soil at 100 % RDK through KBC
T ₆ M2S1	Soil + FYM
T ₇ M2S2	Soil + FYM + KBC at 25 % RDK through KBC
T ₈ M2S3	Soil + FYM + KBC at 50 % RDK through KBC
T ₉ M2S4	Soil + FYM + KBC at 75 % RDK through KBC
T ₁₀ M2S5	Soil + FYM + KBC at 100 % RDK through KBC
T ₁₁ Control	Soil + FYM+ 100 % RDK - CF

RDK: recommended dose of potassium; KBC: potassium-enriched biochar; FYM: farmyard manure; CF: chemical fertiliser.

comparison with the KBC-based treatments (Fig. 2).

Interactions

Incubation procedure and sampling

The treated soil samples were incubated for a period of 90 days under controlled laboratory conditions. Soil moisture was maintained at field capacity (18–20 % depending on the treatments) throughout the incubation period using distilled water. Field capacity was determined gravimetrically prior to incubation and the moisture content was maintained by

periodically weighing the closed incubation containers at 3-day intervals. The loss in weight, attributed to moisture evaporation, was replenished by adding an equivalent quantity of distilled water to restore the soil to its original field capacity and ensuring uniform moisture conditions across all treatments. Sampling was carried out at 1, 7, 14, 21, 30, 60 and 90 days after incubation (DAI) using a destructive sampling approach, wherein separate experimental units were utilised for analysis at each sampling interval to monitor temporal changes in soil properties and K fractions during the incubation period.

Chemical analysis of soil samples

Soil pH and electrical conductivity (EC) were determined in a 1 : 2.5 soil : water suspension using standard pH and conductivity meters (24). Soil OC was estimated by the Walkley and Black wet oxidation method. Exchangeable Ca and Mg were extracted using neutral ammonium acetate and estimated by standard titrimetric methods and expressed in cmol (p⁺) kg⁻¹ (24). Determination of potassium fractions explained in Table 4.

Statistical analysis

The data generated from the incubation study were analysed using analysis of variance (ANOVA) appropriate for a factorial completely randomized design, following the standard procedure (28). Treatment effects were tested using the 'F' test at $p \leq 0.01$ and when found significant, differences among treatment means were

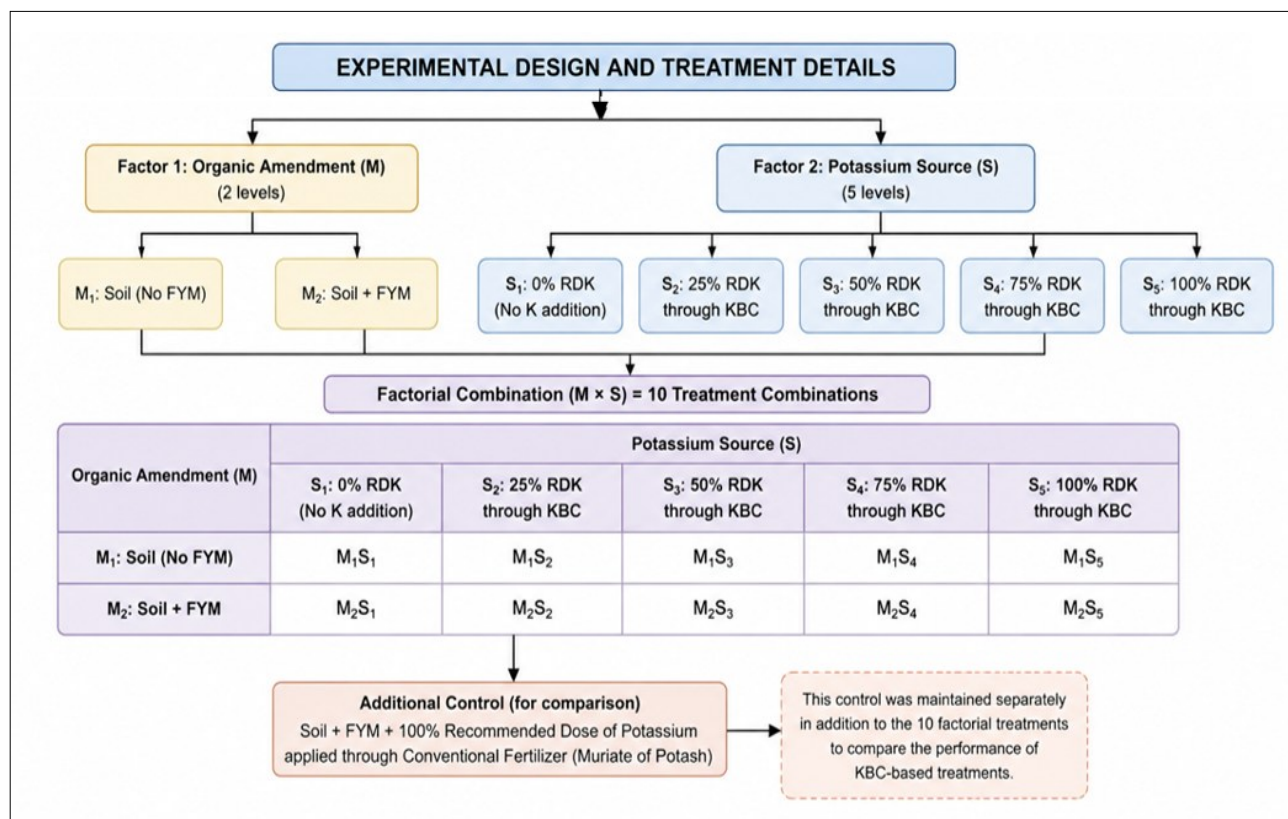


Fig. 2. Schematic diagram of the experimental design and treatment structure.

