



RESEARCH ARTICLE

Evaluation of potassium fractions and fixation capacity in inceptisol of Tamil Nadu

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Received: 26 May 2026; Accepted: 10 July 2026; Available online: Version 1.0: 01 September 2026

Cite this article: Neha VN, Silviya RA, Melvin JM, Rajeshkumar A, Varsha S, Thirumal V. Evaluation of potassium fractions and fixation capacity in inceptisol of Tamil Nadu. *Plant Science Today*. 2026;13(sp5):01–11. <https://doi.org/10.14719/pst.15705>

Abstract

Potassium (K) plays an important role in maintaining plant health by regulating stomatal movement, enhancing water retention and activating enzymes. It is an essential macronutrient whose availability depends on the distribution and transformation of different K fractions in soil. Although soils contain substantial quantities of K, only a small proportion is readily available for plant uptake. Therefore, the objective of this study was to evaluate K fractions, K fixation capacity and their interrelationships in a soil belonging to the inceptisol order. Surface soil samples were collected from SRM College of Agricultural Science, Chengalpattu District, Tamil Nadu, India. An incubation experiment was conducted using a factorial completely randomised design (FCRD) with three replications. A total of seven treatments were evaluated, comprising a distilled-water control, five potassium chloride (KCl) application levels (20, 40, 60, 80 and 100 mg K kg⁻¹ soil) and an absolute control (no water). Soil samples were collected at 0, 10, 20, 30, 40 and 50 days after incubation (DAI). Potassium fractions were determined using water extraction for water-soluble K, neutral 1 N NH₄OAc extraction for exchangeable K, boiling HNO₃ extraction for non-exchangeable K and acid digestion for total K. Potassium levels, incubation periods and acid digestion for total K. Potassium levels, incubation periods and their interactions significantly influenced K fractions ($p < 0.001$). Available K increased from 69.31–759.93 mg K kg⁻¹ soil, while water-soluble K ranged from 92.30–292.33 mg K kg⁻¹ soil. Non-exchangeable K varied from 68.60–109.60 mg K kg⁻¹ soil, indicating the formation of reserve K pools following K application. The highest available K concentration was observed under the 100 mg K kg⁻¹ treatment. Two-way analysis of variance (ANOVA) revealed that K levels, incubation period and their interaction significantly influenced all K fractions ($p < 0.001$). Correlation analysis revealed a significant positive relationship between available K and non-exchangeable K ($r = 0.69$), suggesting that the non-exchangeable pool acts as a buffer or reserve K fraction for maintaining K availability. Potassium fixation capacity showed negative correlations with total K ($r = -0.27$) and non-exchangeable K ($r = -0.17$). X-ray diffraction (XRD) analysis confirmed the presence of clay minerals contributing to K fixation and release dynamics. Principal component analysis (PCA) explained 74.4 % of the total variation, distinguishing dynamic K pools from relatively stable K forms. The findings highlight the dynamic equilibrium among K fractions in inceptisol soil order and emphasise the importance of balanced K management for sustaining soil fertility and crop productivity.

Keywords: inceptisol; potassium dynamics; potassium fixation capacity; potassium fractions; soil fertility; sustainable potassium management

Introduction

The soil collected from SRM College of Agricultural Science (SRMCAS), Chengalpattu, Tamil Nadu belongs to inceptisol soil order. Inceptisols are among the major agricultural soils and exhibit moderate soil development with varying nutrient supplying capacities. Although potassium (K) dynamics have been studied in several soil types, information on the distribution of K fractions, fixation capacity and their temporal transformations in inceptisols under varying K application levels remain limited. A better understanding of the relationships among soluble, exchangeable, non-exchangeable and fixed K pools is essential for efficient K management and sustainable soil fertility. Therefore, the present study was undertaken to evaluate K fractions and fixation capacity in an inceptisol collected from the SRMCAS farm under different K application levels and incubation periods and to

assess the interactions among various K pools governing K availability

Potassium is one of the most abundant cationic nutrients in the soil, constituting approximately 1.9 % of Earth's crust. In terms of plant physiology, K regulates numerous processes, including enzyme activation, photosynthesis, osmotic adjustment, stomatal function and assimilate translocation, all of which contribute to plant growth and productivity (1, 2). The lack of K in soils reduces plant growth and significantly declines the yield and quality. In contrast, adequate K nutrition enhances the plant tolerance to abiotic stresses such as salinity and drought (3–5).

