



Depth-wise Distribution of Potassium Fractions and Micronutrients and their Relationship in Coastal Saline Soils of Raigad, Maharashtra

S.Y. RAKHONDE¹, D.G. JONDHALE^{2*}, M.R. WAHANE³, D.K. BORSE⁴, S.B. DODAKE¹ and JAGADISH PRASAD⁵

¹Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. B.S. Konkan Krishi Vidyapeeth, Dapoli - 415 712, Ratnagiri, Maharashtra, India

²Regional Agricultural Research Station, Karjat - 410 201, Raigad, Maharashtra, India

³Khar Land Research Station, Panvel - 410 206, Raigad, Maharashtra, India

⁴Department of Agronomy, College of Agriculture, Dapoli - 415 712, Ratnagiri, Maharashtra, India

⁵ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur - 440 033, Maharashtra, India

Received: 11.07.2025

Accepted: 15.11.2025

Seven representative pedons from the coastal region of Raigad district, Maharashtra, were analysed to study the relationship between potassium fractions and DTPA-extractable micronutrients. The soils were slightly to moderately acidic (pH 5.05-6.60) with EC (0.15-20.10 dS m⁻¹), high organic carbon (23.10 g kg⁻¹), and high available K (3091.47 mg kg⁻¹). Pedon 1 and Pedon 4 had highest exchangeable K (231.70 mg kg⁻¹) and total K (8215.80 mg kg⁻¹), respectively while highest non-exchangeable K (2442.25 mg kg⁻¹) and lattice K occurred in the sub-surface horizons of Pedon 2. The sequence of potassium fractions was: total K > lattice K > non-exchangeable K > available K > exchangeable K > water-soluble K. Soil pH showed an inverse relationship with organic carbon, while available K was positively correlated with most K forms except lattice K. Water-soluble K was strongly correlated with available K ($r = 0.968^{*}$), non-exchangeable K ($r = 0.791^{***}$), and total K ($r = 0.395^*$). DTPA-Fe and Mn showed significant negative correlations with available and water-soluble K, while exchangeable and non-exchangeable K were negatively related to Fe, Mn, and Cu. Among micronutrients, Fe correlated positively with Mn ($r = 0.434^*$), Cu ($r = 0.469^*$), and Cu with Zn ($r = 0.51^{**}$). PCA revealed four components (eigenvalues >1) explaining 85.87% of total variance. Overall, all K forms except lattice K were significantly associated with DTPA-extractable Fe and Mn, indicating dynamic interactions among K fractions and micronutrients.**

(Key words: Coastal soils, Correlation, Micronutrients, Potassium fractions, Quasi-equilibrium)

Among the various nutrients required by plants, potassium (K) plays a crucial role in plant growth, metabolism, yield and quality of produce. However, it remains the most overlooked nutrient in Indian agriculture (Misal *et al.*, 2020) and intensive cropping practices throughout the years have resulted in the depletion of soil potassium (Islam *et al.*, 2017). The potassium content in the soils of India ranges from 0.5% to 2.5%, with an average of 1.52%. It exists in different forms: water-soluble, exchangeable, non-exchangeable, and lattice K (Rao *et al.*, 1997; Chavan *et al.*, 2024; Raut *et al.*, 2024). The primary form of K that plants can access is water-soluble K, which is directly absorbed by their roots. On the other hand, exchangeable K acts as a crucial buffer in soil systems, maintaining a dynamic equilibrium by replenishing the water-soluble K when it is depleted (Chavan *et al.*, 2024; Raut *et al.*, 2024) available for

both plants and microorganisms (Singh *et al.*, 2010). Although less accessible, non-exchangeable K serves as a reserve pool that supplements the two preceding forms during depletion, also playing a vital role in the long-term fertility of soils and overall buffering (Sparks and Huang, 1985). Lattice or mineral K is the least accessible form, which may convert to other accessible forms when subjected to prolonged weathering (Sarkar *et al.*, 2013). The two most significant management factors that influence K equilibrium in soils, aside from these soil characteristics, are fertilization and cropping (Singh *et al.*, 2002).

Micronutrients are vital components of enzymes, vitamins, and growth hormones in plants; their deficiency or surplus can negatively impact plant growth, affect animal life, and present health risks to humans (Lu *et al.*, 2015). Nearly half of the soils in India are reported

*Corresponding author: E-mail: jondhaless17@gmail.com

to have severe micronutrient deficiencies (Baldantoni *et al.*, 2019). Among the micronutrients, zinc (49%) and boron (33%) are the most deficient nutrients when compared to others, such as molybdenum (13%), iron (12%), manganese (5%), and copper (3%) (Singh, 2008). These deficiencies in multiple nutrients within the soil, combined with inadequate soil organic matter, a lower fertilizer response ratio, and imbalanced fertilization, contribute to a stagnation in crop productivity levels. Also, the arrangement of micronutrients in soils is associated with the composition of the parent materials and is affected by landscape diversity, topographical features, and various climatic conditions (Menezes-de-Souza *et al.*, 2006), along with the processes involved in soil formation that can significantly influence the distribution of trace elements throughout the soil layers. Earlier studies showed that the availability of micronutrients is impacted by soil properties such as pH, electrical conductivity (EC), organic carbon/ matter (Maji *et al.*, 1993; Qiang *et al.*, 2011), fixation, redox condition (Qiang *et al.*, 2011) but not uniform for all soils. Productivity is also affected by the degradation of soil caused by insufficient soil nutrients in various parts of the world (Prasad *et al.*, 2023), such as the Deccan Plateau in India. The status of available micronutrients and their relationship with soil characteristics for other soils have been extremely reported by many researchers. However, the information on micronutrients in coastal saline soil is meagre (Maji *et al.*, 1993; Bandyopadhyay *et al.*, 2003; Abhale *et al.*, 2024).

Nearly all coastal areas experience issues of soil salinity due to periodical seawater invasion by creek or sea water and make them unfit for cultivation (Dodake *et al.*, 2022), leading to reduced crop productivity. The presence of salt may negatively impact plant growth when the EC reaches or exceeds 4 dS m⁻¹. In such conditions, the presence of Na⁺ can decrease the availability of other nutrients such as K⁺, Ca²⁺, Zn²⁺, Fe²⁺, and Mg²⁺ due to osmotic pressure (Hoque *et al.*, 2022). Furthermore, saline soil elevates the concentration of Na⁺ while decreasing the concentration of K⁺, leading to an increased Na⁺/K⁺ ratio, which disrupts plant growth through ionic imbalance (Rasel *et al.*, 2020). Ahmed

et al. (2020) reported that the salinity intrusion can affect the availability and distribution of these essential nutrients, impacting the sustainability of coastal areas. The coarse textured coastal salt-affected soils exhibit multiple soil-related limitations, such as a light texture, inadequate exchange properties, poor nutrient, low soil organic carbon levels, and deficiencies in both macro and micronutrients, low hydraulic conductivity, and aeration of soil. As a result, these soils pose a major challenge in hindering agricultural activities. Hence, it is essential to comprehend coastal soils and their characteristics for prudent and optimal utilization on an appropriate basis. In light of the present-day concept of sustainable agriculture, it is vital to understand that the soil micronutrients in relation to potassium levels is crucial for identifying the existing or anticipatory problems and suggesting suitable reclamation measures for enhancing the productivity of coastal saline soils. A study was therefore carried out to understand the distribution of micronutrients in relation to potassium in the coastal saline soil of Maharashtra.

MATERIALS AND METHODS

A reconnaissance soil survey was conducted in Girne village (18°19'N; 73°05' E) located in the Tala taluka of Raigad district of Maharashtra state, along the Arabian Sea coastline at 20 meters above sea level. The region has rainy (June to October), winter (November to February), and summer (March to May) seasons, with average daily temperatures surpassing 20°C. Nearly 95 percent of the total annual rainfall (1980.0 mm) is recorded between June and October. The climate is described as mild, temperate, and humid. Horizon-wise soil samples collected from seven typical pedon were processed for the physical, and chemical characteristics.