Table 4. Determination of potassium fractions

Potassium fraction (mg k ⁻¹)	Method followed	Reference
Water-soluble K	Extracted with distilled water (1 : 5 soil : solution), shaken for 1 hr and measured using flame	(26)
Available K	Extracted with 1 N neutral ammonium acetate (1 : 5), shaken for 5 min, determined by flame photometer	(24)
Exchangeable K	Calculated as the difference between available K and water-soluble K	-
Nitric acid-soluble K	Extracted by boiling soil with 1 N HNO ₃ (1 : 2.5) for 10 min, measured using flame photometer	(27)
Non-exchangeable K	Obtained by subtracting available K from nitric acid-soluble K	-

K: potassium.

separated using Duncan's multiple range test (DMRT) at the same significance level. All statistical analyses were performed using IBM SPSS Statistics (version 28.0). Graphical representations of the data were prepared using Python (version 3.13) with the Matplotlib library.

Results and Discussion

Effect of potassium enriched biochar and farmyard manure on soil chemical properties

The present investigation was undertaken to elucidate the influence of KBC, alone and in combination with FYM, on soil chemical properties and the temporal dynamics of K fractions under controlled incubation conditions. Particular emphasis was placed on understanding how these amendments regulate nutrient transformation processes, buffering behaviour and the gradual release of K across different pools, thereby contributing to sustained nutrient availability. The findings provide critical insights into the mechanisms governing K retention and transformation, which are essential for improving nutrient use efficiency and soil fertility management.

Effects on soil pH

The data on soil reaction as influenced by KBC and FYM at different stages of incubation (Table 3). Soil pH exhibited only marginal variation across treatments and incubation periods, reflecting the neutral nature and inherent buffering capacity of the experimental soil. Nevertheless, a slight increase in pH was observed with amendment application, particularly under higher levels of KBC and in combination with FYM.

In the untreated soil (M_1S_1), pH remained relatively stable throughout the incubation period, ranging from 7.31 at 1 DAI to 7.31–7.32 at later stages. Treatments receiving FYM recorded comparatively higher pH values than the control. The treatment receiving soil + FYM + 100 % RDK through conventional fertiliser increased from 7.40 at 1 DAI to 7.47 at 90 DAI. A similar but gradual increase was observed in KBC-amended treatments, where pH increased from approximately 7.38–7.39 at 1 DAI to 7.43–7.45 at 90 DAI. Among the interaction treatments, M_2S_4 and M_2S_5 maintained relatively higher pH values throughout the incubation period, reaching a maximum of 7.47. However, the overall variation in pH remained within a narrow range, indicating that the amendments exerted only a modest influence on soil reaction.

The slight increase in soil pH under KBC-amended treatments may be attributed to the presence of alkaline ash constituents and base cations such as K^+ , Ca^{2+} and Mg^{2+} in the BC. The gradual release of these constituents into the soil solution could have contributed to the observed increase in pH. The comparatively higher pH values in FYM-amended treatments may also be associated with changes in soil chemical processes during organic matter decomposition. The relatively stable pH observed across all treatments suggests that the buffering capacity of the soil moderated major changes in soil reaction during incubation. The present findings are in close agreement with earlier studies, which reported that BC application in neutral soils results in minimal but stable increases in pH due to its buffering nature (29). Similar findings were previously reported who observed that BC-induced pH changes are more pronounced in acidic soils, whereas neutral soils exhibit only slight increases depending on application rate (30). The observed trends are in agreement with earlier findings reported in the literature also emphasised that in non-

acidic soils, BC primarily functions as a chemical buffer and nutrient carrier rather than a strong liming agent (31).

Effects on soil electrical conductivity

The temporal changes in soil EC as influenced by KBC and FYM are presented in Table 5. Soil EC increased progressively with incubation, particularly under treatments receiving higher levels of KBC and FYM, indicating an increase in soluble ionic constituents in the soil solution. In the unamended soil (M_1S_1), EC values remained low throughout the incubation period, decreasing slightly from 0.32 dS m^{-1} at 1 DAI to 0.30 dS m^{-1} at 90 DAI. In contrast, KBC application resulted in a dose-dependent increase in EC, with the 100 % RDK-KBC treatment increasing from 0.36 to 0.45 dS m^{-1} during incubation. Among the interaction treatments, M_2S_5 (soil + FYM + 100 % RDK-KBC) recorded the highest EC values, increasing from 0.37 dS m^{-1} at 1 DAI to 0.49 dS m^{-1} at 90 DAI.