In soils, K exists in four different pools: mineral, non-exchangeable, exchangeable and soil solution forms (6, 7). Among these, the exchangeable and solution form of K constitutes the most readily available fraction for plant uptake whereas the

mineral K represents largest pool but remains unavailable for plant uptake. The non-exchangeable fraction serves as a reserve pool, maintaining the equilibrium among K fractions by replenishing the available forms during depletion periods (8).

The distribution and transformation of K among different pools are influenced by various factors such as soil mineralogy, texture, organic matter and management practices (9–11). Potassium availability is governed by adsorption, desorption, fixation and release processes occurring at soil exchange sites (12). Various soil properties like moisture content, cation exchange capacity and the nature of clay play a significant role in regulating the process and consequently improving K availability. A basic understanding of these interactions is essential for predicting the behaviour of K in the soil system (10).

Incubation studies are widely utilised under controlled laboratory (13, 14). In such studies, soils are treated with varying levels of K and analysed at regular intervals. This approach allows researchers to evaluate the dynamics of different K fraction with an insight on adsorption-desorption mechanism. Periodic assessment of K release, fixation and redistribution among soil fractions provides valuable information on nutrient retention and availability (15). This information helps to predict soil K supply to plants and supports plant growth (16). It was hypothesised that increasing levels of K application would significantly alter the distribution of K among different soil fractions during incubation, enhance K fixation capacity and influence the equilibrium between readily available and reserve K pools in the inceptisol. Furthermore, this insight supports the development of sustainable management practices aimed at enhancing the crop productivity and maintain longterm soil fertility. Therefore, the present study was undertaken to evaluate the effects of graded K application on different K fractions and fixation capacity in an inceptisol under controlled incubation conditions. The study also aimed to examine the relationships among K pools using correlation and principal component analyses (PCAs).

Materials and Methods

Collection of soil sample and characterisation

Surface soil samples (0–15 cm depth) were collected from the instructional farm of SRM College of Agricultural Science (SRMCAS), Chengalpattu District, Tamil Nadu, India (12.372855° N, 79.742466° E). Six soil cores were collected following a V-shaped zig-zag sampling pattern across the experimental field and thoroughly homogenised to obtain a representative composite sample. The experimental soil was classified as an inceptisol according to the USDA Soil Taxonomy. The collected soil was air-dried at room temperature ($30 \pm 2^\circ\text{C}$), gently crushed using a wooden mallet and passed through a 2 mm sieve before being stored in labelled polyethylene zip-lock bags until further analysis. The initial physicochemical properties of the experimental soil, including pH, electrical conductivity (EC), organic carbon (OC), available nitrogen

Table 1. Initial physicochemical properties of experimental soil

S. No	Constituents	Content	Methods
1	pH	7.42	1:2.5 soil water suspension
2	EC (dSm^{-1})	0.25	1: 2: 5 soil water suspension
3	Organic carbon (%)	0.54	Chromic acid wet digestion method
4	Available N (kg ha^{-1})	285	Alkaline permanganate method
5	Available P (kg ha^{-1})	18.6	Olsen method
6	Available K (kg ha^{-1})	285	Neutral normal ammonium acetate method
7	Texture	Sandy clay loam	Bouyoucos hydrometer method
8	CEC cmol (+) kg^{-1}	18.5	1 N NH_4OAc (pH 7.0) method

(N), available phosphorus (P), available K, soil texture and cation exchange capacity (CEC), were determined using standard analytical procedures prior to the incubation experiment and the results are presented in Table 1. The mineralogical characteristics of the experimental soil were examined using X-ray diffraction (XRD) analysis employing $\text{Cu K}\alpha$ radiation over a scanning range of $5\text{--}100^\circ$ (2θ). The resulting diffractogram was used to characterise the crystalline mineral phases present in the experimental soil. The XRD pattern of the soil is presented in Fig. 1.