The soil pH (1:2.5), electrical conductivity (EC, 1:2.5) and available potassium (AVK) were determined by standard laboratory protocols as outlined by Jackson (1973). Water-soluble potassium (WSK) was extracted using a 1:5 soil-to-water ratio as per the method described by Grewal and Kanwar (1966). Exchangeable potassium (EK) was obtained through 1 N NH₄OAc extraction, following the procedure described by

Hanway and Heidel (1952). The non-exchangeable potassium (NEK) was analysed using the 1 N boiling HNO₃ extraction method as described by Wood and Deturk (1941). Lattice potassium (LK) was calculated as the difference between total potassium and the sum of water-soluble, exchangeable, and non-exchangeable potassium (Wiklander, 1954). Total potassium was assessed by extracting the soil in a platinum crucible at temperatures ranging from 220 to 225°C, utilizing a mixture of H₂SO₄, HClO₄, and HF as per Jackson (1973). A flame photometer was employed to quantify the potassium content present in the extracts. The DTPA extraction method (Lindsay and Norvell, 1978) was used to assess iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) on an Atomic Absorption Spectrophotometer. The Pearson's correlation and linear regression between different variables was examined using the statistical approach detailed by Panse and Sukhatme (1961) by using MS-Excel. Principal Component Analysis (PCA) was applied to the data using the R statistical analysis tool (Posit package version 4.5.1) in order to identify significant differences and assess the impact of each soil attribute on overall variability. To determine the components of a set of variables, a multivariate method known as Principal Component Analysis (PCA) is employed. According to Schepers *et al.* (2004), the Principal Components (PCs) with the greatest eigenvalues (>1.0) are thought to be the most reliable representations of soil properties. PCs were shown to have eigenvalues larger than 1 (Walche *et al.*, 2023). The loadings of the soil attributes have been shown using a bi-plot, which helps to clarify the varying significance of values across different principal components.

RESULTS AND DISCUSSION

The soils varied from moderately deep to deep except for Pedon 5 (P5), which was shallow. (Table 1). The soil depth had positive relationship with exchangeable K ($r = 0.618^{***}$, $p < 0.001$) and negative with DTPA-Fe ($r = -0.552^{**}$, $p < 0.001$) and Cu ($r = -0.681^{***}$, $p < 0.001$). The relevant chemical characteristics of the pedons (Table 1) indicated that the soil pH varied from moderately acid to slightly acid.

The soil pH varied from 5.05–5.78 (P1), 5.52–6.44 (P2), 5.15–6.07 (P3), 5.52–6.10 (P4), 5.56–5.78 (P5) and 5.22–5.60 (P7) which was inconsistent with soil depth but in P6 pH varied from 5.23 to 6.05 and increased with soil depth. Such results were put-forth by Nandy (2020). The increase in pH with depth may be ascribed to excessive leaching of salts from heavy rainfall, and the introduction of salts via capillary movement and thus pH got transformed. The lower soil pH in the surface horizon may be due to the addition of organic matter through plant residues. Such consequences in coastal saline soils of Maharashtra were also reported by Dodake *et al.* (2022, 2023). Furthermore, it was found that an increase in soil pH corresponded with decrease in the availability of micronutrients. The data (Table 2) showed that the soil pH had very strong and negative association with organic carbon ($r = -0.665^{***}$, $p < 0.001$) which indicated that acidity may be due to higher organic carbon in the soil (Dodake *et al.*, 2022, 2023). The content of organic carbon decreased as pH levels increased owing to the hydrolysis of organic matter (Chavan *et al.*, 2024). The electrical conductivity (EC) varied from 0.20 to 14.40 dS m⁻¹ (Table 1). The lower EC was observed in P1 (0.52-2.29 dS m⁻¹), P2 (0.20-0.49 dS m⁻¹), and P7 (0.15-0.24 dS m⁻¹) in the surface horizons could be associated with the leaching of soluble salts (Dodake *et al.*, 2022, 2023). The higher salinity in the surface horizons of P3 (20.10 dS m⁻¹), P4 (2.55 dS m⁻¹), and P6 (14.40 dS m⁻¹) might be due to accumulation of salts via upward capillary movement from creek water. The higher electrical conductivity values in coastal saline soils are typically associated with clay-rich soil (Pattani *et al.*, 2021). The salt concentration reduces as the depth increases because of the differences in groundwater depth and quality, proximity to the coastline and/ or, absence of proper drainage. These results are consistent with those reported by Merse *et al.* (2024).

The organic carbon (OC) content ranged from 3.60 to 23.10 g kg⁻¹ in different pedons (Table 1). In these soils, carbon persists for an extended duration due to the prevailing pedo-edaphic environments and regular addition of plant biomass. Generally, surface soils had higher OC content compared to sub-surface soils

Table 1. Initial and final parameter estimates of sandy loam soil

Horizon	Depth (cm)	Soil pH	EC (dS m ⁻¹)	Organic carbon (g kg ⁻¹)	DTPA-extractable micronutrients (mg kg ⁻¹)			
					Fe	Mn	Zn	Cu
Pedon 1: Typic Halaquepts								
Ap	0-14	5.05	0.73	16.50	56.20	55.62	6.77	15.25
Bw	14-43	5.25	0.55	7.80	55.13	43.56	6.92	13.00
Bg1	43-67	5.68	0.52	3.60	34.06	45.14	3.40	7.49
Bg2	67-104	5.78	0.78	3.26	23.44	31.45	2.41	7.01
Bg3	104-116	5.45	2.29	3.00	17.00	30.78	6.10	6.58
Pedon 2 : Typic Halaquepts								
Ap	0-22	5.52	0.27	18.60	52.45	59.78	8.74	9.75
Bw	22-38	5.70	0.31	7.20	49.05	58.22	3.27	9.36
Bg1	38-59	6.18	0.31	2.70	38.61	58.14	2.69	4.79
Bg2	59-84	6.60	0.49	2.10	26.46	60.03	7.00	4.25
Bg3	84-110	6.44	0.20	1.50	27.56	59.25	2.94	3.07
Pedon 3 : Typic Halaquepts								
Ap	0-13	5.15	20.10	23.10	12.58	42.75	6.01	11.08
Bw	13-31	6.07	6.25	5.10	16.61	41.56	6.20	8.66
Bg1	31-48	6.02	5.97	3.00	31.29	40.68	2.26	5.19
Bg2	48-64	6.05	7.68	3.30	24.59	40.01	4.57	5.39
Pedon 4 : Typic Halaquepts								
A	0-16	5.52	2.55	18.90	40.56	48.65	2.36	7.72
Bw	16-37	6.02	7.51	10.20	36.87	46.87	5.47	5.86
Bg1	37-64	6.10	8.20	4.20	30.01	43.93	2.13	6.93
Bg2	64-70	6.06	6.05	3.90	26.12	39.47	2.20	5.12
Pedon 5 : Typic Halaquepts								
A	0-9	5.56	9.08	17.70	47.25	55.12	9.16	12.08
Bg1	9-24	5.78	9.00	16.79	45.84	52.48	9.01	11.72
Bg2	24-47	5.60	8.85	14.20	30.12	50.75	8.26	9.99
Pedon 6 : Aerice Endoaqualfs								
A	0-13	5.23	13.20	12.30	45.26	30.74	3.01	12.08
Bt	13-33	5.52	14.40	9.90	42.52	30.99	2.12	8.28
Btg	33-60	6.05	10.08	5.10	32.88	28.56	2.81	6.02
Pedon 7 : Typic Haplustepts								
Ap	0-7	5.55	0.24	12.90	58.03	65.30	3.06	8.03
Bw1	7-23	5.60	0.15	17.10	64.02	50.87	2.35	9.53
Bw2	23-50	5.22	0.18	9.30	60.23	48.78	2.82	7.16

owing to addition of organic matter from leaf litter, root distribution, and microbial activity.

Joshi and Kadrekar (1987) also observed significant amounts of organic carbon in the lower horizons of the pedons, which may be due to decomposition of woody materials into the coastal saline soils of Maharashtra. The organic carbon displayed a strong negative correlation with soil pH ($r = -0.665^{***}$, $p < 0.001$).