Treatments receiving FYM alone or in combination with KBC also exhibited a gradual increase in EC during incubation. The conventional fertiliser treatment (soil + FYM + 100 % RDK-CF) showed relatively higher EC values during the initial stages, which may be attributed to the rapid dissolution of readily soluble K salts. In contrast, KBC-amended treatments exhibited a gradual increase in EC throughout the incubation period. This trend may be attributed to the release of soluble ions from the BC matrix, including K and other base cations such as Ca and Mg.

The increase in EC was accompanied by an increase in water-soluble K across the incubation period, suggesting a positive association between soluble K and soil EC. Higher KBC levels consistently maintained greater EC values, which may be due to the increased concentration of soluble ions in the soil solution. In FYM-amended treatments, decomposition of organic matter may have further contributed to the release of soluble nutrients, resulting in higher EC values compared to the control. Similar increases in soil EC following BC application have been reported previously and were attributed to the release of soluble salts and electrolytes, with the magnitude depending on BC application rate and feedstock characteristics (32).

Effects on soil organic carbon

The influence of KBC and FYM on soil OC at different incubation stages is presented in Table 6. Soil OC was significantly influenced by both treatment and incubation period. Across all amended treatments, OC increased up to 21 DAI and thereafter declined gradually towards 90 DAI. The combined application of FYM and KBC resulted in higher OC contents throughout the incubation period compared to the control and conventional fertiliser treatments. Among the treatments, M_2S_5 (soil + FYM + 100 % RDK-KBC) recorded the highest OC, increasing from 6.06 g kg^{-1} at 1 DAI to 6.66 g kg^{-1} at 21 DAI before declining to 5.86 g kg^{-1} at 90 DAI, which was statistically on par with M_2S_4 (soil + FYM + 75 % RDK-KBC). In contrast, the unamended control (M_1S_1) consistently recorded the lowest OC values, decreasing from 4.27 to 3.97 g kg^{-1} over the incubation period. The conventional fertiliser treatment (soil + FYM + 100 % RDK-CF) also showed lower OC values, declining from 4.87 g kg^{-1} at 21 DAI to 4.37 g kg^{-1} at 90 DAI.

The initial increase in OC up to 21 DAI may be attributed to the addition of C through FYM and BC, which supplied both labile and stable C fractions. The subsequent decline in OC is likely due to microbial decomposition and mineralisation of the readily degradable organic matter during incubation. However, the

Table 5. Effect of different levels of potassium enriched biochar (KBC) application on soil pH and electrical conductivity at different intervals

Treatments	Soil reaction (pH)					EC (dS m ⁻¹)									
	Days after incubation (DAI)														
	1	7	14	21	30	60	90	1	7	14	21	30	60	90	
Main factor (M): Soil condition															
M1: Soil	7.36	7.37	7.37	7.38	7.39	7.40	7.40	0.34	0.34	0.35	0.35	0.35	0.36	0.37	
M2: Soil + FVM	7.39	7.40	7.40	7.41	7.42	7.42	7.44	0.35	0.38	0.39	0.40	0.41	0.43	0.43	
S. Em±	0.03										0.001	0.001	0.001	0.002	0.002
CD at 1 %	NS										0.005	0.005	0.006	0.006	0.006
Sub factor (S): Levels of KBC															
S1: Absolute control	7.36	7.34	7.34	7.35	7.35	7.34	7.34	0.32	0.32	0.32	0.33	0.33	0.33	0.33	
S2: 25 % RDK-KBC	7.38	7.39	7.39	7.40	7.41	7.42	7.43	0.33	0.34	0.35	0.36	0.37	0.37	0.38	
S3: 50 % RDK-KBC	7.38	7.39	7.39	7.41	7.42	7.43	7.44	0.34	0.36	0.37	0.38	0.39	0.40	0.40	
S4: 75 % RDK-KBC	7.39	7.40	7.40	7.42	7.43	7.44	7.45	0.35	0.38	0.39	0.39	0.40	0.42	0.43	
S5: 100 % RDK-KBC	7.39	7.41	7.41	7.42	7.43	7.43	7.45	0.36	0.40	0.41	0.42	0.43	0.44	0.45	
S. Em ±	0.05										0.002	0.002	0.002	0.002	0.002
CD at 1 %	NS										0.008	0.009	0.009	0.009	0.010
M × S															
M1S1	7.33	7.31	7.31	7.32	7.32	7.31	7.31	0.32	0.31	0.31	0.31	0.30	0.30	0.30	
M1S2	7.37	7.39	7.39	7.39	7.39	7.41	7.41	0.33	0.34	0.34	0.35	0.35	0.35	0.36	
M1S3	7.37	7.38	7.38	7.39	7.41	7.42	7.42	0.34	0.34	0.35	0.35	0.36	0.36	0.37	
M1S4	7.38	7.39	7.39	7.40	7.42	7.43	7.43	0.35	0.36	0.36	0.37	0.37	0.38	0.39	
M1S5	7.37	7.38	7.38	7.40	7.41	7.41	7.42	0.36	0.37	0.38	0.39	0.40	0.41	0.42	
M2S1	7.39	7.37	7.37	7.37	7.37	7.36	7.36	0.33	0.34	0.34	0.35	0.36	0.36	0.37	
M2S2	7.38	7.39	7.39	7.41	7.42	7.42	7.44	0.34	0.35	0.36	0.38	0.39	0.39	0.40	
M2S3	7.39	7.40	7.40	7.42	7.42	7.44	7.46	0.35	0.38	0.40	0.41	0.43	0.44	0.44	
M2S4	7.40	7.41	7.41	7.43	7.44	7.45	7.47	0.36	0.41	0.42	0.42	0.44	0.47	0.48	
M2S5	7.40	7.43	7.43	7.43	7.44	7.45	7.47	0.37	0.43	0.44	0.45	0.46	0.48	0.49	
*Control	7.38	7.37	7.36	7.36	7.37	7.38	7.38	0.39	0.44	0.44	0.45	0.46	0.47	0.47	
S. Em ±	0.06										0.003	0.003	0.003	0.003	0.004
CD at 1 %	NS										0.012	0.013	0.013	0.014	0.014

