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Vertical Distribution of Forms of Potassium in Rice-based Cropping Systems of Gangetic Alluvial Soil of West Bengal, India

Haripada Mondal and M. C. Kundu

Dept. of Soil Science and Agricultural Chemistry, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati, Sriniketan, West Bengal (731 236), India

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Corresponding mckundu@gmail.com

0000-0003-4575-7472

ABSTRACT

The study was conducted during *rabi* (e.g., November, 2022–April 2023) at the North 24 Parganas district of West Bengal, India. The objective was to assess the K status in rice-based cropping systems of Gangetic alluvial soil of North 24 Parganas Potassium (K) is required for crops, affecting growth, yield, tissue strength, resistance to pests, and activation of enzymes. A total of 225 soil samples were collected from varying depths and rice-based cropping systems and were analysed for different forms of potassium and physico-chemical properties. The results showed extreme variation in the forms of potassium: available K, water-soluble K, exchangeable K, non-exchangeable K, total K, and lattice K with the cropping systems and depths. The Rice-Vegetables system had the highest values of available K, water-soluble K, exchangeable K, and HNO_3 soluble K, and the Rice-Rice system had the highest values of non-exchangeable, lattice, and total K. On the other hand, the Rice-Mustard-Jute system had the lowest values in many forms of potassium, except water-soluble K, which was lowest in the Rice-Rice system. Overall, all fractions of K were maximum at 30–45 cm depth and minimum at 15–30 cm depth, increasing with increasing depth of soil. Various forms of potassium significantly and positively correlated with clay content and bulk density, and with each other, resulting in a dynamic equilibrium that was conducive to the supply of K to the crops.

KEYWORDS: Potassium forms, cropping systems, depths, correlations, soil properties

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1. INTRODUCTION

Potassium, the 3rd most essential plant nutrient following nitrogen and phosphorus, is extensively distributed in the Earth's crust and constitutes about 2.60% by weight (Wedepohl, 1995) and effective potassium management is crucial based on soil K availability (Vijayakumar et al., 2024; Xu et al., 2025). It occurs mostly in the soil in the form of structural forms, primarily in minerals like muscovite, biotite, feldspar, and secondary clay minerals like illite. K-feldspars release potassium directly into the soil solution. The roles of potassium in plants include facilitating the translocation of synthases, enhancing water transport, strengthening plant tissues, avoiding lodging, enhancing resistance to pests and diseases, regulating stomatal movement, and activating enzymes, thus making it the "quality element" or master cation (Ahmed et al., 2023; Sidhu et al., 2024; Sidhu et al., 2025a; Sidhu et al., 2025b). Soil potassium occurs in different forms: water-soluble, exchangeable, non-exchangeable, HNO_3 soluble, lattice, and total. Water-soluble potassium is available to microbes and plants but is amenable to leaching. Exchangeable potassium is held electrostatically by humic acids and clay minerals and are small fractions of total potassium in the soil (0.1–0.2 %) water-soluble and 1–2 % exchangeable (Sparks, 1987). Non-exchangeable potassium, somewhat trapped among mineral layers, has moderate availability for plants (Sparks and Huang, 1998; Lalitha and Dakshinamoorthy, 2014; Fontana et al., 2022; Rani et al., 2023; Islam et al., 2023). Potassium mineral, included in the crystal structures of soil minerals, constitutes a significant portion of the overall potassium present in the soil (Sadusky et al., 1987). Understanding the dynamic equilibrium of forms of potassium in the soil is crucial as it has a significant impact on the concentration available in the solution and its availability to plants (Ndukwu et al., 2012; Harinkhere et al., 2025). If crops fail to utilize available potassium, the reserve in the soil will not be utilized, thus preventing the release of exchangeable and non-exchangeable potassium. Potassium dynamics in the soil solution, such as exchange rates, retention, mineral composition, and leaching, are critical in determining its availability (Sparks, 2000; Xiong et al., 2023; Hashemi et al., 2024; Xu et al., 2025). Equilibrium between soluble and exchangeable potassium is rapidly established, while that between exchangeable and non-exchangeable is established slowly and in many cases is affected by soil amendments and leaching (Fontana et al., 2022; Das et al., 2024). Balanced nutrition, incorporating all essential nutrients, is vital for sustainable crop production. Increased cropping intensity and the shift to high-yielding varieties have caused potassium deficiencies, even in soils that appear to have sufficient potassium levels. In West Bengal, potassium availability status is variable: low in red and lateritic soils, low to medium in hill and tarai soils, and medium to high in alluvial and coastal saline soils (Sanyal and Majumdar, 2001; Langmuana, 2014). Despite multiple potassium levels, its usage remains low due to the belief that soils are K-rich; however, intensive cultivation can deplete potassium reserves rapidly. Information regarding potassium forms in rice-based cropping systems in the Gangetic alluvial zone, particularly in the North 24 Parganas district, is limited, which complicates sustainable soil fertility management. Fertilizer recommendations based on accurate estimates of the potassium-supplying power of soils from available K content and interactions between its forms are necessary. Accordingly, studies on potassium dynamics and its interactions with soil attributes in this area are vital not only to present the long-term availability of nutrients to crops but also to ideal fertilizer regimes. The objective of this study was to explore the impact of rice-based cropping system on the forms of potassium in the soils, to understand interrelations among the forms of potassium, as well as their associations with the physical and chemical properties of the soils.

2. MATERIALS AND METHODS

2.1. Description of study area

The study was conducted during *rabi* (e.g. November, 2022–April, 2023) at North 24 Parganas district of West Bengal, India. The climate of North 24 Parganas was tropical with a June-to-mid-October monsoon, late November-to-mid-February dry winter, and high summer humidity. The temperature was between 41 °C in May and 10 °C in January, with 1,579 mm of rainfall in a year. The physiography of the district was mostly plain and had rivers such as Bhagirathi, Jalangi, and Icchamati flowing from north to south. The elevation of the district was between 1 m and 25 m, with an average of 6 m.