The available potassium ranged from 92.47 to 3091.47 kg ha⁻¹ in different pedons (Fig. 2). The lowest available K content was recorded in P7 as of 92.47 kg ha⁻¹, while the highest was found in P3 (3091.47 kg ha⁻¹). The available potassium showed variation in pedons with the highest concentration of K in P3 (3091.47 kg ha⁻¹). The higher content of available potassium could be

attributed to the weathering of potash-bearing minerals, leading to the release of soluble potassium compounds Nandy (2020), Pattani *et al.* (2021) and Abhale *et al.* (2024) also reported a higher amount of available potassium in the coastal saline soils of Andhra Pradesh, Gujarat and Maharashtra, respectively. A significant and strong positive association was found between available potassium and water-soluble potassium ($r = 0.968^{***}$, $p < 0.001$), non-exchangeable potassium ($r = 0.814^{***}$, $p < 0.001$), total potassium ($r = 0.473^*$, $p < 0.05$), and exchangeable potassium ($r = 0.403^*$, $p < 0.05$) (Table 2). The positive correlations between these forms of potassium suggest that the available potassium is influenced by water-soluble, non-exchangeable and total potassium and had dynamic relationship between them as reported by Raut *et al.* (2024). A strong and

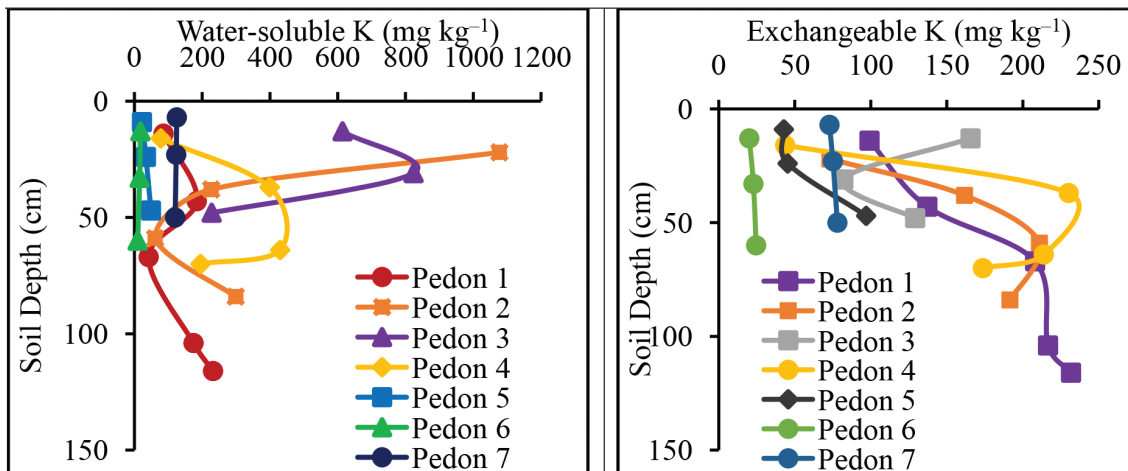


Fig. 1. Depth-wise distribution of water-soluble and exchangeable potassium in the studied pedons

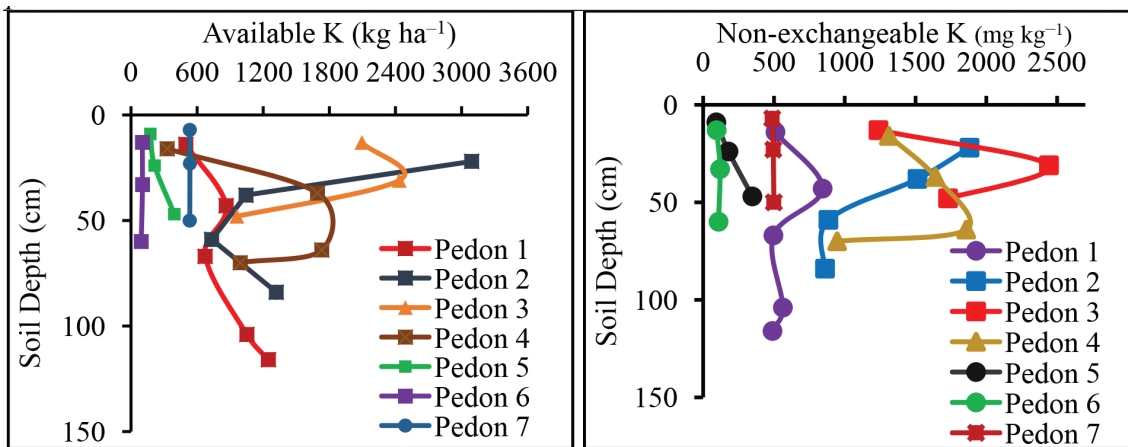


Fig. 2. Depth-wise distribution of available and non-exchangeable potassium in the studied pedons

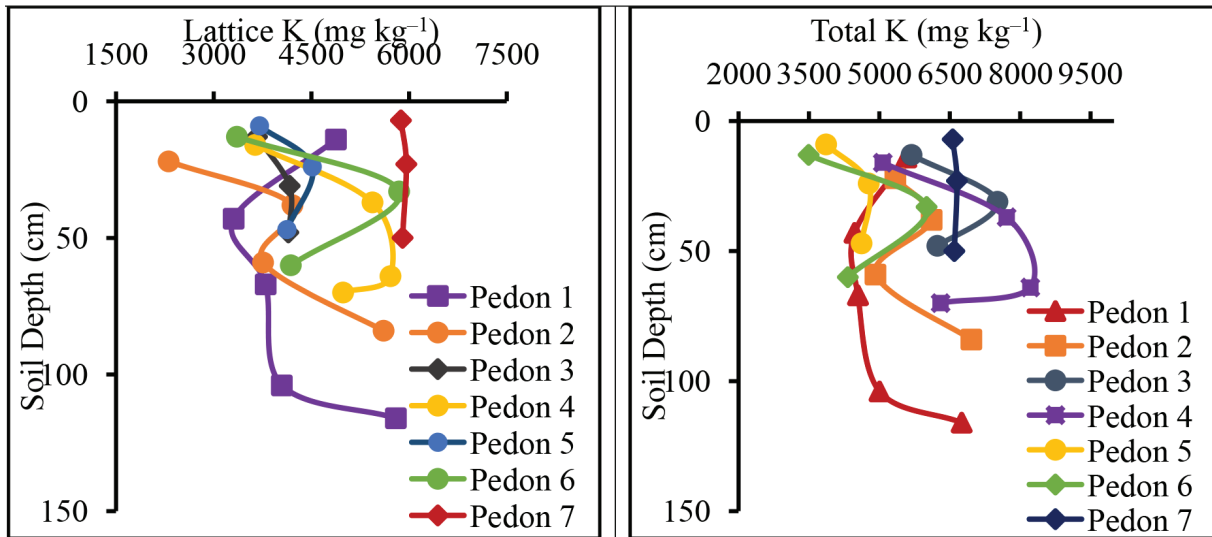


Fig. 3. Depth - wise distribution of lattice and total potassium in the studied pedons

significant negative correlation was observed between available potassium and DTPA-Mn ($r = -0.628^{***}$, $p < 0.001$) and DTPA-Fe ($r = -0.518^{**}$, $p < 0.01$). Relatively higher content of micronutrients in coastal saline soils was reported by Patil *et al.* (2018).