RDK: recommended dose of potassium; KBC: potassium-enriched biochar.

Table 6. Effect of different levels of potassium enriched biochar (KBC) application on organic carbon (OC) content at different intervals

Treatments	Organic carbon (g kg ⁻¹)						
	Days after incubation (DAI)						
	1	7	14	21	30	60	90
Main factor (M): Soil condition							
M1: Soil	4.51	4.59	4.65	4.69	4.59	4.49	4.49
M2: Soil + FYM	5.84	5.86	6.00	6.06	5.80	5.48	5.24
S.Em±	0.020	0.020	0.021	0.021	0.020	0.019	0.019
CD at 1 %	0.079	0.08	0.081	0.082	0.079	0.076	0.074
Sub Factor (S): Levels of KBC							
S1: Absolute control	4.92	4.52	4.57	4.47	4.42	4.27	4.22
S2:25 % RDK-KBC	5.07	5.17	5.22	5.31	5.12	4.82	4.72
S3:50 % RDK-KBC	5.12	5.26	5.36	5.41	5.22	5.02	4.87
S4:75 % RDK-KBC	5.31	5.51	5.66	5.71	5.56	5.36	5.22
S5:100 % RDK-KBC	5.46	5.66	5.81	5.96	5.66	5.46	5.31
S. Em±	0.032	0.032	0.033	0.033	0.032	0.031	0.03
CD at 1 %	0.125	0.126	0.129	0.130	0.125	0.120	0.117
M × S							
M1S1	4.27	4.17	4.17	4.07	4.07	3.97	3.97
M1S2	4.37	4.47	4.47	4.57	4.57	4.47	4.47
M1S3	4.37	4.57	4.67	4.67	4.67	4.57	4.57
M1S4	4.67	4.77	4.87	4.87	4.77	4.67	4.67
M1S5	4.87	4.97	5.07	5.26	4.87	4.77	4.77
M2S1	5.56	4.87	4.97	4.87	4.77	4.57	4.47
M2S2	5.76	5.86	5.96	6.06	5.66	5.17	4.97
M2S3	5.86	5.96	6.06	6.16	5.76	5.46	5.17
M2S4	5.96	6.26	6.46	6.56	6.36	6.06	5.76
M2S5	6.06	6.36	6.56	6.66	6.46	6.16	5.86
*Control	4.47	4.77	4.87	4.77	4.67	4.47	4.37
S. Em±	0.045	0.045	0.046	0.047	0.045	0.043	0.042
CD at 1 %	0.178	0.180	0.184	0.186	0.179	0.172	0.167

relatively higher OC maintained in KBC-amended soils suggests enhanced C stabilisation and retention. This may be attributed to the recalcitrant nature of BC carbon and its ability to protect organic matter through improved soil aggregation and organo-mineral interactions. Similar improvements in soil C sequestration and stability following BC application have been reported previously (33, 34). Previous studies have also reported a synergistic effect of BC and organic amendments in enhancing soil OC and reducing the mineralisation of native soil organic matter (35, 36).

Effects of potassium-enriched biochar on exchangeable calcium and magnesium

The results pertaining to exchangeable Ca and Mg as influenced by different levels of KBC and FYM at different intervals of incubation are presented in Table 7.

Exchangeable Ca content in soil was significantly influenced by both KBC levels and incubation period, with a consistent increasing trend observed from 1–90 DAI across treatments. The magnitude of increase was more pronounced under treatments receiving FYM in combination with higher levels of KBC. The treatment M2S5 recorded the highest exchangeable Ca, increasing from 6.05–7.40 cmol (p⁺) kg⁻¹ and was statistically on par with 75 % RDK-KBC, which also showed a substantial increase over time. In contrast, the unamended soil (M1S1) maintained nearly stable Ca levels (~6.00–5.99 cmol (p⁺) kg⁻¹), indicating minimal contribution from native sources. The conventional fertiliser treatment recorded comparatively lower values (6.02–6.26 cmol (p⁺) kg⁻¹), suggesting limited contribution to exchangeable Ca compared to KBC-based treatments.