This district falls under the new alluvial region of the lower Gangetic Plain, which was considered the most fertile for crop production. The soil type was variable, ranging from sandy clay to sandy loam, with a distribution ratio of high, medium, and low land being 17:33:39. The northern region was dominated by sandy soils, the central one by sandy clay loam, and the southern region by clay loam. Soils of this zone were derived from recent alluvial deposits brought down by the river Ganga; hence, the soil order is *Inceptisol*. Soils were deep, well-drained, with high base saturation and CEC. Soil reaction varied around neutral from mildly acidic to mildly alkaline, and crops gave a good response to NPK fertilizer.

2.2. Soil sampling

In 2023, a visual field survey was conducted to assess the differences in the study region. The areas were selected for soil sampling based on rice production systems that have been in place for at least ten years. Fifteen representative fields were selected from each cropping system *viz.*, Rice-Vegetable, Rice-Fallow, Rice-Rice, Rice-Jute, and Rice-Mustard-Jute. Soils were sampled from three various spots of each field using a screw type soil auger from three different depths: 0–15 cm, 15–30 cm, and 30–45 cm. A single composite soil sample was prepared by collecting sub-samples from each field at each depth. Thus, total of 225 [5 (rice-based cropping systems)×15 (representative fields)×3 (depths)=225] numbers of soil samples were collected for analysis. For the determination of physical and chemical properties like potassium forms, soil samples from the different land use categories were air dried, blended, and sieved. The sample points were identified through GPS, and the core samples were taken at 0–15 cm, 15–30 cm, and 30–45 cm depths from each field for bulk density determination.

2.3. Analysis of soil physicochemical properties

Particle size analysis was conducted using the Bouyoucos hydrometric method after organic matter removal with 6% H_2O_2 and soil dispersion with 5% sodium hexametaphosphate (Gee and Baunder, 1986). A cylindrical core sampler was inserted into the soil at varying depths and removed to maintain sample volume. The sample was dried to 105 °C for bulk density determination by oven-dried soil weight divided by field volume (Blake and Hartge, 1968). Soil pH was determined with the glass electrode method employing a 1:2.5 soil:water suspension ratio and a Systronics pH meter as defined by Jackson (1958). Electrical conductivity (EC) was determined in the same way, with measurements taken following overnight settling of the soil suspension as defined by Jackson (1958). Walkley and Black (1934) wet digestion method was employed to determine organic carbon in which 1 g of soil was digested with potassium dichromate and sulfuric acid, and then titrated with ferrous ammonium sulphate. Available nitrogen was estimated using the alkaline $KMnO_4$ method, which involved oxidizing soil organic matter and distilling with NaOH, with ammonia captured in sulfuric acid and titrated with standard alkali. Available phosphorus was determined by the Olsen method using 0.5 M $NaHCO_3$, with P_2O_5 content analyzed by spectrophotometry at 660 nm. Available sulphur was computed using a 0.15% $CaCl_2$ solution, shaken and filtered, with spectrophotometric readings taken at 440 nm after the addition of $BaCl_2$ and gum acacia.

2.4. Analysis of different forms of potassium (K)

2.4.1. Available potassium

Available potassium was extracted from a 5 g soil sample using 25 ml neutral ammonium acetate (1:5 w/v) and measured with a flame photometer, following the method of Jackson (1958).

2.4.2. Water-soluble potassium

Water soluble potassium was extracted using Mc Lean's method (1960), shaking soil and water (1:2 ratio) for 2 h, standing for 16 h, and measuring potassium with a flame photometer (Jackson, 1958).

2.4.3. Nitric acid soluble potassium

This was also dissolved in 1N HNO3 in the ratio of 1:10 and boiled for 10 min according to the protocol outlined by Wood and DeTurk (1941), and its potassium was determined with a flame photometer (Jackson, 1958).

2.4.4. Exchangeable potassium

The value was derived by the subtraction of the water-soluble potassium readings from the available potassium readings.

2.4.5. Non-exchangeable potassium

Non-exchangeable potassium was calculated by deducting available potassium from the nitric acid-soluble potassium.

2.4.6. Lattice potassium

The lattice potassium was computed as difference between total potassium and the sum of water soluble, exchangeable and non-exchangeable K fractions

2.4.7. Total potassium

Using Pratt's method (1951), in a platinum crucible, 0.1 g of soil was digested in 5 ml of hydrofluoric acid and 0.5 ml of perchloric acid. 5 ml of 6 (N) HCl and 5 ml of water were added after cooling, and they were gently heated. The residue was transferred into a 100 ml volumetric flask, volume was adjusted to the mark. Then, potassium was measured by a flame photometer from the extract (Jackson, 1958).

2.4.8. Statistical analysis

Range, mean, and standard deviation of physicochemical attributes and potassium content of the soil were calculated in Excel. Potassium content differences, both in cropping system and depth, were compared using Duncan's multiple-range test in SPSS 20.0. Simple correlation analysis was also conducted to explore the correlation among various potassium forms and soil attributes, in SPSS 20.0.