The water-soluble potassium varied from 9.80 to 824.00 mg kg⁻¹ and showed inconsistency with depth, except P5 (120.11-125.00 mg kg⁻¹) and P7 (9.80-18.00 mg kg⁻¹), where it decreased with depth (Fig. 1). The lowest concentration of water-soluble K was recorded in P7 (9.80 mg kg⁻¹), while the highest was found in P6 (824.00 mg kg⁻¹). The higher content of water-soluble K in sub-surface could be due to upward translocation of K by capillary rise (Sharma *et al.*, 2009). The positive and strong relationship was found between water-soluble K and available K ($r = 0.968^{***}$, $p < 0.001$), non-exchangeable K ($r = 0.791^{***}$, $p < 0.001$) and total K ($r = 0.395^*$, $p < 0.05$) (Table 2) indicating the different forms of K had also interrelation, which indicate that a dynamic equilibrium exists among the various forms of K found in the soil. Chavan *et al.* (2024) reported similar findings. The water-soluble K had strong but inverse correlation with DTPA-Mn ($r = -0.529^{**}$, $p < 0.01$) and DTPA-Fe ($r = -0.384^*$, $p < 0.05$) owing to higher manganese and iron contents in soil which reduce the availability of water-soluble K in soil. Exchangeable potassium varied between 20.10 and 231.70 mg kg⁻¹

across the pedons (Fig. 1). The exchangeable K in P2 (42.80–153.00 mg kg⁻¹), P3 (73.10–211.00 mg kg⁻¹), P4 (43.70–173.80 mg kg⁻¹), and P6 (81.90–165.60 mg kg⁻¹) exhibited an inconsistent trend with depth of soil. However, an increasing trend of exchangeable K was noticed in P1 (99.20–321.70 mg kg⁻¹), P5 (72.80–78.01 mg kg⁻¹), and P7 (20.10–24.60 mg kg⁻¹) with depth. The surface horizons of the pedons had lower levels of exchangeable K than the sub-surface horizons, barring P6, which recorded the lowest value in the sub-surface horizon (81.90 mg kg⁻¹). This indicates that the exchangeable K increases with depth because sub-soils are rich in K-source or low crop uptake from this horizon. The exchangeable K showed positive association with soil depth ($r = -0.618^{***}$), available K ($r = 0.403^*$, $p < 0.05$), total K ($r = 0.422^{**}$, $p < 0.01$), this implies that exchangeable potassium tends to accumulate more in deeper horizons (Prasad, 2010). The strong negative relationship of DTPA-Fe ($r = -0.642^{***}$, $p < 0.001$), DTPA-Mn ($r = -0.543^{**}$, $p < 0.01$) and DTPA-Cu ($r = -0.401^*$, $p < 0.05$) (Table 2) with exchangeable K to hints chelation of these nutrients with organic carbon content in different horizons. The higher content of exchangeable K and lower Fe content indicates competitive relationship in mineral weathering zones or mobility difference. Non-exchangeable potassium concentrations ranged from 92.85 to 2442.25 mg kg⁻¹

in different horizons of pedons. It varied from 489.50–843.25 mg kg⁻¹ in P1, 946.0–1640.75 mg kg⁻¹ in P4, 1238.75–2442.25 mg kg⁻¹ in P6 and 95.55–119.65 mg kg⁻¹ in P7 (Fig. 2). However, a decrease was observed in P2 (92.85–491.35 mg kg⁻¹) and P3 (860.0–1881.75 mg kg⁻¹), while an increase was found in P5 (487.40–499.16 mg kg⁻¹) with depth. This could be attributed to the introduction of fixed potassium to offset the extraction of water-soluble potassium and exchangeable potassium by plants (Dhillon *et al.*, 1985). The non-exchangeable K had strong and positive relationship with available K ($r = 0.814^{***}$, $p < 0.001$), water-soluble K ($r = 0.791^{***}$, $p < 0.001$) and total K ($r = 0.539^{**}$, $p < 0.01$) but strong and inverse relationship with DTPA–Mn ($r = -0.611^{***}$, $p < 0.001$) and DTPA–Fe ($r = -0.426^*$, $p < 0.05$) (Table 2). This points that whenever fixed potassium was released, it moves down, via steps, to available forms, for plant uptake. The positive relationship between non-exchangeable K and water-soluble and total K was observed by and Raut *et al.* (2024). Lattice K ranged from 2308.00 to 6219.00 mg kg⁻¹ and its content vary with depths. The lowest lattice K was reported in P3 (2308.00 mg kg⁻¹) and it was the highest in P5 (6219.00 mg kg⁻¹) (Fig. 3). It was further observed that mineral potassium levels were lower in surface soils compared to sub-surface soils. This discrepancy may be attributed to the intense weathering of potassium minerals occurring at the surface than in the sub-surface. These results are in agreement with that of Sharma *et al.* (2009). The lattice K showed accomplished strong positive relationship with total K ($r = 0.697^{***}$, $p < 0.001$), confirming that structural K minerals form a major part of the total K reserves in these soils and that signifies replenishment of the non-exchangeable K pool from mineral or lattice K (Raut *et al.*, 2024). The total potassium content varied from 1861.90 to 8215.80 mg kg⁻¹ in all the pedons but showed an uneven distribution with soil depth (Fig. 3). The lowest total K was found in P7 (3490.65 mg kg⁻¹) while the highest was recorded in P4 (8215.80 mg kg⁻¹). The low total K levels were observed in the surface horizons of P2 (3863.05 mg kg⁻¹), P4 (5070.65 mg kg⁻¹), P6 (5684.35 mg kg⁻¹), and P7 (3490.65 mg kg⁻¹), however highest total K was noticed in the sub-surface horizons across the pedons. Strong positive and significant

correlation was observed between total K and lattice K ($r = 0.697^{***}$, $p < 0.001$), non-exchangeable K ($r = 0.539^*$, $p < 0.05$), available K ($r = 0.473^*$, $p < 0.05$), exchangeable K ($r = 0.422^*$, $p < 0.05$) and water-soluble K ($r = 0.395^*$, $p < 0.05$) (Table 2) suggesting a rapid restoration of balance among these potassium forms. This reflects that the lattice K contribute more in total K content. Raut *et al.* (2024) opined similar views.

DTPA–Fe fluctuated between 12.58 and 64.02 mg kg⁻¹ (Table 1) in different horizons of pedons. The highest concentration of DTPA–Fe was found in the surface horizon, with the exception of P3 (12.58 mg kg⁻¹). In P1 (17.00–56.20 mg kg⁻¹), P4 (26.12–40.56 mg kg⁻¹), P5 (30.12–47.25 mg kg⁻¹), and P6 (32.88–45.26 mg kg⁻¹), DTPA–Fe decreased with depth, while in P2 (26.46–52.45 mg kg⁻¹), P3 (12.58–31.29 mg kg⁻¹), and P7 (58.03–60.23 mg kg⁻¹), it varied with depth. The higher concentration of iron in the surface layer could be due to the accumulation of organic matter and biological recycling processes. The higher amounts of micronutrient cations in these soils could be due to the soil's acidic reaction (Patil *et al.*, 2018; Nandy, 2020). The DTPA–Fe had a strong inverse correlation with soil depth ($r = -0.532^{**}$), exchangeable K ($r = -0.642^{***}$, $p < 0.001$), available K ($r = -0.518^{**}$, $p < 0.01$), non-exchangeable K ($r = -0.426^*$, $p < 0.05$), total K ($r = -0.406^*$, $p < 0.05$), and water-soluble K ($r = -0.384^*$, $p < 0.05$) (Table 2). This shows that the concentration of iron influences the availability of potassium and in particular total K owing to different sources and mobility pathways of these elements. DTPA–Fe had a significant positive relationship with DTPA–Mn ($r = 0.434^*$, $p < 0.05$) and DTPA–Cu ($r = 0.469^*$, $p < 0.05$) reflect their interconnected behaviour under redox conditions that are characteristic of wet soils. The DTPA–Mn was ranged from 28.56 to 65.30 mg kg⁻¹ in these pedons (Table 1). There was decrease in DTPA–Mn with depth in P4 (39.47–48.65 mg kg⁻¹), P5 (50.75–55.12 mg kg⁻¹) and P7 (48.78–65.30 mg kg⁻¹) but varied with depth in P1 (30.78–55.62 mg kg⁻¹), P2 (58.14–60.03 mg kg⁻¹), P3 (40.01–42.75 mg kg⁻¹) and P6 (28.56–30.74 mg kg⁻¹). The higher DTPA–Mn was recorded in the surface horizon of P1 (55.62 mg kg⁻¹), P3 (42.75 mg kg⁻¹), P4 (55.12 mg kg⁻¹), and P7 (65.30