A similar trend was observed for exchangeable Mg, which exhibited a progressive increase with incubation time and amendment levels. Treatments receiving FYM in combination with KBC showed significantly higher Mg content compared to unamended soil and conventional fertiliser treatments. The

highest Mg content was recorded under 100 % RDK-KBC, increasing from 2.14–3.40 cmol (p⁺) kg⁻¹ between 1 and 90 DAI, followed closely by 75 % RDK-KBC. In contrast, the control maintained relatively low and stable Mg levels (2.10–2.08 cmol (p⁺) kg⁻¹), while the conventional fertiliser treatment showed only a moderate increase (2.11–2.31 cmol (p⁺) kg⁻¹), indicating comparatively lower enrichment.

An important outcome of the study is the strong interrelationship between soil OC and exchangeable cation status. Treatments that recorded higher OC, particularly those receiving FYM and higher levels of KBC, also exhibited increased levels of exchangeable Ca and Mg. This relationship can be explained through BC and organic matter-induced enhancement of cation exchange capacity (CEC). The increase in OC contributes to the development of negatively charged functional groups, which enhance the soil's ability to adsorb and retain base cations. Simultaneously, BC with its high surface area and variable charge characteristics, further augments CEC, thereby improving the retention of Ca²⁺ and Mg²⁺ on exchange sites. This synergistic effect not only prevents leaching losses but also ensures a sustained supply of secondary nutrients in plant-available forms. These findings are in agreement with early findings who reported increased exchangeable base cations following BC application due to the presence of ash and alkaline constituents (37). Similar results were previously documented who observed enhanced availability of Ca and Mg with BC addition, attributed to improved soil chemical properties and nutrient retention mechanisms (38).

Effects of potassium enriched biochar on soil potassium dynamics

The distribution and temporal transformation of different P fractions as influenced by KBC and FYM are presented in Fig. 3. The results revealed distinct yet interrelated trends among water-soluble, exchangeable, available, non-exchangeable and nitric acid-soluble K, highlighting the dynamic equilibrium governing P

Table 7. Effect of different levels of potassium enriched biochar (KBC) application on exchangeable calcium and magnesium content at different intervals

Treatments	Exchangeable Ca [cmol (p ⁺) kg ⁻¹]										Exchangeable Mg [cmol (p ⁺) kg ⁻¹]									
	Days after incubation (DAI)																			
	1	7	14	21	30	60	90	1	7	14	21	30	60	90						
Main factor (M): Soil condition																				
M1: Soil	6.02	6.12	6.15	6.25	6.31	6.36	6.39	2.11	2.13	2.16	2.20	2.24	2.26	2.30						
M2: Soil + FVM	6.04	6.19	6.34	6.49	6.66	6.91	7.06	2.12	2.20	2.30	2.41	2.54	2.73	2.94						
S. Em ±	0.023	0.024	0.024	0.0247	0.0252	0.0257	0.026	0.008	0.008	0.009	0.0089	0.0093	0.0098	0.010						
CD at 1 %	0.091	0.093	0.094	0.096	0.098	0.100	0.102	0.032	0.033	0.034	0.035	0.036	0.038	0.040						
Sub Factor (S): Levels of KBC																				
S1: Absolute control	6.01	6.04	6.07	6.10	6.11	6.16	6.17	2.10	2.11	2.14	2.16	2.16	2.18	2.19						
S2: 25 % RDK-KBC	6.02	6.15	6.21	6.33	6.43	6.56	6.69	2.11	2.14	2.19	2.24	2.30	2.41	2.53						
S3: 50 % RDK-KBC	6.03	6.16	6.26	6.41	6.53	6.72	6.84	2.12	2.17	2.24	2.31	2.43	2.52	2.67						
S4: 75 % RDK-KBC	6.03	6.19	6.31	6.48	6.67	6.83	6.92	2.12	2.19	2.27	2.36	2.51	2.65	2.78						
S5: 100 % RDK-KBC	6.04	6.22	6.36	6.54	6.71	6.89	6.99	2.13	2.22	2.32	2.45	2.56	2.73	2.93						
S. Em ±	0.037	0.038	0.038	0.039	0.040	0.041	0.041	0.013	0.013	0.014	0.014	0.015	0.015	0.016						
CD at 1 %	0.144	0.147	0.149	0.152	0.155	0.159	0.161	0.050	0.052	0.053	0.055	0.057	0.060	0.063						
M × S																				
M1S1	6.00	6.00	6.01	6.00	6.00	5.99	5.99	2.10	2.10	2.11	2.11	2.09	2.09	2.08						
M1S2	6.02	6.14	6.16	6.28	6.35	6.37	6.38	2.11	2.12	2.13	2.15	2.18	2.23	2.28						
M1S3	6.02	6.15	6.18	6.31	6.38	6.44	6.46	2.11	2.13	2.16	2.19	2.22	2.25	2.31						
M1S4	6.03	6.15	6.19	6.33	6.40	6.47	6.55	2.12	2.15	2.19	2.23	2.36	2.37	2.38						
M1S5	6.04	6.16	6.21	6.34	6.44	6.54	6.58	2.13	2.17	2.22	2.32	2.36	2.38	2.46						
M2S1	6.03	6.08	6.14	6.20	6.23	6.34	6.36	2.10	2.13	2.17	2.21	2.24	2.26	2.30						
M2S2	6.03	6.17	6.26	6.38	6.51	6.75	7.00	2.11	2.17	2.24	2.33	2.42	2.60	2.78						
M2S3	6.04	6.18	6.34	6.51	6.68	7.00	7.23	2.13	2.21	2.31	2.43	2.65	2.78	3.03						
M2S4	6.04	6.24	6.44	6.64	6.93	7.19	7.30	2.13	2.24	2.36	2.50	2.65	2.93	3.18						
M2S5	6.05	6.28	6.51	6.73	6.97	7.25	7.40	2.14	2.26	2.42	2.58	2.76	3.08	3.40						
*Control	6.02	6.06	6.10	6.14	6.18	6.24	6.26	2.11	2.14	2.17	2.20	2.23	2.26	2.31						
S. Em ±	0.052	0.053	0.054	0.055	0.056	0.057	0.058	0.018	0.019	0.019	0.020	0.021	0.022	0.023						
CD at 1 %	0.208	0.212	0.215	0.219	0.223	0.228	0.231	0.073	0.075	0.077	0.079	0.082	0.086	0.091						