3. RESULTS AND DISCUSSION

3.1. Effects of rice-based cropping systems and soil depths on various forms of potassium (K) in soil

3.2. Effect on available K content

Findings indicated remarkable depth-wise variation in available potassium (K) content in different rice-based cropping systems and depths (Table 1). In all systems (Rice-fallow, Rice-Rice, Rice-Jute, Rice-Mustard-Jute), the highest mean available K was at the 30-45 cm soil depth,

Table 1: Variations in available K, water soluble K and exchangeable K content at different soil depths under different rice-based cropping systems

Soil Depth/Cropping systems (CS)	Rice-fallow	Rice-Rice	Rice-Jute	Rice-Mustard-Jute	Rice-Vegetable	Mean (irrespective of CS)
Variation of Available K (kg ha^{-1})						
0–15	339.60^{Ba}	312.8^{Bb}	362.12^{Ba}	275.81^{Bc}	364.41^{Aa}	330.95^{C}
15–30	353.50^{ABb}	328.57^{ABc}	377.83^{ABa}	293.68^{ABd}	378.38^{Aa}	346.39^{b}
30–45	371.68^{Aa}	343.97^{Ab}	390.27^{Aa}	311.73^{Ac}	391.00^{Aa}	361.73^{a}
Mean (irrespective of depth)	354.92^{B}	328.45^{C}	376.74^{A}	293.74^{D}	377.93^{A}	
Variation of water soluble K (kg ha^{-1})						
0–15	10.21^{Ba}	9.49^{Ca}	10.49^{Ba}	9.86^{Ba}	10.84^{Ca}	10.18^{c}
15–30	12.86^{Aa}	11.32^{Ba}	12.10^{ABa}	11.60^{Ba}	13.06^{Ba}	12.19^{b}
30–45	14.32^{Aab}	12.96^{Ab}	13.77^{Ab}	13.60^{Aab}	15.28^{Aa}	13.99^{a}
Mean (Irrespective of depth)	12.46^{AB}	11.26^{C}	12.12^{ABC}	11.69^{BC}	13.06^{A}	
Variation of exchangeable K (kg ha^{-1})						
0–15	329.39^{Ba}	303.31^{Bb}	351.64^{Aa}	265.95B^{c}	353.57A^{a}	320.77^{c}
15–30	340.64^{ABb}	317.25^{ABc}	365.73^{ABa}	282.08AB^{d}	365.32A^{a}	334.20^{b}
30–45	357.36^{Aa}	331.01^{Ab}	376.50^{Aa}	298.13A^{c}	375.72A^{a}	347.74^{a}
Mean (Irrespective of depth)	342.46^{B}	317.19^{C}	364.62^{A}	282.05^{D}	364.87^{A}	

Different small letters between columns and capital letters between rows indicate significant differences (p<0.05) according to DMRT for separation of means

statistically on par with that at the 15–30 cm depth. The lowest was found in the 0–15 cm depth, also statistically similar to the 15–30 cm depth. Only in the Rice-Vegetable system, available K was statistically at par across soil depths. The mean available K (irrespective of cropping systems) was highest in the 30–45 cm depth [361.73 kg ha^{-1}], and lowest in the 0–15 cm depth [330.95 kg ha^{-1}], generally increasing with depth.

Variation was also observed among cropping systems at various soil depths. At 0–15 cm depth, Rice-Vegetable contained highest K content [364.41 kg ha^{-1}], equal to Rice-Jute and Rice-Fallow statistically, and Rice-Mustard-Jute contained least [275.81 kg ha^{-1}]. At 15–30 cm depth, Rice-Vegetable had maximum [378.88 kg ha^{-1}], equal to Rice-Jute. Rice-Mustard-Jute contained least [293.68 kg ha^{-1}]. At 30–45 cm depth, Rice-Vegetable contained maximum [391.00 kg ha^{-1}], with Rice-Jute and Rice-Fallow being equal, and Rice-Mustard-Jute the least [311.73 kg ha^{-1}]. Overall, Rice-Vegetable system contained maximum mean available K [377.93 kg ha^{-1}], in comparison to Rice-Mustard-Jute [293.74 kg ha^{-1}].

Greater potassium was found in subsurface soils, which was most probably due to removal of potassium from the surface crop causing leaching and concentration below (Alfaro et al., 2004; Vijayakumar et al., 2024; Xu et al., 2025). This layer also possessed a greater quantity of clay and organic matter, according to Kundu et al. (2014). The Rice-Vegetable cropping system had the majority of the potassium at all depths, which required frequent high applications of potassic fertilizer. But the Rice-Mustard-Jute system had the least potassium, which was due to intense crop uptake or removal of indigenous reserves, indicating a disorder in nutrition by fertilization, according to Katkar et al. (2011).

3.3. *Effect on water soluble K content*

Results showed great depth-wise difference in water-soluble K content among rice-based cropping systems (Rice-fallow, Rice-Rice, Rice-Jute, Rice-Mustard-Jute, Rice-Vegetable) (Table 1). Mean maximum K content was at 30–45 cm depth, statistically no different from 15–30 cm depth in Rice-Fallow and Rice-Jute. Minimum K content was observed at 0–15 cm depth, similar to 15–30 cm in Rice-Rice, Rice-Jute, Rice-Mustard-Jute, Rice-Vegetable. The maximum mean water-soluble K content occurred at 30–45 cm depth (13.99 kg ha^{-1}) and was minimum at 0–15 cm depth (10.18 kg ha^{-1}) and increased with depth of the soil.

Outcomes showed remarkable differences in water-soluble

K content among diverse rice-based cropping systems at diverse soil depths. Within the 0–15 cm depth, Rice-Vegetable recorded the highest average water-soluble K at 10.84 kg ha^{-1}, statistically equivalent to others, and Rice-Mustard-Jute had the lowest at 9.49 kg ha^{-1}. Within the 15–30 cm depth, Rice-Vegetable still recorded the highest K content at 13.06 kg ha^{-1}, and Rice-Rice had the lowest (11.32 kg ha^{-1}). Rice-Vegetable once more dominated the 30–45 cm layer with 15.28 kg ha^{-1}, followed by rice-mustard-jute and rice-fallow, while the lowest was 12.96 kg ha^{-1} for rice-rice. The mean water-soluble K content was greatest in the rice-vegetable cropping system (13.06 kg ha^{-1}), followed by rice-fallow and rice-jute, while rice-rice contained the least (11.26 kg ha^{-1}), followed by rice-jute and rice-mustard-jute.