Table 2. Pearson's correlation coefficient of different soil properties

	Depth	pH	EC	OC	AVK	WSK	EK	NEX	LK	TK	Fe	Mn	Zn	Cu
Depth	1													
pH	0.017	1												
EC	-0.034	-0.092	1											
OC	-0.081	-0.665***	0.318	1										
AVK	-0.013	-0.011	-0.066	0.21	1									
WSK	-0.182	-0.067	0.025	0.303	0.968***	1								
EXK	0.618***	0.203	-0.352	-0.282	0.403*	0.162	1							
NEX	-0.114	-0.011	0.086	0.211	0.814***	0.791***	0.316	1						
LK	0.33	-0.018	0.069	0.13	-0.225	-0.293	0.186	-0.213	1					
TK	0.221	-0.024	0.09	0.274	0.473*	0.395*	0.422*	0.539**	0.697***	1				
Fe	-0.552**	-0.133	0.201	-0.009	-0.518**	-0.384*	-0.642***	-0.426*	-0.067	-0.406*	1			
Mn	-0.265	-0.186	0.237	0.273	-0.628***	-0.529**	-0.543**	-0.611***	0.165	-0.33	0.434*	1		
Zn	-0.239	-0.288	-0.255	0.127	-0.088	-0.057	-0.14	-0.219	0.282	0.106	0.012	0.311	1	
Cu	-0.681***	-0.355	-0.303	0.089	0.054	0.167	-0.401*	-0.047	-0.181	-0.17	0.469*	0.068	0.51**	1

EC—electrical conductivity; OC—organic carbon; AVK—available potassium; WSK—water soluble potassium; EK—exchangeable potassium; NEX—non-exchangeable potassium; LK—lattice potassium; TK—total potassium; *** Correlation is significant at 0.001 level (two tailed); ** Correlation is significant at 0.01 level (two tailed); * Correlation is significant at 0.05 level (two tailed)

mg kg⁻¹), but it was higher in sub-surface horizon of P3 (31.29 mg kg⁻¹) and P7 (64.02 mg kg⁻¹). The higher content of organic matter and biological recycling may be the reason for the higher DTPA–Mn in the surface horizons. The DTPA–Mn had significant and positive association with DTPA–Fe ($r = 0.434^*$, $p < 0.05$) (Table 2) because of their similar behaviour. Significant inverse relationship with available K ($r = -0.628^{***}$, $p < 0.001$), water-soluble K ($r = -0.529^{**}$, $p < 0.01$), exchangeable K ($r = -0.543^{**}$, $p < 0.01$) and non-exchangeable K ($r = -0.611^{***}$, $p < 0.001$) indicated low availability of potassium due to higher content of manganese in the soil.

The DTPA–Zn varied from 2.12 to 9.16 mg kg⁻¹ in different horizons of pedons (Table 1). The highest DTPA–Zn was detected in P5 (8.26–9.16 mg kg⁻¹), while the lowest was recorded in P6 (2.12 mg kg⁻¹). There was marked variation in DTPA–Zn in the sub-surface horizons of P1 (2.41–6.92 mg kg⁻¹), P2 (2.94–8.74 mg kg⁻¹), P3 (2.26–6.20 mg kg⁻¹), P4 (2.13–5.47 mg kg⁻¹) and P6 (2.12–3.01 mg kg⁻¹), barring P5 (8.26–9.16 mg kg⁻¹). The higher concentrations of Zn in these soils may be ascribed to the acidic nature of the soil (Patil *et al.*, 2018; Nandy, 2020). DTPA–Zn was positively correlated with DTPA–Cu ($r = 0.51^{**}$, $p < 0.01$), indicating potential common controlling factors such as organic matter or soil pH. DTPA–Cu levels varied between 3.07 and 15.25 mg kg⁻¹ across the pedons (Table 1). The higher DTPA–Cu concentration was recorded in the surface horizon of P1 (15.25 mg kg⁻¹), P2 (9.75 mg kg⁻¹), P3 (11.08 mg kg⁻¹), P4 (7.72 mg kg⁻¹), P5 (12.08 mg kg⁻¹), and P6 (12.08 mg kg⁻¹), with the exception of P7 (9.53 mg kg⁻¹). In general, DTPA–Cu decreased with depth, except for P3 and P4 where the trend was inconsistent with depth. The increased level of DTPA–Cu in these soils can be linked to the soil's acidic reaction (Patil *et al.*, 2018; Nandy, 2020). Significantly strong negative correlation was observed between DTPA–Cu and soil depth ($r = -0.681^{***}$) and Cu and exchangeable K ($r = -0.401^*$, $p < 0.05$), indicating that a notably lower availability of copper in the soil correspond to the soil depth and higher levels of exchangeable K. Conversely, a positive and strong correlation was found with DTPA–

Zn ($r = 0.51^{**}$, $p < 0.01$) and DTPA–Fe ($r = 0.469^*$, $p < 0.05$) (Table 2) indicated that the iron increased the zinc availability in the soil.

Linear regression between soil depth and potassium fractions

The slope for each potassium fraction showed that as soil depth increases, potassium content changes. The available potassium concentration falls as soil depth increases, according to the linear regression (Fig. 4). Nonetheless, shallow soils were shown to have a somewhat higher accessible potassium concentration. As the depth increased, the water-soluble potassium decreased, suggesting that the exchangeable potassium was depth dependent. Additionally, it was noted that exchangeable potassium was negatively and very weakly impacted by soil depth. The non-exchangeable potassium was barely affected by the depth of the soil. Nonetheless, a rise in non-exchangeable potassium is correlated with a deeper soil. Higher levels of total K are found in the subsurface layers, suggesting that the deeper soils had higher levels of total potassium. With the exception of exchangeable K ($R^2 = 0.38$), all individual regression R^2 values are less than 0.25, demonstrating inadequate predictive power—soil depth accounts for less than 25% of the variation in any potassium fraction.

Principal component analysis

Four of the eleven main components that were calculated in the analysis had eigenvalues larger than 1. (Kaiser's rule states that primary components larger than one should be taken into account for additional analysis).

Table 3 displays the factor loadings for the first four components, which account for 87.95% of the variation and are the correlations of individual characters with the corresponding components. With an eigenvalue of 4.4, PC1 (39.63%) accounted for the largest variation. With eigenvalues of 2.0, 1.8, and 1.5, respectively, the principal components PC2, PC3, and PC4 explained variances of 17.95%, 16.44%, and 13.93%. In particular, principal component 1 (PC1), which accounts for 39.63% (Fig.5) of the variation, has the highest positive loadings of all potassium fractions with the exception