*Soil + FVM + 100 % RDK - CF; RDK: recommended dose of potassium; KBC: potassium-enriched biochar.

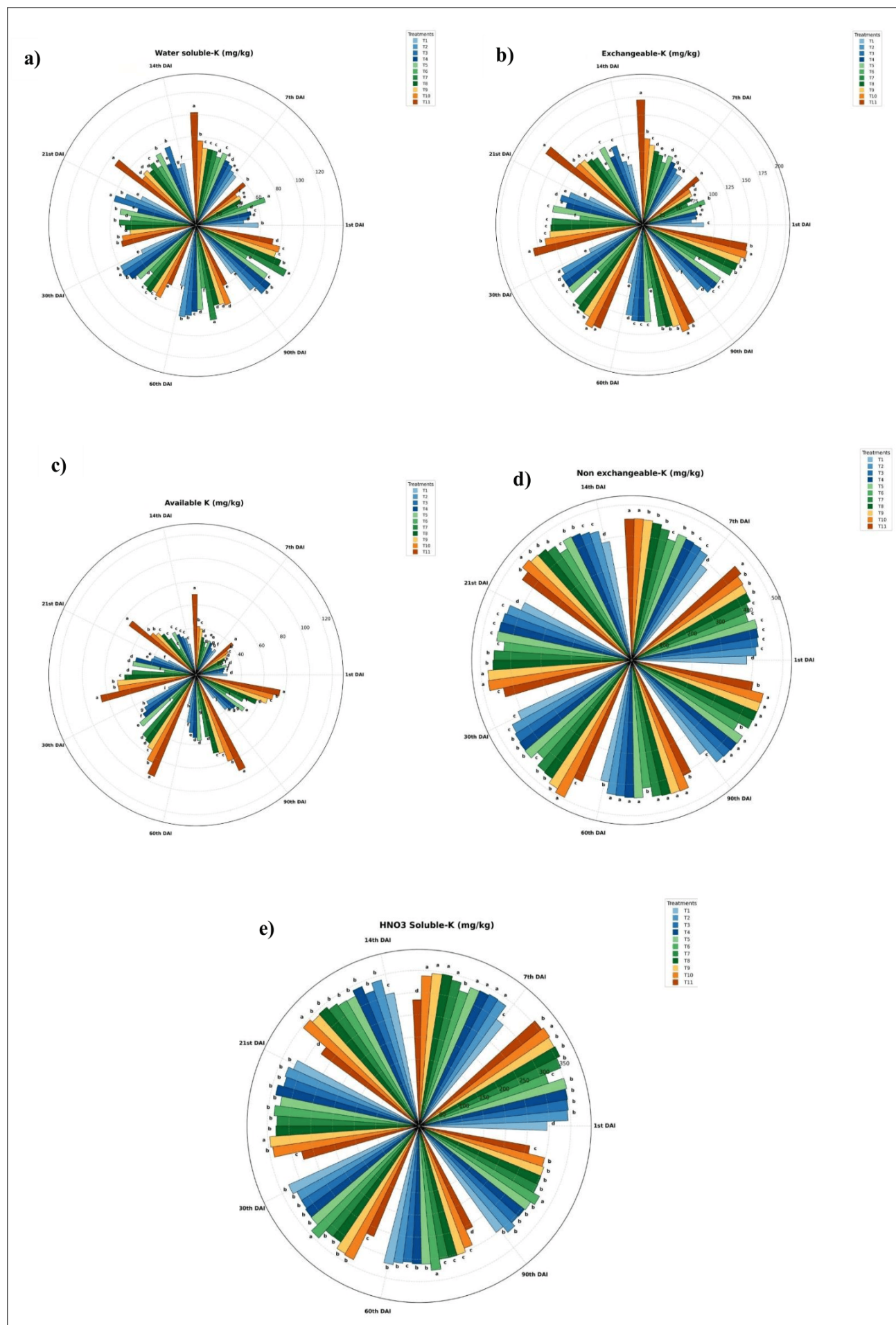


Fig. 3. Changes in potassium (K) fractions during incubation under different doses of potassium-enriched biochar: (a) water-soluble K, (b) exchangeable K, (c) available K, (d) non-exchangeable K and (e) nitric acid-soluble K. Values represent mean $\pm$ standard error. Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test.