Incubation experiment

The incubation experiment was conducted using a factorial completely randomised design (FCRD) with three replications. The experiment consisted of seven K treatments and six incubation periods (0, 10, 20, 30, 40 and 50 days after incubation (DAI)), resulting in a total of 126 experimental units ($7 \times 6 \times 3$). The treatment details are presented in Table 2. For each experimental unit, 50 g of air-dried and processed soil was placed in a 100 mL plastic container and 50 mL of the respective treatment solution was added according to the treatment schedule. Potassium was applied as potassium chloride (KCl) solution only once at the beginning of the incubation experiment, while distilled water was added only to the distilled-water control treatment. No additional water or K solution was supplied throughout the incubation period. The treated soil samples were incubated at room temperature ($32 \pm 2^\circ\text{C}$) under ambient laboratory conditions. The containers were kept undisturbed and protected from direct sunlight throughout the incubation period. Soil samples were collected at 0, 10, 20, 30, 40 and 50 DAI for the determination of K fractions and K fixation capacity. The K levels were selected to represent a gradient from low to high K availability commonly encountered under agricultural conditions.

Preparation of potassium solutions

A 1000 mg K L^{-1} stock solution was prepared by dissolving analytical-grade KCl in distilled water. Working solutions containing 20, 40, 60, 80 and 100 mg K L^{-1} were prepared by appropriate dilution of the stock solution. The prepared solutions were stored in clean, dry polyethylene bottles and applied to the respective treatments at the beginning of the incubation experiment. Observations were recorded at 10 day intervals throughout the incubation period.

Table 2. Treatment details

S. No	Treatment	Details
1	T_1	Absolute control (no solution)
2	T_2	Control (distilled water)
3	T_3	20 ppm KCl solution
4	T_4	40 ppm KCl solution
5	T_5	60 ppm KCl solution
6	T_6	80 ppm KCl solution
7	T_7	100 ppm KCl solution

The K levels were selected to represent a gradient from low to high K availability commonly encountered under agricultural conditions. The treatment details of the incubation experiment is mentioned as follows,