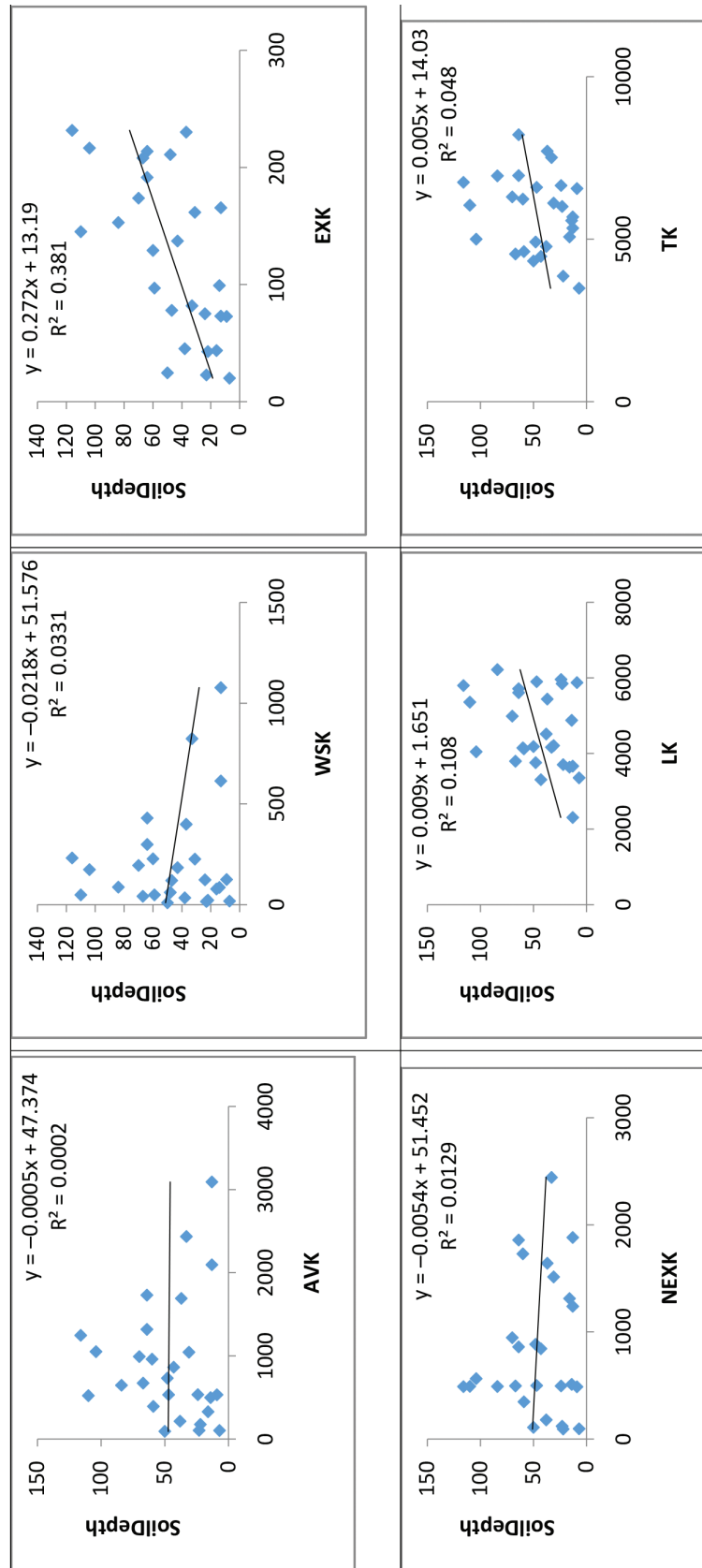


Fig. 4. Linear regression between soil depth and potassium fractions

of lattice K and negative loadings of Fe, Mn, Zn, and Cu (Table 3). As a result, nutrient components had a significant impact on the first factor. A general pattern of soil fertility, richness, or nutrient concentration is shown by high positive loadings from EXK, TK, and AVK, which imply that soils richer in these nutrients cluster together.

Given the highly substantial positive correlations with variables AVK ($r = 0.44^{**}$), NEX ($r = 0.41^{**}$), WSK ($r = 0.38^{**}$), EXK ($r = 0.32^{**}$), and TK ($r = 0.32^{**}$), a correlation analysis (Fig. 6) may provide a better explanation for PC1. The soil EC and DTPA-extractable Mn ($r = -0.38^{**}$), Fe ($r = -0.34^{**}$), Cu ($r = -0.14^{**}$), and Zn ($r = -0.10^*$) had a substantial negative interaction with one another, according to the PCA and correlation research. The variables LK ($r = 0.63^{**}$), Zn ($r = 0.44^{**}$), TK ($r = 0.41^{**}$), EXK ($r = 0.22^{**}$), and Mn ($r = 0.13^{**}$) were positively correlated with the main component PC2 (Fig. 6).

Variation in potassium fixation versus mobility is indicated by high positive loading for LK, TK, or EXK. However, the variables Cu ($r = -0.02$), AVK ($r = -0.11^*$), NEX ($r = -0.18^{**}$), WSK ($r = -0.19^{**}$), EC ($r = -0.19^{**}$), and Fe ($r = -0.23^{**}$) showed significant and unfavourable relationships. In addition to reflecting potassium dynamics with more available and non-available potassium forms, the PC2 suggested nutrient balance or availability stress in soils.

The principal component PC3 had a positive correlation with variables EXK ($r = 0.27^{**}$), EC ($r = 0.11^*$), LK ($r = 0.02$), and Mn ($r = 0.01$), while a negative correlation with variables TK ($r = -0.11^*$), NEX ($r = -0.16^{**}$), AVK ($r = -0.22^{**}$), Fe ($r = -0.29^{**}$), WSK ($r = -0.32^{**}$), Zn ($r = -0.45^{**}$), and Cu ($r = -0.66^{**}$) (Fig.6) indicates the relation between soil-specific characteristics (e.g., mineral structure or texture) with a smaller contribution. The principal component PC4 had a positive correlation with variables EC ($r = 0.72^{**}$), TK

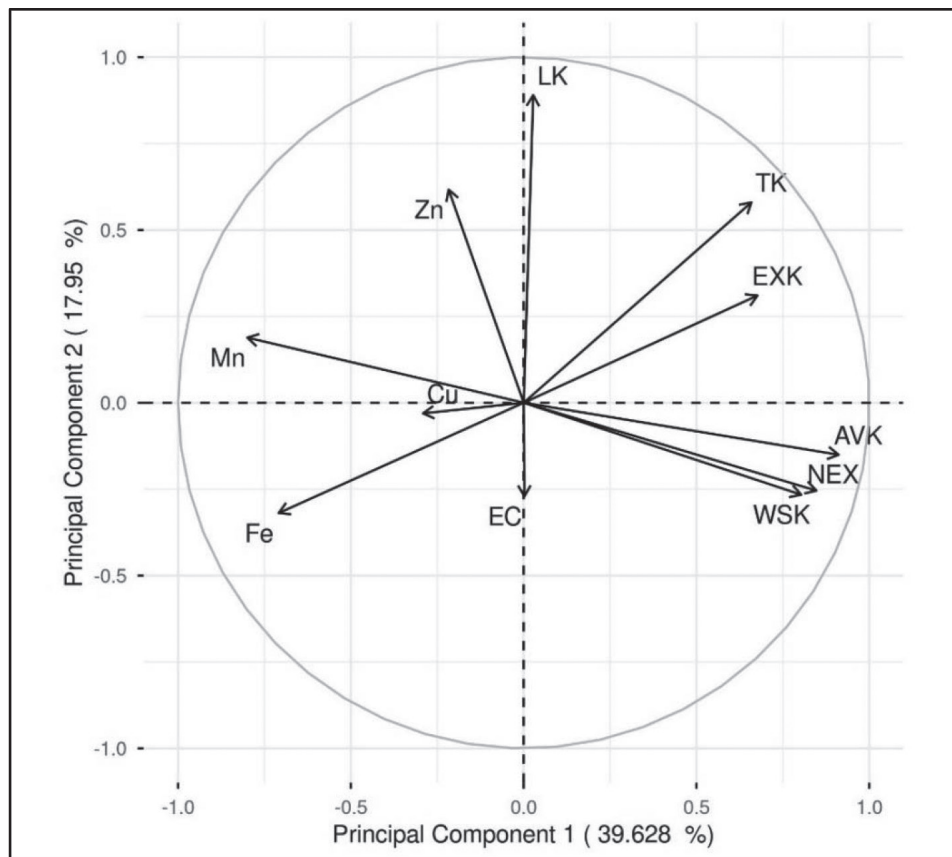


Fig. 5. Principal Component Analysis of soil properties biplot

Table 3. Rotated component matrix of the four principal component accounting for most of the total variance

Soil properties	PC1	PC2	PC3	PC4
Electrical conductivity	0.0010	-0.1927	0.1084	0.717
Available K	0.4365	-0.1072	-0.2160	0.0286
Water-soluble K	0.3845	-0.1893	-0.3248	0.1409
Exchangeable K	0.3240	0.2208	0.2653	-0.3450
Non-exchangeable K	0.4057	-0.1810	-0.1584	0.1287
Lattice K	0.0132	0.6334	0.0167	0.3013
Total K	0.3156	0.4126	-0.1145	0.3258
DTPA–Fe	-0.3395	-0.2271	-0.2914	0.1872
DTPA–Mn	-0.3831	0.1341	0.0129	0.2294
DTPA–Zn	-0.1040	0.4388	-0.4484	-0.1141
DTPA–Cu	-0.1395	-0.0219	-0.6641	-0.179
Eigen value	4.4	2.0	1.8	1.5
Standard deviation	2.0878	1.4052	1.3447	1.2378
Percentage of variance	39.628	17.95	16.439	13.928
Cumulative Percent	39.628	57.578	74.017	87.945

($r = 0.33^{**}$), LK ($r = 0.30^{**}$), Mn ($r = 0.23^{**}$), Fe ($r = 0.19^{**}$), WSK ($r = 0.14^{**}$), NEX ($r = 0.13^{**}$), and AVK ($r = 0.03$), while a negative correlation with variables Zn ($r = -0.11^*$), Cu ($r = -0.18^{**}$), and EXK ($r = -0.34^{**}$) represents residual or local variations due to minor soil processes in comparison to PC1 and PC2.