Greater water-soluble potassium at lower soil depths was associated with organic content and clay. Kundu et al. (2014) and Niams et al. (2024) also noted the same findings. The rice-vegetable system had the most potassium due to more potassic fertilizer application, whereas the rice-rice system had lower values, possibly as a result of inadequate potassium application or leaching.

3.4. Effect on exchangeable K content

The research reported considerable variations in depth-wise exchangeable K content in different cropping systems based on rice (Table 1). In Rice-fallow, Rice-Rice, Rice-Jute, and Rice-Mustard-Jute, the greatest average exchangeable K content was observed at 30-45 cm depth, as well as at 15–30 cm depth, and equivalent to 0–15 cm in Rice-Jute. The lowest exchangeable K was noted at 0–15 cm depth, aligned with the 15–30 cm depth's values. In contrast, Rice-Vegetable had statistically equal available K content across all soil depths. Mean exchangeable K content was highest at 30–45 cm (347.74 kg ha^{-1}) and lowest at 0–15 cm (320.77 kg ha^{-1}), increasing with soil depth across cropping systems.

Findings indicated large differences in the content of available K in various rice-based cropping systems at different depths of the soil. In the 0–15 cm depth, rice-vegetable contained more exchangeable content of K (353.57 kg ha^{-1}), similar to Rice-Fallow and Rice-Jute, while Rice-Mustard-Jute contained the least (265.95 kg ha^{-1}). In the 15–30 cm depth, Rice-Jute contained the most (365.73 kg ha^{-1}), similar to Rice-Vegetable, with Rice-Mustard-Jute containing the least (282.08 kg ha^{-1}). At 30–45 cm depth, Rice-Jute again recorded the maximum (376.50 kg ha^{-1}), which was at par with Rice-Vegetable and Rice-Fallow, and Rice-Mustard-Jute recorded the minimum (298.13 kg ha^{-1}). Irrespective of soil depths, it was observed that the mean exchangeable K content was highest in Rice-Vegetable cropping system [364.87 kg ha^{-1}] which was however statistically at par with Rice-Jute cropping system and lowest in Rice-Mustard-Jute [282.05 kg ha^{-1}] cropping system.

Higher exchangeable K in sub-surface soils can be due to high CEC due to high clay and organic carbon content, as reported by Kundu et al. (2014). The greatest exchangeable K in Rice-Vegetable cropping systems would be due to extensive use of K fertilizer or greater clay content, as reported by Das et al. (2024).

3.5. Effect on non-exchangeable potassium (Non-Ex K) content

Results showed considerable differences in the content of non-exchangeable potassium (K) between different rice-based cropping systems (Table 2). Maximum mean non-ex K was observed at 30–45 cm depth in Rice-fallow, Rice-Rice, Rice-Jute, and Rice-Mustard-Jute systems, equal to 15–30 cm depth. Minimum non-ex K was noted at 0–15 cm depth, equivalent to 15–30 cm depth. In Rice-Vegetable systems, content of available K was statistically similar at all depths examined. Mean non-exchangeable K content was maximum at 30–45 cm depth (564.69 kg ha^{-1}) and minimum at 0–15 cm depth (519.98 kg ha^{-1}) with an increase in soil depth.

The results showed significant variations in the non-exchangeable potassium (K) content across different soil levels and rice-based cropping systems. Similar to Rice-Jute and Rice-Vegetable, Rice-Rice had the highest mean level of non-ex K at 566.07 kg ha^{-1} in the 0–15 cm depth, whereas Rice-Mustard-Jute had the lowest at 413.60 kg ha^{-1}. At 15–30 cm depth, Rice-Rice again took the lead with 592.94 kg ha^{-1}, and at 30–45 cm with 619.44 kg ha^{-1}, always outpacing Rice-Mustard-Jute, which contributed lower values in both the depths. The highest mean non-ex K content of 592.81 kg ha^{-1} was recorded by Rice-Rice cropping system, which was comparable to Rice-Jute and Rice-Vegetable, while Rice-Mustard-Jute was the lowest (439.17 kg ha^{-1}).

Higher amounts of non-exchangeable potassium (K) in deeper soil were might be beacuse of presence of higher clay, whereas plant uptake and leaching might be the cause of lower levels in top soil. This was consistent with the findings of Kundu et al. (2014), Saini and Grewal (2014), Divya et al. (2016) and Nayak et al. (2019). While excessive potassium uptake and inadequate application in the Rice-Mustard-Jute system lead to K depletion, increased clay and organic matter in the Rice-Rice system result in higher non-exchangeable K levels (Sharma and Paliyal, 2015a; Islam et al., 2023).