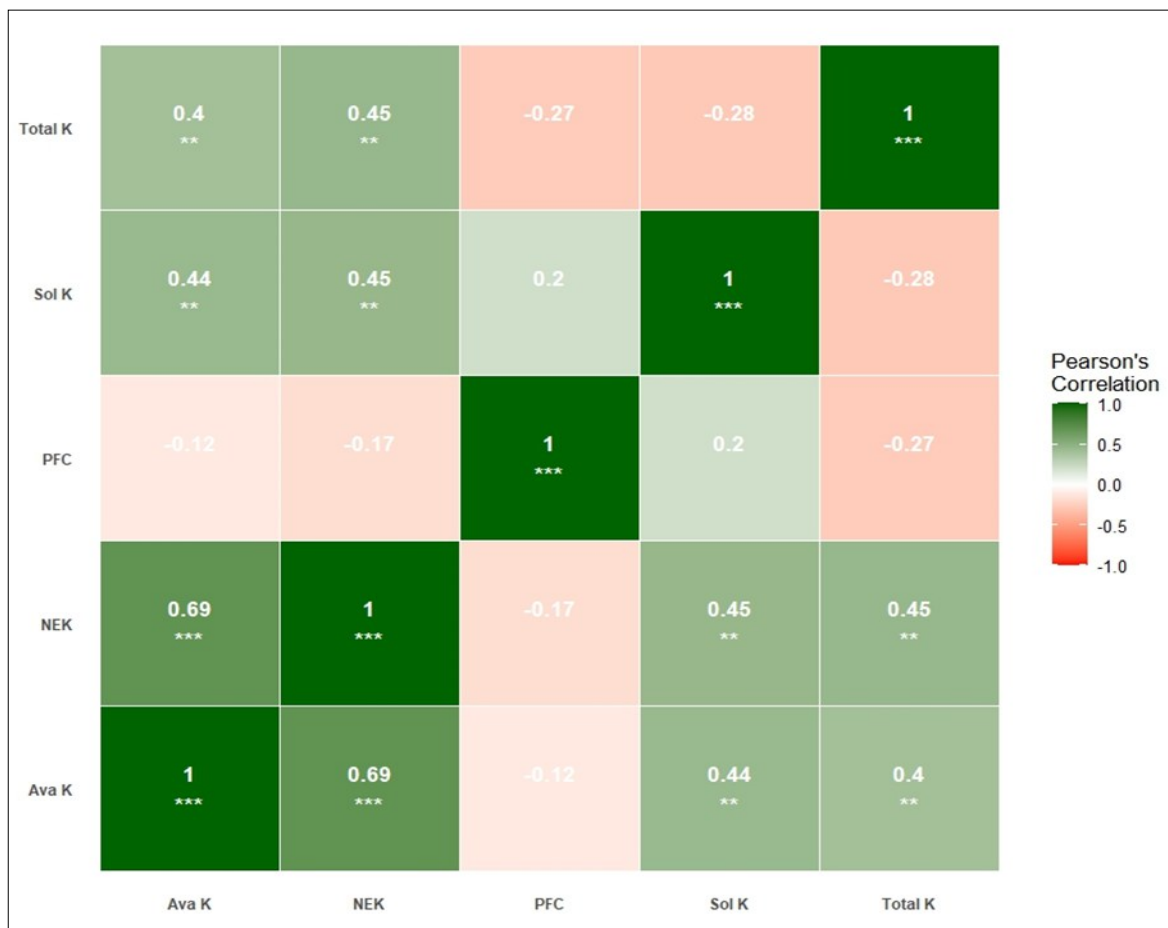


Fig. 1. Pearson correlation matrix illustrating relationships among potassium (K) fractions and K fixation capacity. Total K: Total potassium; PFC : potassium fixation capacity; Sol K : Soluble potassium; NEK : Non-exchangeable potassium; Ava K : Available potassium

Estimation of potassium fractions

Potassium fractions were determined using standard analytical procedures. Water-soluble K was extracted by shaking 10 g of soil with 50 mL of distilled water for 30 min, followed by filtration through Whatman No. 42 filter paper. Potassium concentration in the filtrate was determined using a flame photometer. Exchangeable K was extracted from the residue using 1 N neutral ammonium acetate (NH_4OAc ; pH 7.0) following the method described in a previous study (17). Non-exchangeable K was determined by boiling the residue with 1 N HNO_3 for 10 min (18, 19). Total K was determined after digesting finely ground soil samples with a tri-acid mixture (HNO_3 ; HClO_4 ; HF) until complete dissolution. Potassium concentration in the digest was measured using a flame photometer following (20).

Potassium fixation capacity was determined using the wetting-and-drying method (21). Briefly, a known quantity of K solution was added to the soil, followed by repeated wetting and drying cycles to facilitate K fixation. After equilibration, exchangeable K was extracted with 1 N NH_4OAc (pH 7.0) and the amount of fixed K was calculated as the difference between the quantity of K applied and the quantity recovered after extraction. Potassium fixation capacity was expressed as the percentage of K applied.

Statistical analysis

Potassium concentrations in all extracts were measured using a flame photometer and quantification was carried out using standard calibration curves prepared from K standard solutions. The experimental data were subjected to analysis of variance (ANOVA) prior to ANOVA, the assumptions of normality of residuals and homogeneity of variances were examined which is appropriate for a

factorial completely randomised design (FCRD). A two-way ANOVA was performed to evaluate the main effects of K level (Factor A), incubation period (Factor B) and their interaction ($A \times B$). The significance of treatment effects, incubation periods and their interactions was tested at the 5 % probability level ($p \leq 0.05$). Whenever significant differences were observed, treatment means were compared using the critical difference (CD) test at the 5 % level of significance. Statistical analyses were performed using R software (Version 4.4.1) through the RStudio integrated development environment. Pearson's correlation analysis was performed to examine the relationships among different K fractions and K fixation capacity. Principal component analysis (PCA) was performed using R software (Version 4.4.1) and identify the major sources of variation and to assess the associations among K fractions under different K application levels and incubation periods.