behaviour in soil systems.

Water-soluble potassium

Water-soluble K, representing the immediately available pool, was significantly influenced by both treatments and incubation period (Fig. 3a). Across all stages, KBC and FYM-amended soils recorded higher water-soluble K compared to soil alone, which maintained the lowest and relatively stable values (27.39–25.21 mg kg⁻¹ from 1–90 DAI).

A clear temporal pattern was observed, with water-soluble K increasing up to 30 DAI followed by a decline thereafter. Among treatments, 100 % RDK-KBC showed a substantial increase from 34.39–84.35 mg kg⁻¹ at 30 DAI, followed by 75 % RDK-KBC (31.27–74.98 mg kg⁻¹). The conventional fertiliser treatment recorded higher initial values (41.56 mg kg⁻¹) and peaked at 94.64 mg kg⁻¹ at 30 DAI but declined sharply to 75.35 mg kg⁻¹ at 90 DAI. In contrast, KBC + FYM treatments exhibited a more gradual decline, maintaining comparatively higher water-soluble K at later stages (e.g., 100 % RDK-KBC: 84.35–70.15 mg kg⁻¹). The initial increase is attributed to release of K from BC ash and FYM mineralisation, while the slower decline under KBC indicates controlled release and reduced losses. The role of FYM-derived organic acids in mobilising K from less available pools further contributes to sustained availability. These findings are consistent with previous studies (39, 40), that indicated integrating organic and inorganic K sources maintains higher water-soluble K due to gradual nutrient release and sustaining K availability in soil.

Exchangeable potassium

Exchangeable K, which serves as a buffering pool for soil solution K, showed a distinct build-up over time in KBC-amended treatments, in contrast to declining trends in unamended soil. Soil alone showed a gradual decrease from 57.73–54.75 mg kg⁻¹, indicating depletion in the absence of external inputs. The conventional fertiliser treatment exhibited a sharp initial increase (up to 101.76 mg kg⁻¹ at 7 DAI) followed by a rapid decline to 58.75 mg kg⁻¹ at 30 DAI, reflecting quick solubilisation and subsequent fixation or redistribution. In contrast, KBC + FYM treatments demonstrated a steady and sustained increase. For instance, 25 % RDK-KBC increased from 42.06–93.37 mg kg⁻¹ and 50 % RDK-KBC from 46.81–85.17 mg kg⁻¹ over the incubation period (Fig. 3b). Higher KBC levels maintained elevated exchangeable K even at later stages, indicating enhanced retention and reduced fixation.

This trend can be attributed to the enriched K content of BC, improved cation exchange capacity (CEC) and increased availability of adsorption sites. The porous structure of BC facilitates adsorption-desorption equilibrium, while FYM enhances K mobilisation through organic acid production. These observations align with the findings of previous studies, who reported improved exchangeable nutrient status with biochar application (37, 38).

Available potassium

Available K, comprising water-soluble and exchangeable fractions, followed trends similar to these pools. The KBC-amended soils maintained higher available K throughout incubation compared to control treatments. A progressive increase up to 30 DAI was observed, followed by a slight decline. The treatment 100 % RDK-KBC increased from 80.38–157.78 mg kg⁻¹ at 30 DAI and maintained 150.47 mg kg⁻¹ at 90 DAI, while 75 % RDK-KBC showed comparable values (79.33–146.26 mg kg⁻¹, maintaining 144.65 mg kg⁻¹). The

conventional fertiliser treatment also showed high initial values (153.39 mg kg⁻¹ at 30 DAI) but declined more sharply (148.25 mg kg⁻¹ at 90 DAI) compared to KBC treatments (Fig. 3c). This indicates that although mineral fertilisers provide immediate K, they lack sustained supply. The higher and sustained availability under KBC treatments is attributed to K enrichment, slow-release behaviour and enhanced CEC, which together synchronise K release with soil demand. FYM further contributes by mobilising K from non-exchangeable pools (29, 37). The decline in available K observed towards 90 days suggests possible utilisation and redistribution into less available forms. The incubation period was restricted to 90 days, as this duration represents a critical phase during which dynamic transformations among various soil K pools are most pronounced and significantly influence K availability, absorption and assimilation by crop plants. Understanding these transformations during this period is particularly important, as they largely determine the K-supplying capacity of the soil throughout a typical crop growth cycle. However, K transformations beyond 90 days may continue to alter the distribution of K fractions and contribute to residual K availability. Therefore, long-term investigations are required to elucidate the fate of applied K and its residual effects on succeeding crops under field conditions.