3.6. Effect on HNO_3 soluble potassium (HNO_3 Soluble K) content

The research indicated immense depth-wise fluctuation in HNO_3 soluble K content among rice-based cropping systems (Table 2). Under Rice-fallow, Rice-Rice, Rice-Jute, and Rice-Mustard-Jute, maximum mean HNO_3 soluble

Table 2: Variations in Non-exchangeable K, HNO_3 soluble K, lattice K and total K content at different soil depths under different rice-based cropping systems

Soil Depth/Cropping systems (CS)	Rice-fallow	Rice-Rice	Rice-Jute	Rice-Mustard-Jute	Rice-Vegetable	Mean (irrespective of CS)
Variation of non-exchangeable K (kg ha^{-1})						
0–15	512.01^{Bb}	566.07^{Ba}	552.19^{Bab}	413.60^{Bc}	556.04^{Aa}	519.98^{c}
15–30	530.20^{ABb}	592.94^{ABa}	574.02^{ABa}	439.25^{ABc}	574.86^{Aa}	542.25^{b}
30–45	560.50^{Ab}	619.44^{Aa}	588.34^{Aab}	464.66^{Ac}	590.53^{Aab}	564.69^{a}
Mean (Irrespective of depth)	534.24^{B}	592.81^{A}	571.52^{A}	439.17^{C}	573.81^{A}	
Variation of HNO_3 soluble K (kg ha^{-1})						
0–15	851.61^{Ba}	878.87^{Ba}	914.32^{Ba}	689.41^{Bb}	920.45^{Aa}	850.93^{c}
15–30	883.70^{ABb}	921.51^{ABa}	951.85^{ABa}	732.92^{ABc}	953.24^{Aa}	888.64^{b}
30–45	932.18^{Aa}	963.41^{Aa}	978.60^{Aa}	776.39^{Ab}	981.54^{Aa}	926.42^{a}
Mean (Irrespective of depth)	889.16^{B}	921.26^{AB}	948.26^{A}	732.91^{C}	951.74^{A}	
Variation of lattice K (kg ha^{-1})						
0–15	17708.43^{Ba}	19158.84^{Ba}	18874.38^{Ba}	14075.95^{Bb}	18909.39^{Aa}	17745.40^{c}
15–30	18442.12^{ABb}	20155.84^{ABa}	19708.41^{ABab}	15029.73^{ABc}	19652.66^{Aab}	18597.75^{b}
30–45	19430.00^{Ab}	21128.34^{Aa}	20367.09^{Aab}	15991.48^{Ac}	20320.63^{Aab}	19447.51^{a}
Mean (Irrespective of depth)	18526.9^{B}	20147.7^{A}	19650.0^{A}	15032.4^{C}	19627.6^{A}	
Variation of total K (kg ha^{-1})						
0–15	18506.04^{Bb}	20213.90^{Ba}	19732.22^{Bab}	15047.56^{Bc}	19854.45^{Aab}	18670.83^{c}
15–30	19261.97^{ABb}	21227.22^{ABa}	20584.64^{ABab}	16018.07^{ABc}	20612.90^{Aab}	19540.96^{b}
30–45	20245.71^{Ab}	22216.25A^{a}	21260.10^{Aab}	16998.37^{Ac}	21298.61^{Aab}	20403.81^{a}
Mean (Irrespective of depth)	19337.9^{B}	21219.1^{A}	20525.7^{A}	16021.3^{C}	20588.7^{A}	

Different small letters between columns and capital letters between rows indicate significant differences ($p<0.05$) according to DMRT for separation of means

K occurred at 30–45 cm depth, just like at the 15–30 cm depth. The minimum content occurred at 0–15 cm, just like 15–30 cm levels. However, the Rice-Vegetable system had consistent HNO_3 soluble K content at all soil depths. Mean HNO_3 soluble K content rose with increasing depth of the soil, being highest in the 30–45 cm (926.42 kg ha^{-1}) and lowest in 0–15 cm (850.93 kg ha^{-1}) in all cropping systems.

The research showed great differences in HNO_3 soluble K content among rice-based cropping systems at different soil depths. Rice-Vegetable cropping system recorded a maximum mean K content (920.45 kg ha^{-1}) in the 0–15 cm depth, followed by Rice-Jute, Rice-Rice, and Rice-Fallow. It was the lowest in Rice-Mustard-Jute (689.41 kg ha^{-1}). At 15–30 cm, Rice-Vegetable once more was the highest (953.24 kg ha^{-1}), followed by Rice-Jute and Rice-Rice, and the lowest was Rice-Mustard-Jute (732.92 kg ha^{-1}). At the 30–45 cm depth, Rice-Vegetable was the highest (981.54 kg ha^{-1}), followed closely by the same systems, and the lowest was Rice-Mustard-Jute (776.39 kg ha^{-1}). Mean HNO_3-soluble K content was highest in Rice-Vegetable (951.74 kg ha^{-1}), statistically similar to Rice-Jute and Rice-Rice, and lowest in Rice-Mustard-Jute (732.91 kg ha^{-1}).

Higher content of HNO_3 sol. K in subsurface soil might be due to higher content of potassium bearing minerals and long-term fertilization practices that enhance mineral-associated K retention in deeper horizons (Xiong et al., 2023). Shah et al. (2022) also reported similarly high content of HNO_3 soluble K in agriculture irrigated soils and its lowest content in wasteland soils of lesser Himalayas. Sharma et al. (2015b), however, reported that its higher content in lower depth might be due to presence of higher amount of clay and clay bearing minerals in soils.

3.7. Effect on lattice potassium (Lat- K) content

Results showed critical depth-wise fluctuation in Lattice K content between varying rice-based cropping systems (Table 2). For all systems but Rice-Vegetable, the peak mean content of Lattice K was at 30–45 cm depth, which was similar to 15–30 cm. The lowest content of Lattice K, in contrast, was at 0–15 cm depth, which was similar to 15–30 cm for all systems except Rice-Vegetable, where Lattice K content was statistically equivalent for all depths. Mean Lattice K content was highest at 30–45 cm soil depth (19447.51 kg ha^{-1}) and lowest at 0–15 cm (17745.40 kg ha^{-1}), increasing with soil depth. Mean Lattice K content was highest at 30–45 cm soil depth (19447.51 kg ha^{-1}) and lowest at 0–15 cm (17745.40 kg ha^{-1}), increasing with soil depth.