Results And Discussion

Effect of treatments on potassium fractions

The analysis of variance for the effects of K levels, incubation periods and their interaction on K fractions and K fixation capacity is presented in Table 3. The ANOVA revealed that different K levels (Factor A), treatment conditions (Factor B) and their interaction ($A \times B$) had a highly significant ($p < 0.001$) effect on available K, soluble K and total K. This indicates that both external K administration and treatment conditions have substantial effects on the dynamics of K in soil. As shown in Table 3, K level contributed the highest F-values for available K (13225.5), non-exchangeable K (24773.97) and total K (300.4), whereas incubation period also exerted a significant influence on all measured K fractions and K fixation capacity. The K

Table 3. Analysis of variance (FCRD) for K fractions and K fixation capacity in an inceptisol soil during incubation

Source of variation	df	Available K	Soluble K	Non-exchangeable K	Total K	K fixation capacity
K level (K)	6	13225.5	1054.9	24773.97	300.4	46.04
Incubation period (D)	6	477.2	378.8	71.97	1138.9	77.96
K × D interaction	36	223.1	171.4	516.12	127.1	27.83
Error MS	96	37.81	19.20	2.57	0.011	3.483
SEm ±	--	3.55	2.53	0.93	0.061	1.077
CD ($P = 0.05$)	--	7.05	5.02	2.63	0.121	2.14
CV (%)	--	3.07	2.11	1.80	2.08	3.00

Note: MS = Mean Square; df = Degrees of Freedom; SEm ± = Standard Error of Mean; CD ($p = 0.05$) = Critical Difference at the 5% level of significance; CV (%) = Coefficient of Variation; K = Potassium level; D = Incubation period; K × D = Interaction between potassium level and incubation period; Error MS = Error Mean Square.

transformation may be controlled by a combination of factors rather than by individual factors alone, according to the substantial interaction effect. Similarly, considerable interaction effects influencing K release and fixing in inceptisols were observed (13). Noting that fertiliser dosages and incubation conditions had a substantial impact on K availability reported similar results (14).

Available potassium (Ava K)

Available K was significantly increased by K application levels, incubation periods and their interaction ($p < 0.001$). The mean available K ranged from 77.49 mg K kg⁻¹ soil in the absolute control to 524.08 mg K kg⁻¹ soil in the 100 ppm treatment, whereas the maximum value of 759.93 mg K kg⁻¹ soil was recorded under the 100 ppm treatment during the incubation period. Duncan's multiple range test showed that the 100 ppm treatment was significantly superior to all other treatments, while the absolute control and distilled-water control recorded the lowest available K values.

The increase in available K with increasing K application was primarily attributed to the direct addition of K through KCl and the subsequent enrichment of the soil solution and exchangeable K pools. Following K application, K ions initially remained in the soil solution and were subsequently adsorbed onto negatively charged clay minerals and organic matter. This dynamic adsorption-desorption equilibrium maintained a continuous supply of K in the available pool throughout the incubation period. Furthermore, a portion of the applied K gradually moved into the non-exchangeable fraction, while another portion was released back into the available pool, thereby sustaining K availability. Similar findings were reported, which explained that K fertilisation shifts the equilibrium among soluble, exchangeable, non-exchangeable and mineral K fractions, thereby increasing the readily available K pool (22). Likewise, it was reported that continuous adsorption-desorption reactions and microbial-mediated K solubilisation help maintain K availability in agricultural soils (23).

The gradual increase in available K observed during incubation indicates continuous redistribution of K among soluble, exchangeable and non-exchangeable fractions until a dynamic equilibrium was established. Cation exchange reactions, diffusion processes and reversible fixation within the interlayer spaces of clay minerals. These processes enhance the buffering capacity of the soil and regulate K availability to plants over time. It was similarly observed that graded K application promoted the transformation of K among different soil fractions, thereby improving soil K buffering capacity and sustaining K availability during the incubation period (24). Comparable observations were also reported, which emphasised that balanced K fertilisation replenishes labile K pools and helps maintain long-term soil fertility under intensive cropping systems (25).

The present findings are consistent with previous studies conducted on inceptisols, where graded K fertilisation significantly increased the available K pool while improving the soil's buffering capacity. Thereby co-workers reported that intensive cultivation of entisols and inceptisols progressively depleted available K, emphasising the importance of balanced K fertilisation to maintain soil fertility. Similarly, colleagues demonstrated that soils with greater reserve K were better able to sustain K availability through gradual replenishment of the exchangeable pool. The comparable response observed in the present inceptisol confirms that balanced K application effectively maintains equilibrium between readily available and reserve K fractions.