Non-exchangeable potassium

Non-exchangeable K, representing the reserve pool, showed a declining trend with incubation time, indicating its gradual transformation into available forms. Initial values were higher in KBC treatments (356.32 mg kg⁻¹ under 100 % RDK-KBC) compared to soil alone (336.63 mg kg⁻¹). Over time, values declined across treatments, with soil alone decreasing to 306.74 mg kg⁻¹, while FYM-amended soil showed a similar reduction. KBC treatments exhibited a more gradual decline (361.89–298.13 mg kg⁻¹ under M2S5), whereas the conventional fertiliser treatment showed a sharper depletion (356.49–259.57 mg kg⁻¹) (Fig. 3d). The gradual reduction under KBC treatments indicates regulated release of fixed K, supported by equilibrium-driven desorption mechanisms. Biochar enhances retention while FYM-derived organic acids facilitate release from mineral lattices. In contrast, rapid depletion under conventional fertiliser suggests exhaustion of reserve pools due to lack of buffering mechanisms (41).

Nitric acid soluble potassium

Nitric acid-soluble K, representing total reserve K, increased up to 30 DAI and declined thereafter. Soil alone increased from 413.21–444.61 mg kg⁻¹, then decreased to 424.39 mg kg⁻¹ at 90 DAI (Fig. 3e). A similar pattern was observed in FYM-treated soil. The KBC treatments recorded higher peak values, with 100 % RDK-KBC reaching 475.95 mg kg⁻¹ at 30 DAI, followed by a decline to 444.29 mg kg⁻¹ at 90 DAI. In contrast, the conventional fertiliser treatment showed a continuous decline (456.24–407.81 mg kg⁻¹). The moderated decline under KBC treatments suggests better buffering and retention of K within soil fractions, attributed to increased CEC and adsorption capacity. The continuous depletion under conventional fertiliser indicates rapid solubilisation without replenishment of reserve pools. The previous findings also indicate stabilisation of K fractions with applications of organic amendments (41).

The results clearly demonstrate that K in soil exists in a dynamic equilibrium among different fractions and the application of KBC significantly modifies this equilibrium. Initially, K released from KBC and FYM contributes to an increase in the water-soluble pool, which is readily available for plant uptake. As incubation

progresses, a portion of this soluble K is adsorbed onto exchange sites, leading to an increase in the exchangeable fraction, while some is temporarily fixed into non-exchangeable forms within soil minerals. At the same time, non-exchangeable K acts as a reserve pool, gradually releasing K to replenish the water-soluble and exchangeable fractions as these become depleted, thereby maintaining equilibrium among different K pools. The nitric acid-soluble fraction represents the overall reserve capacity of K in the soil, which was better maintained under KBC treatments due to improved buffering and reduced losses over time.

The conventional fertiliser treatment exhibited a rapid increase in water-soluble and exchangeable K followed by a sharp decline, due to rapid dissolution, fixation and possible losses. In contrast, KBC treatments, particularly in combination with FYM, showed a more regulated and synchronised transformation pattern characterised by gradual release, enhanced retention and sustained availability of K. This behaviour can be attributed to the K enrichment of BC, its porous structure and high surface area, which facilitate adsorption-desorption processes. In addition, the enhanced cation exchange capacity of BC improves K retention, while FYM-mediated mineralisation produces organic acids that promote the release of K from non-exchangeable pools. Thus, the combined application of KBC and FYM ensures a balanced transformation of K among different pools, maintains dynamic equilibrium and sustains plant-available K over time. This has important implications for improving K use efficiency, minimising nutrient losses and enhancing long-term soil fertility and crop productivity.

Conclusion

The present study demonstrated that potassium-enriched rice husk biochar (KBC), particularly when integrated with farmyard manure (FYM), significantly improved soil potassium (K) dynamics and enhanced soil chemical properties. The combined application of KBC and FYM increased water-soluble, exchangeable, available and nitric acid-soluble K fractions, while facilitating a balanced transformation among different K pools and sustaining plant-available K over time. Improvements in soil organic carbon (OC), exchangeable calcium (Ca) and magnesium (Mg) further highlighted the beneficial effects of the amendment on soil fertility. Future research should focus on long-term field evaluations to assess residual K availability to succeeding crops, the persistence of K transformations under cropping systems and the energy and environmental implications associated with BC production and K-enrichment processes. Nevertheless, the present findings clearly demonstrate the potential of KBC, particularly when combined with FYM, as a sustainable nutrient management strategy for improving K use efficiency, reducing nutrient losses and enhancing long-term soil fertility.

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Authors' contributions

KD conducted and designed the study, performed the investigation and formal analysis, curated the data and drafted the manuscript. SR contributed to the study conceptualisation and methodology, carried out the investigation, validated the results, reviewed and edited the manuscript and provided supervision. ANN, YSB, AMA and RV designed and conceived the study idea and comprehensively reviewed and edited the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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