Lattice K content was widely different in rice-based cropping systems at different depths in the soil. Rice-Rice contained a maximum mean Lattice K content of 19158.84 kg ha^{-1} in the 0–15 cm depth, as with Rice-Jute, Rice-Fallow, and Rice-Vegetable, and the minimum of 14075.95 kg ha^{-1} in Rice-Mustard-Jute. At 15–30 cm, Rice-Rice again had the highest at 20155.84 kg ha^{-1}, comparable to Rice-Jute and Rice-Vegetable; Rice-Mustard-Jute was the lowest at 15029.73 kg ha^{-1}. In 30–45 cm, Rice-Rice was highest at 21128.34 kg ha^{-1}, with Rice-Mustard-Jute lowest at 15991.48 kg ha^{-1}. Mean Lattice K content was most in Rice-Rice system (20147.7 kg ha^{-1}), followed by Rice-Jute and Rice-Vegetable, and least in Rice-Mustard-Jute (15032.4 kg ha^{-1}).

Lattice K content was greater in subsurface compared to surface soil, with positive correlation with clay fraction, which was probably the result of greater potassium-bearing minerals and clay at lower depths. Charankumar and Munaswamy (2023) have observed similar results. Increased lattice K in subsurface soil might be due to mica-rich parent material with more potassium in the mica-lattice, as evidenced by Ghosh and Singh (2001) and Ahlersmeyer et al., (2025). High K content in the lattice of Rice-Rice cropping system soils probably was due to K-containing parent material or clay mineral content.

3.8. Effect on total potassium (Total- K) content

The investigation established considerable variation in total K content among various cropping systems of rice (Table 2). In Rice-fallow, Rice-Rice, Rice-Jute, and Rice-Mustard-Jute, the maximum mean content of total K was at 30–45 cm depth, followed by 15–30 cm depth. The minimum total K content among these systems was in 0–15 cm depth, which was comparable to 15–30 cm depth. In Rice-Vegetable systems, total K content was statistically similar for all the soil depths. Mean K content was maximum at 30–45 cm soil depth (20403.81 kg ha^{-1}) and minimum at 0–15 cm (18670.83 kg ha^{-1}), increasing with the depth of the soil.

Results showed wide differences in total K content in rice-based cropping systems at various soil depths. At the 0–15 cm depth, Rice-Rice contained the highest mean total K content of 20213.90 kg ha^{-1}, followed by Rice-Jute and Rice-Vegetable, and lowest for Rice-Mustard-Jute at 15047.56 kg ha^{-1}. In the 15–30 cm depth, Rice-Rice still had the highest with 21227.22 kg ha^{-1}, and was followed by values corresponding to Rice-Jute and Rice-Vegetable; it was lowest in Rice-Mustard-Jute with 16018.07 kg ha^{-1}. In the 30–45 cm depth, Rice-Rice was highest with 22216.25 kg ha^{-1}, once again statistically equivalent to the others, whereas Rice-Mustard-Jute was still lowest with 16998.37 kg ha^{-1}. Mean total potassium content was highest in Rice-Rice cropping system (21219.1 kg ha^{-1}), similar to Rice-Jute and Rice-Vegetable, and lowest in Rice-Mustard-Jute (16021.3 kg ha^{-1}).

Total K content was greater in subsurface soil, positively correlated with clay fraction. Such increase probably due to high potassium-bearing minerals and clay in lower layers, agreeing with Charankumar and Munaswamy (2023). The highest total K content in the subsurface soil was might be due to the presence of higher amount of organic material and clay. Lower value of total K in surface soil might be due to plant uptake and leaching, as evidenced by Kundu et al. (2014). Highest total K content in Rice-Rice cropping system might be due to the presence of high lattice K concentration (Sowmya et al., 2025).

3.9. Physicochemical properties of soils of rice-based cropping systems

Irrespective of all cropping systems and irrespective of all depths, the result showed that BD of the soil varied from 1.16–1.63 Mg m^{-3} with mean value 1.42 Mg m^{-3}; clay content of the soil varied from 14.72–35.82 with mean value 24.16; pH of the soil varied from 6.71–7.79 with mean value 7.24; EC of the soil varied from 0.09–0.98 dS m^{-1} with mean value 0.22 dS m^{-1}; OC percentage of the soil varied from 0.14–1.10 with mean value 0.51; the available Nitrogen content of the soil varied from 112.84–375.20 kg ha^{-1} with mean value 219.19 kg ha^{-1}; the available Phosphorus content of the soil varied from 8.93–59.82 kg ha^{-1} with mean value 21.09 kg ha^{-1}; available Sulphur content of the soil varied from 4.76–35.90 kg ha^{-1} with mean value 19.77 kg ha^{-1} (Table 3).