Soluble potassium (Sol K)

Water-soluble K was significantly affected by K application levels, incubation periods and their interaction ($p < 0.001$). The mean water-soluble K ranged from 92.32–259.15 mg K kg⁻¹ soil, while the highest concentration (292.33 mg K kg⁻¹ soil) was recorded under the 100 mg K kg⁻¹ treatment during incubation. Duncan's multiple range test indicated that the highest K application significantly increased the water-soluble K concentration compared with the lower K treatments and controls.

The increase in water-soluble K with increasing K application was mainly attributed to the dissolution of applied KCl, which immediately increased the concentration of K⁺ ions in the soil solution. During incubation, K remained in a dynamic equilibrium with exchangeable and non-exchangeable K fractions through continuous adsorption and desorption reactions. As the concentration of K in the soil solution declined because of adsorption onto clay minerals and fixation within interlayer sites, K was simultaneously replenished from exchangeable forms, thereby maintaining equilibrium among the different K pools.

The increase in available K with increasing K application reflects the dynamic equilibrium among soluble, exchangeable, non-exchangeable and mineral K pools in the soil. Following K application, K continuously undergoes adsorption, desorption, fixation and release reactions, thereby maintaining the concentration of K in the soil solution. Similar observations were reported, which highlighted those continuous transformations among K fractions regulate K availability under intensive agricultural systems (25). Likewise, the chemistry of K fertilisers in soil is governed by equilibrium reactions among different K pools, which determine the long-term availability of K to plants (26).

The non-linear response observed among the intermediate K treatments indicates that a portion of the applied K was temporarily retained on cation exchange sites or fixed within interlayer spaces of clay minerals instead of remaining entirely in the soil solution. These reversible adsorption-desorption and fixation-release processes contribute to the buffering capacity of soils and

ensure a sustained supply of plant-available K. Similar findings reported, K dynamics across different Indian soil orders and emphasised the continuous redistribution of K among solution, exchangeable, non-exchangeable and mineral fractions (27). Furthermore, it was demonstrated that K transformations among different soil fractions are influenced by fertiliser application and microbial activity, resulting in continuous replenishment of the available K pool during incubation (28).

These findings demonstrate that water-soluble K represents the most readily available form of K for plant uptake but also serves as the most dynamic fraction, continuously interacting with other K pools during incubation. Comparable observations were reported, which found that soil solution K is continuously replenished from exchangeable and reserve K pools through reversible adsorption-desorption reactions (29). Similarly, increasing K application enhances water-soluble K while maintaining equilibrium with exchangeable and non-exchangeable forms, thereby improving the K-supplying capacity of inceptisols (30).

Non-exchangeable potassium (NEK)

Non-exchangeable K was significantly influenced by K application levels, incubation periods and their interaction ($p < 0.001$). The mean non-exchangeable K ranged from 68.60–109.60 mg K kg⁻¹ soil, with an overall mean value of 89.10 mg K kg⁻¹ soil. The highest non-exchangeable K content was recorded under the 100 mg K kg⁻¹ treatment, indicating greater conversion of applied K into reserve forms as K application increased.

The increase in non-exchangeable K following K application suggests that a portion of the applied K was retained within the interlayer spaces of 2:1 clay mineral through K fixation. During incubation, K ions initially accumulated in the soil solution and exchangeable pools before gradually becoming fixed between the layers of clay minerals such as illite and vermiculite. This process reduced the immediate availability of K while increasing the reserve K pool that can subsequently replenish the exchangeable and soluble fractions when soil solution K declines.

Similar findings reported, that K fixation is a reversible process through which K is temporarily retained within K-bearing minerals and subsequently released to maintain K availability in soils (31). Likewise, it was demonstrated that non-exchangeable K contributes substantially to the replenishment of exchangeable K and should be considered an important component of soil K availability (32).

The gradual accumulation of non-exchangeable K during incubation demonstrates the reversible nature of K fixation and release. Although this fraction is not immediately available for plant uptake, it serves as an important reserve source by supplying K to the exchangeable pool through slow weathering, desorption and diffusion processes. Consequently, the non-exchangeable K fraction plays a crucial role in maintaining long-term K availability and buffering the soil against K depletion. Similarly, it was reported that reserve K contributes significantly to maintaining K availability in inceptisols under continuous cropping systems (30).