CONCLUSION

The correlation analysis indicated that soil pH had a strong negative correlation with organic carbon. A very strong positive correlation was found between available potassium and water-soluble potassium, non-exchangeable K and total K, indicating that higher K availability in these soils is primarily associated with higher quantities of different fractions of potassium that exists in equilibrium. The micronutrient cations tend to accumulate in surface horizons while exchangeable K slightly increase with depth in certain layers. Lattice potassium exhibited a strong positive correlation with total potassium, confirming its dominant contribution to total K reserves in these soils. DTPA–Fe and DTPA–Mn was positively correlated indicating their common behaviour under similar redox conditions. DTPA–Fe and total K were negatively correlated, indicating possible interactions in mineral

weathering or parent material influence. DTPA–Zn and DTPA–Cu were weakly but significantly correlated, hinting at shared geochemical controls or similar sources. Linear regression indicated that AVK and WSK decrease with depth; however, EXK, NEXK, LK, and TK increase with increasing soil depth. Important tools for comprehending the soil fertility potential and potassium fractions are the principal component and correlation matrix employed in this study. Four components were found using the PCA applied to the soil parameters under investigation. Potassium fractions are found to be significantly correlated with the elements Fe, Mn, Zn, Cu, pH, and OC. These correlations provide valuable insights into the nutrient dynamics and chemical behaviour of the soils in this region.

ACKNOWLEDGEMENT

The authors express their gratitude to Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli for the invaluable support provided in conducting the research work.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

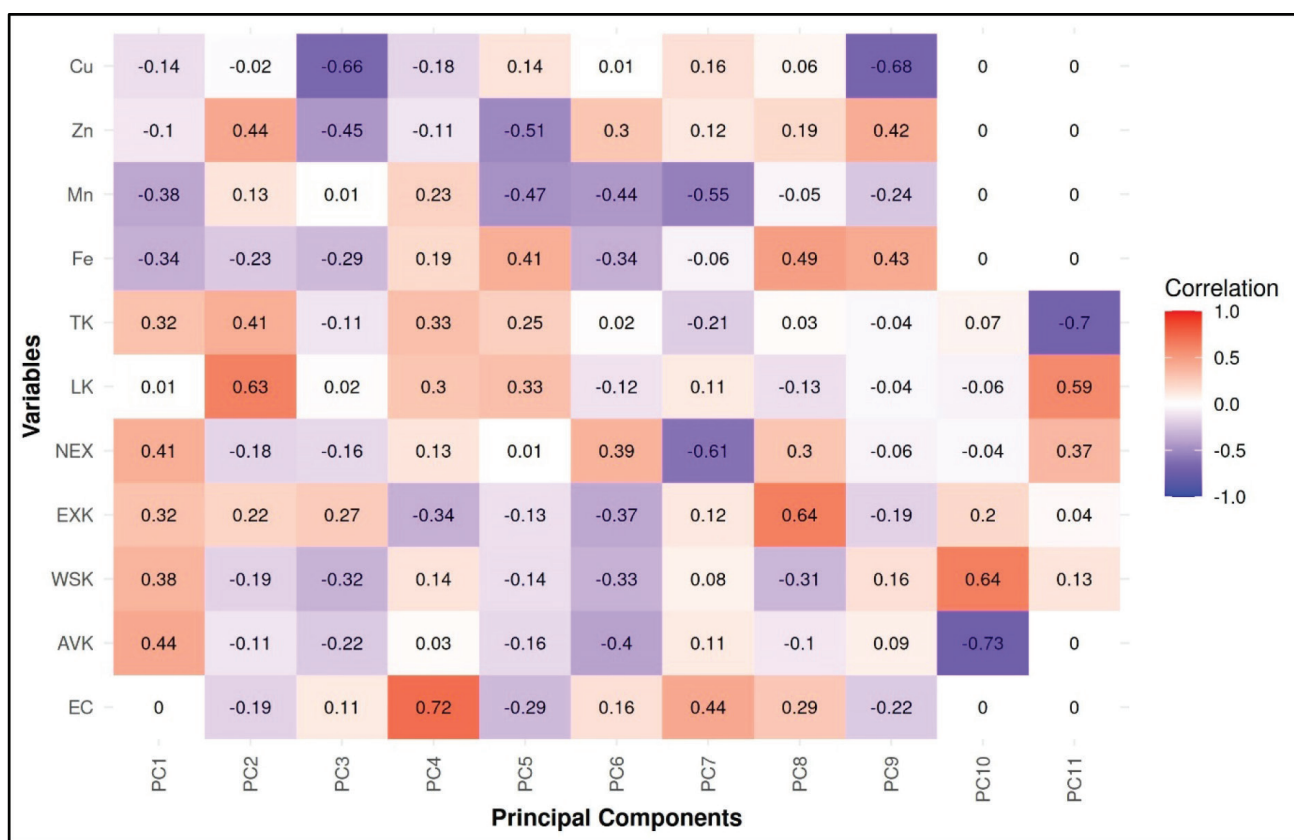


Fig. 6. Correlation between principal components and variables

REFERENCES

- Abhale, S.B., Wahane, M.R., Khobragade, N.H., Dodake, S.B., Chavan, V.G., Patil, S.S. Pisal, V.V. and Nevase, S.V. (2024). Integration of organic manures and inorganic fertilizers on soil properties at different growth stages and yield of paddy in coastal saline soil of Maharashtra. *International Journal of Research in Agronomy* 7(10): 306–312.
- Ahmed, S., Kayes, I., Shahriar, S.A., Kabir, M.M., Salam, M.A. and Mukul, S.A. (2020). Soil salinity and nutrients pattern along a distance gradient in coastal region. *Global Journal of Environmental Science and Management* 6(1): 59–72. <https://doi.org/10.22034/gjesm.2020.01.05>
- Baldantoni, D., Saviello, G. and Alfani, A. (2019). Nutrients and nonessential elements in edible crops following long-term mineral and compost fertilization of a Mediterranean agricultural soil. *Environmental Science and Pollution Research* 26: 35353–35364. <https://doi.org/10.1007/s11356-018-3353-8>.
- Bandyopadhyay, B.K., Maji, B., Sen, H.S. and Tyagi, N.K. (2003). *Coastal Soils of West Bengal – Their Nature, Distribution and Characteristics*. Bulletin No. 1/2003. Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal. pp 1–62.
- Chavan, A.R., Wahane, M.R., Khobragade, N.H., Dodake, S.B. and Damodhar, V.P. (2024). Potassium fractions distribution and their variation in soils of Mango Research Sub-Centre, Rameshwar, Devgad of Maharashtra. *Journal of the Indian Society of Soil Science* 72: 360–363. <https://doi.org/10.5958/0974-0228.2024.00053.9>