3.10. Inter-relationships between forms of soil potassium and soil properties

Correlation coefficient investigations on various Rice based cropping systems indicated some important correlations among soil forms of potassium and other soil properties (Table 4, Figure 1). Available potassium (Av-K) was significantly correlated with bulk density (BD) (r=0.295, $p\leq0.05$) and clay content (r=0.259, $p\leq0.05$). Similar findings were also reported by Das et al. (2002) and Singh et al., (2022). Clay content and water-soluble potassium (WS-K) were strongly positively correlated (r=0.260, $p\leq$ 0.05). Exchangeable potassium (exchangeable-K) linked adversely with pH (r=-0.236, $p\leq$ 0.05) but significantly positively with BD (r=0.297, $p\leq0.01$) and clay content (r= 0.261, $p\leq0.05$). Das et al. (2002) stressed the positive correlation of BD with various potassium forms. Non-exchangeable potassium (non-ex K) was strongly positively related to BD (r= 0.491, $p\leq$ 0.01) and clay content (r= 0.259, $p\leq0.05$), but negatively with electrical conductivity (EC) (r=-0.252, $p\leq0.05$). Das et al. (2002) noted a significant positive correlation between soil bulk density and potassium forms. Additionally, research by Setia and Sharma (2004); Jatav and Dewangan (2012); Reza et al. (2014); Kundu et al. (2014); Behera et al. (2015), Nayak et al. (2019), Anjali et al. (2025) and Tulasi et al. (2025) affirmed a strong correlation between clay content and soil potassium. A correlation coefficient study indicated significant positive correlations between HNO_3-Soluble K in soil from various rice-based cropping systems with bulk density (BD, r=0.439, $p\leq0.01$) and clay content (r=0.265, $p\leq0.05$). Like lattice K, lattice K had a strong positive correlation with BD (r=0.495, $p\leq0.01$) and fraction clay (r=0.263, $p\leq0.05$), but a negative correlation with electrical conductivity (EC, r=-0.249, $p\leq0.05$). Earlier research (Das et al., 2002) also indicated positive correlations between soil BD and forms of potassium. Additionally, total K demonstrated significant positive correlations with BD (r=0.492, $p\leq0.01$) and clay fraction (r=0.259, $p\leq0.05$), alongside a negative correlation with EC (r=- 0.249, $p\leq0.05$).

Table 3: Range, mean and standard deviation of some soil properties of the studied rice based cropping systems

Soil properties	BD (Mg m^{-3})	Clay (%)	pH	EC (dS m^{-1})	OC (%)	Av. N (kg ha^{-1})	Av. P (kg ha^{-1})	Av. S (kg ha^{-1})
Min	1.16	14.72	6.71	0.09	0.14	112.84	8.93	4.76
Max	1.63	35.82	7.79	0.98	1.10	375.20	59.82	35.90
Range	1.16–1.63	14.72–35.82	6.71–7.79	0.09–0.98	0.14–1.10	112.84–375.20	8.93–59.82	4.76–35.90
Mean	1.42	24.16	7.24	0.22	0.51	219.19	21.09	19.77
SD	0.13	5.07	0.20	0.16	0.21	60.21	11.15	7.12

Table 4: Pearson's correlation matrix for linear relationship of various forms of potassium with soil physicochemical properties

	Av-K	Ws-K	Ex-K	Non-Ex-K	HNO3-Sol-k	Lat-K	Tot-K
BD	0.295*	0.138	0.297**	0.491**	0.439**	0.495**	0.492**
Clay	0.259*	0.260*	0.261*	0.259*	0.265*	0.263*	0.259*
pH	-0.221	0.120	-0.236*	-0.203	-0.220	-0.203	-0.191
EC	-0.119	-0.026	-0.122	-0.252*	-0.213	-0.249*	-0.249*
OC	0.145	0.120	0.140	0.107	0.113	0.104	0.102
Av. N	-0.036	-0.119	-0.030	0.022	0.001	0.012	0.013
Av. P	0.049	-0.212	0.062	-0.041	-0.008	-0.060	-0.061
Av. S	-0.011	-0.110	-0.005	-0.143	-0.098	-0.137	-0.146

**: Correlation is significant at the 0.01 level (2-tailed); *: Correlation is significant at the p=0.05 level (2-tailed)

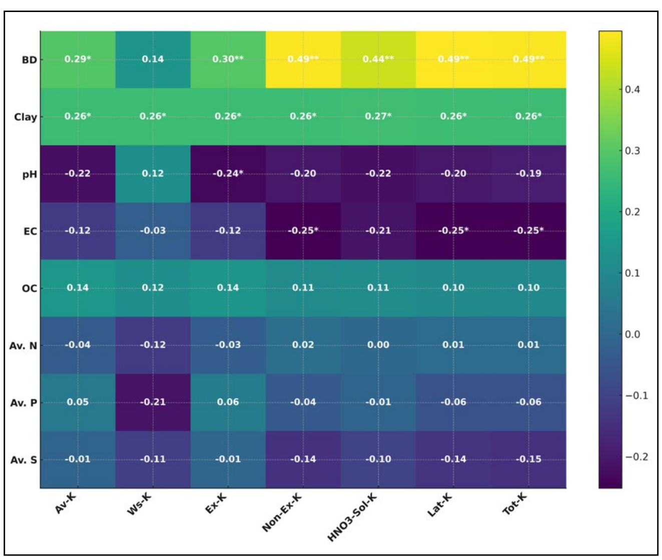

Figure 1: Correlation heatmap for the linear relationship of various forms of potassium with various soil physicochemical properties

Many researchers, including Setia and Sharma (2004); Jatav and Dewangan (2012); Kundu et al. (2014); Reza et al. (2014); Behera et al. (2015); Nayak et al. (2019), and Anjali et al. (2025), also reported significant and positive correlation of clay with various forms of soil potassium.