The observed increase in non-exchangeable K with increasing K application supports the concept that soils receiving higher K inputs tend to retain a greater proportion of applied K in reserve forms. This transformation enhances the K buffering capacity of the soil and contributes to the long-term sustainability of K nutrition. It was emphasised that equilibrium among different K

pools govern K availability and fertiliser-use efficiency (33). Furthermore, it was showed that non-exchangeable K serves as an important reserve pool capable of replenishing available K through gradual release processes (34).

The present results also agree with studies conducted on inceptisols, which have shown that non-exchangeable K serves as an important reserve capable of replenishing exchangeable K during crop uptake. Similar observations reported that reserve K substantially contributes to the K-supplying capacity of intensively cultivated entisols and inceptisols (35). These findings indicate that the non-exchangeable K pool should be considered when evaluating K fertility in inceptisol soils.

Total potassium (Total K)

Total K was significantly influenced by K application levels, incubation periods and their interaction ($P < 0.001$), thereby exhibiting considerable variability among the treatments. The total K content varied from 4.34–6.70 %, with the highest value observed under the 100 mg K kg⁻¹ treatment. Although significant differences were observed among treatments, the variation in total K was considerably smaller than that of available and water-soluble K, indicating that short-term K application primarily affected the distribution of K among different soil fractions rather than the total K reserve.

A fraction of the applied K was redistributed into fixed or non-exchangeable forms, which led to an increase in total K but did not necessarily increase its bioavailability for plant uptake.

The relatively small variation in total K may be attributed to the fact that total K includes both plant-available K and structural K present within primary and secondary minerals. During the incubation period, the applied K was redistributed among the water-soluble, exchangeable and non-exchangeable fractions through adsorption, desorption, fixation and release processes, while the structural K contained in soil minerals remained largely unchanged. Consequently, changes in total K were less pronounced than those observed for the more dynamic K fractions. Similar observations were reported, which observed that long-term K fertilisation primarily modifies the distribution of K among labile and reserve pools, whereas the total K content remains largely controlled by soil mineralogy (36). Likewise, the distribution of total K is strongly influenced by parent material, clay mineralogy and soil-forming processes, while changes due to fertiliser application are mainly reflected in the more labile K fractions (37).

The increase in total K under higher K application rates reflect the incorporation of applied K into different soil K pools rather than a direct increase in immediately available K. This demonstrates that K undergoes continuous transformation among soil fractions, contributing to both short-term nutrient availability and long-term K reserves. Therefore, total K alone cannot be considered a reliable indicator of K availability to plants because a substantial proportion remains structurally bound within primary minerals. Similarly reports suggest that assessment of soil K availability should focus on extractable K fractions rather than total K alone (35). Furthermore, it was emphasised that evaluation of soil K fertility requires consideration of the different K pools because each contributes differently to crop K nutrition (36).

These findings indicate that K fertilisation mainly influences the partitioning of K among different soil fractions while only marginally affecting the total K content during short-term

incubation. The total K is predominantly governed by mineralogical characteristics, whereas the relative distribution among K fractions is more responsive to soil properties and management practices (37). Similarly, it was concluded that K fractionation provides a more meaningful assessment of soil K fertility and nutrient-supplying capacity than total K alone (38).

Correlation analysis

Positive correlations

Pearson's correlation analysis from revealed strong interrelationships among K fractions, indicating functional connectivity within the soil K system (Fig. 1). The positive correlation between available K and non-exchangeable K ($r = 0.69$) suggests that reserve K acts as a key source for replenishing plant-available K through gradual release processes. This reflects a dynamic equilibrium governed by adsorption-desorption and fixation-release reactions within the soil matrix. This relationship suggests the existence of a dynamic equilibrium between readily available and reserve K fractions, whereby K is continuously redistributed through adsorption-desorption and fixation-release reactions. Similar observations were reported, which demonstrated that non-exchangeable K serves as a major reserve contributing to crop-available K through gradual release (39). Likewise, it was reported that continuous redistribution among K fractions during incubation, thereby sustaining K availability (28).