- Dhillon, S.K., Sidhu, P.S., Dhillon, K.S. and Sharma, V.P. (1985). Distribution of various forms of potassium in some benchmark soils of north-west India. *Journal of Potassium Research* **1**: 154–165.
- Dodake, S.B., Khobragade, S.S., Borse, D.K., Vaidya, K.P., Kaledhonkar, M.J., Wahane, M.R. and Palkar, J.J. (2022). Effect of saline water irrigation on growth, yield and economics of spinach, radish and dill under coastal saline soils of North Konkan region of Maharashtra. *Journal of Soil Salinity and Water Quality* **14**(1): 76–83.
- Dodake, S.B., Khobragade, S.S., Borse, D.K., Wahane, M.R., Vaidya, K.P., Kaledhonkar, M.J. and Meena, B.L. (2023). Effect of irrigation level and sowing date on yield of field bean in saline soils of Konkan region of Maharashtra. *Journal of Agricultural Engineering (India)* **60**(1): 100–107. <https://doi.org/10.52151/jae2023601.1800>
- Grewal, J.S. and Kanwar, J.S. (1966) Forms of potassium in Punjab soils. *Journal of the Indian Society of Soil Science* **14**: 63–67.
- Hanway, J.J. and Heidel, H. (1952). *Soil Analysis Method used in IOWA State College Soil Testing Laboratory*, Bulletin of IOWA State College **57**: 1–13.
- Hoque, M., Hannan, A., Imran, S., Paul, N.C., Mondal, M., Sadhin, M., Rahman, M., Bristi, J.M., Dola, F.S., Hanif, M. and Ye, W. (2022). Plant growth-promoting rhizobacteria-mediated adaptive responses of plants under salinity stress. *Journal of Plant Growth Regulation* 1-20. <https://doi.org/10.1007/s00344-022-10633-1>
- Islam, A., Sirajul Karim, A.J.M., Solaiman, A.R.M., Islam, Md.S. and Saleque, Md.A. (2017). Eight-year long potassium fertilization effects on quantity/intensity relationship of soil potassium under double rice cropping. *Soil and Tillage Research* **169**: 99–117.
- Jackson, M.L. (1973). *Soil Chemical Analysis*, Prentice Hall of India Pvt. Ltd. New Delhi, India.
- Joshi, R.G. and Kadrekar, S.B. (1987). Fertility status of coastal salt affected soils of Maharashtra. *Journal of Indian Society of Coastal Agricultural Research* **5**(1):111–116.
- Lindsay, W.L. and Norvell, W.A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal* **42**: 474–481.
- Lu, S.Y., Zhang, H.M., Sojinu, S.O., Liu, G.H., Zhang, J.Q. and Ni, H.G. (2015). Trace elements contamination and human health risk assessment in drinking water from Shenzhen, China. *Environmental Monitoring and Assessment* **187**, 4220.
- Maji, B., Chatterji, S. and Bandyopadhyay, B.K. (1993). Available iron, manganese, zinc and copper in coastal soils of Sundarbans, West Bengal in relation to soil characteristics. *Journal of the Indian Society of Soil Science* **41**(3):468–471.
- Menezes-de-Souza, Z., Junior, J.M., Pereira, G.T. and Barbieri, D.M. (2006). Small relief shape variations influence spatial variability of soil chemical attributes. *Scientia Agricola* **63**(2): 161–168.
- Merse, M., Lemma, W. and Solomon, T. (2024). Characterization and classifications of saline/sodic soils of ambo area of irrigated farm land in Golina watershed in Raya valley, Amhara region, Ethiopia. *International Journal on Food, Agriculture, and Natural Resources* **5**(3): 112–118.
- Misal, N.B., Sukul P. and Polara K.B. (2020) Dynamics of potassium fractions in the calcareous soils of Gujarat. *Journal of the Indian Society of Soil Science* **68**: 62–69.
- Nandy, T. (2020). Nutrient status of some coastal soils of Guntur district, Andhra Pradesh. *Journal of Indian Society of Coastal Agricultural Research* **38**(1): 70–75.

- Panse, V.G. and Sukhatme, P.V. (1961). *Statistical Methods for Agricultural Workers*, ICAR, New Delhi, India.
- Patil, K.D., More, S.S., Wahane, M.R., Puranik, U.Y. and Khobragade, N.H. (2018). Micronutrients importance in hi-tech horticulture. *Journal of Pharmacognosy and Phytochemistry* **7**(3): 628–635.
- Pattani, V.B., Kaneriya, J.P. and Joshi, K. (2021). Study of micronutrients and macronutrients in soils of coastal and Gir forest region of Saurashtra, Gujarat. *Environment and Ecology* **39**(2): 473–481.
- Prasad, J. (2010). Forms of potassium in shallow soils of different origin and land uses in Nagpur district of Maharashtra. *Journal of the Indian Society of Soil Science* **58**(3): 327–330.
- Prasad, J., Glasser, B., Singh, B.R., Nadzana, G.M. and Kome, G.K. (2023). Soil management for improved productivity and soil health. *Journal of Chemical, Biological and Physical Sciences* **13**: 140–152.
- Qiang, L., Jiheng, Z., Yiyang, Z., Wenfang, T., Zhengyan, Z., Yan, X. and Xiaoying, L. (2011). Study on spatial distribution of soil available microelement in Qujing tobacco farming area, China. *Procedia Environmental Science* **10**: 185–191.
- Rao, S. Ch., Prasad, J., Singh, S.P. and Takkar, P.N. (1997). Distribution of forms of potassium and K release kinetics in some Vertisol profiles. *Journal of the Indian Society of Soil Science* **45**(3): 465–468.
- Rasel, M., Tahjib-Ul-Arif, M., Hossain, M.A., Hassan, L., Farzana, S. and Brestic, M. (2020). Screening of salt-tolerant rice landraces by seedling stage phenotyping and dissecting biochemical determinants of tolerance mechanism. *Journal of Plant Growth Regulation*. <https://doi.org/10.1007/s00344-020-10235>.
- Raut, A.R., Wahane, M.R., Khobragade, N.H., Thorat, S.B., Rajemahadik, V.A. and Dodake, S.B. (2024). Impact of NPK fertilizer levels on soil properties and potassium fractions in lateritic soil of coastal Maharashtra. *Journal of Indian Society of Coastal Agricultural Research* **42**(2): 122–128. <https://doi.org/10.54894/JISCAR42.2.2024.147091>
- Sarkar, G.K., Chattopadhyay, A.P. and Sanyal, S.K. (2013). Release pattern of non-exchangeable potassium reserves in Alfisols, Inceptisols and Entisols of West Bengal, India. *Geoderma* **207**: 8-14. <https://doi.org/10.1016/j.geoderma.2013.04.029>
- Schepers, A., Shanahan, J.F., Liebig, M.A., Schepers, J.S., Johnson, S. and Luchiarri, A. (2004). Delineation of management zones that characterize spatial variability of soil properties and corn yields across years. *Agronomy Journal* **96**: 195-203. <https://doi.org/10.2134/agronj2004.0195>.
- Sharma, A., Jalali, V.K., Arya, V.M. and Rai, P. (2009). Distribution of various forms of potassium in soils representing intermediate zone of Jammu Region. *Journal of the Indian Society of Soil Science* **57**(2): 205–207.
- Singh, J.P., Singh, S. and Singh, V. (2010). Soil potassium fractions and response of cauliflower and onion to potassium. *Journal of the Indian Society of Soil Science* **58**(4): 384–387.
- Singh, M., Tripathi, A.K. and Reddy, D.D. (2002). Potassium balance and release kinetics of non-exchangeable K in a Typic Haplusterts as influenced by cattle manure application under a soybean-wheat system. *Soil Research* **40**: 533–541. <https://doi.org/10.1071/SR00064>
- Singh, M.V. (2008). Micronutrient deficiencies in crops and soils in India. In: *Micronutrient Deficiencies in Global Crop Production*, Springer, Dordrecht. pp 93–125.
- Sparks, D.L. and Huang, P.M. (1985). Physical chemistry of soil potassium. In: *Potassium in Agriculture*, R.D. Munson (ed.), American Society of Agronomy, Madison, Wisconsin,

USA. pp 201-276.

Walche, A., Haile, W., Kiflu, A. and Tsegaye, D. (2023). Assessment and characterization of agricultural salt-affected soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley. *Applied and Environmental Soil Science* 2025: 3946508. <https://doi.org/10.1155/2023/3946508>

Wiklander, L. (1954). Forms of potassium in the soil. *Potassium Symposium*, International Potash Institute, Berne, Switzerland. pp 109-121.

Wood, L.K. and De Turk, E.E. (1941). The adsorption of potassium in soil in non-exchangeable forms. *Proceedings of the Soil Science Society of America* **5**: 152–161.