3.11. Inter-relationship among different forms of potassium

The correlation coefficient study on potassium forms in rice-based cropping systems indicated strong interrelationships among various potassium fractions in the soil (Table 5, Figure 2). Available potassium (K) demonstrated a significant positive correlation with water-soluble K (r=0.637, $p\leq0.01$), exchangeable K (r=0.999, $p\leq$ 0.01), non-exchangeable K (r=0.798, $p\leq0.01$), HNO_3 soluble K (r=0.918, $p\leq0.01$), lattice K (r=0.825, $p\leq0.01$), and total K (r=0.808, $p\leq0.01$). Previous studies (Setia and Sharma, 2004; Jatav and Dewangan, 2012; Kundu et al., 2014; Reza et al., 2014; Behera et al., 2015; Nayak et al., 2019 and Anjali et al., 2025) corroborate the significant correlation between available K and other potassium forms. Water-soluble K similarly showed significant positive correlations with exchangeable K (r=0.603, $p\leq$ 0.01), non-exchangeable K (r=0.451, $p\leq0.01$), HNO_3 soluble K (r=0.548, $p\leq0.01$), lattice K (r=0.491, $p\leq0.01$), total K (r=0.490, $p\leq0.01$), and available K (r=0.637, p ≤0.01). The results concurred with Nayak et al. (2019) and others who reported the same positive correlations between water-soluble K and other forms of potassium in the soil. Exchangeable K was also strongly and positively correlated with non-exchangeable K (r =0.800, $p\leq0.01$), HNO_3 soluble K (r=0.919, $p\leq0.01$), lattice K (r=0.826, $p\leq0.01$), total K (r=0.809, $p\leq0.01$), and available K (r=0.999, $p\leq0.01$) as well as water-soluble K (r=0.603, $p\leq0.01$). This finding was consistent with the previous research conducted by the same group of researchers. For non-exchangeable K, significant positive correlations were identified with HNO_3 soluble K (r=0.972, $p\leq0.01$), lattice K (r=0.997, $p\leq0.01$), total K (r=0.999, $p\leq0.01$), and with available K (r=0.798, $p\leq0.01$), water-soluble K (r=0.451, $p\leq0.01$), and exchangeable K (r=0.800, $p\leq0.01$). Similar findings were also reported by Lakaria et al. (2012), Kundu et al. (2014), Divya et al. (2016) and Charankumar et al. (2022). The HNO_3 soluble K was positively correlated with lattice K (r=0.980, $p\leq0.01$) and total K (r=0.975, $p\leq0.01$), as well as with available K (r=0.918, $p\leq0.01$), water-soluble K (r=0.548, $p\leq0.01$), exchangeable K (r=0.919, $p\leq$ 0.01), and non-exchangeable K (r=0.972, $p\leq0.01$). Lattice K exhibited significant positive correlations with total K (r=0.999, $p\leq0.01$), available K (r=0.825, $p\leq0.01$), water-soluble K (r=0.491, $p\leq0.01$), exchangeable K (r=0.826, $p\leq0.01$), non-exchangeable K (r=0.997, $p\leq0.01$), and HNO_3 soluble K (r=0.980, $p\leq0.01$), paralleling findings by Kundu et al. (2014); Charankumar and Munaswamy (2023). Total K showed significant positive correlations with available K (r=0.808, $p\leq0.01$), water-soluble K (r=0.490, $p\leq0.01$), exchangeable K (r=0.809, $p\leq0.01$), non-exchangeable K (r=0.999, $p\leq0.01$), HNO3 soluble K (r=0.975, $p\leq0.01$), and lattice K (r=0.999, $p\leq0.01$). Kundu et al. (2014) also registered high correlations of total K with the lattice K and other forms of potassium. Positive correlations between different forms of K in soils, as described in the work of Lungmuana et al. (2014), validated the dynamic equilibrium among the forms of potassium for providing K supply to

Table 5: Pearson's correlation matrix for linear relationship among different forms of soil potassium

	Av-K	Ws-K	Ex-K	Non-Ex-K	HNO3-Sol-k	Lat-K	Tot-K
Av-K	1.000						
Ws-K	0.637**	1.000					
Ex-K	0.999**	0.603**	1.000				
Non-Ex-K	0.798**	0.451**	0.800**	1.000			
HNO_3-Sol-k	0.918**	0.548**	0.919**	0.972**	1.000		
Lat-K	0.825**	0.491**	0.826**	0.997**	0.980**	1.000	
Tot-K	0.808**	0.490**	0.809**	0.999**	0.975**	0.999**	1.000

**: Indicates correlation is significant at the p=0.01 level (2-tailed)

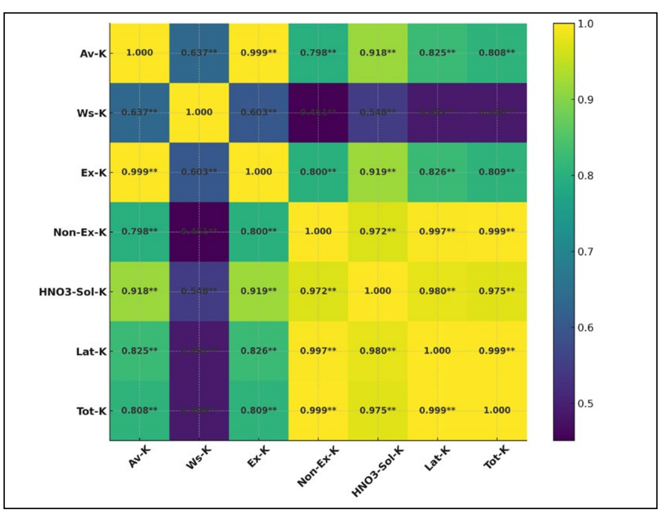

Figure 2: Correlation heatmap for the linear relationship among various forms of potassium

crop roots directly or indirectly (Harinkhere et al., 2025).

4. CONCLUSION

Potassium (K) forms showed significant variation across soil depth and cropping systems. The Rice-Vegetables system had the highest levels of available, water-soluble, exchangeable, and HNO_3 soluble K, while Rice-Rice system had the highest non-exchangeable, lattice, and total K. The Rice-Mustard-Jute system contained the lowest levels of all forms except water soluble K. All forms of K increased with soil depth, peaking at 30–45 cm, and exhibited strong correlations with clay percentage and bulk density, ensuring its availability for crops.

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