Water-soluble K also exhibited a moderate positive correlation with non-exchangeable K ($r = 0.45$), as shown in Fig. 1, suggesting that the reserve K pool contributed to maintaining K concentration in the soil solution. These positive associations indicate that different K fractions are closely interconnected and collectively regulate K availability. During incubation, K released from the non-exchangeable pool replenished the exchangeable and water-soluble pools, thereby maintaining plant-available K. Similar findings reported that, significant positive correlations among water-soluble, exchangeable, non-exchangeable and total K fractions, reflecting continuous K redistribution (40). Comparable results were reported, which demonstrated that the interactions among K fractions are largely governed by soil mineralogy and physicochemical properties (41).

Overall, the correlation analysis presented in demonstrates that reserve K fractions play an important role in buffering soil K and maintaining a continuous supply of K for plant uptake (Fig. 1). Similar conclusions were reported that long-term K fertilisation modifies the distribution of K among labile and reserve pools, thereby sustaining soil K fertility (35). Likewise, it was emphasised that non-exchangeable K is a major contributor to the K-supplying capacity of agricultural soils (39).

Negative correlations

As shown in Fig. 1, potassium fixation capacity (PFC) exhibited negative correlations with total K ($r = -0.27$) and non-exchangeable K ($r = -0.17$). These relationships indicate that increasing K fixation temporarily reduces the proportion of K remaining in readily available forms by retaining it within the interlayer spaces of clay minerals. Similar observations were reported, which demonstrated that clay mineralogy strongly influences K retention and the distribution of K fractions (41). Likewise, the release of K from non-exchangeable pools is largely governed by the mineralogical characteristics of the soil (39).

The negative association between K fixation capacity and non-exchangeable K, illustrated in Fig. 1, suggests that although fixed K contributes to reserve pools, excessive fixation temporarily limits K release and reduces immediate K availability. Similar findings were reported, who observed that K transformations among different fractions are regulated by fixation-release reactions during incubation (28). Furthermore, it was highlighted that K retention within mineral structures influences soil K buffering capacity and nutrient availability (42).

Overall, the correlation analysis confirmed that K transformations are governed by continuous redistribution among soluble, exchangeable, non-exchangeable, fixed and mineral K fractions (Fig. 1). These interrelationships emphasise the importance of maintaining equilibrium among K pools to sustain K availability, improve fertiliser-use efficiency and enhance long-term soil fertility. Comparable conclusions were also reported (35, 41).

Principal component analysis (PCA)

Principal component analysis (PCA) was performed to evaluate the multivariate relationships among K fractions and K fixation capacity. As presented in Fig. 2, the first two principal components explained 74.40 % of the total variation, indicating that these components adequately represented the variability in K dynamics during incubation. Similar applications of PCA for evaluating K fractions reported, which successfully differentiated K fractions based on soil properties and mineralogical characteristics (41).

The PCA biplot revealed a clear separation between dynamic K fractions (available K and water-soluble K) and relatively stable pools (non-exchangeable K and total K) (Fig. 2). Available K showed a strong association with non-exchangeable K, indicating active exchange between labile and reserve forms during incubation. In contrast, K fixation capacity exhibited an inverse relationship. Water-soluble K also showed a positive association with available K, reflecting the dynamic equilibrium among readily available K fractions. Comparable observations were reported, which observed significant associations among water-soluble, exchangeable, non-exchangeable and total K fractions, indicating continuous redistribution among K pools (40).

In contrast, K fixation capacity was positioned opposite to available K and water-soluble K, indicating an inverse relationship between K fixation and K availability (Fig. 2). Total K occupied a relatively distinct position, reflecting its predominance in mineral-bound forms and its comparatively low short-term variability. Similar findings were reported, that mineral-bound K behaves differently from labile K fractions in multivariate analyses (42).

The PCA biplot clearly distinguished K fractions into two functional groups (Fig. 2). The first group comprised the dynamic K pool, consisting of water-soluble, available and exchangeable K, whereas the second group comprised the relatively stable K pool, including non-exchangeable, fixed and mineral K. Similar classifications were reported which demonstrated that multivariate statistical techniques effectively differentiate K fractions according to their functional role in soil K dynamics (40, 41). This multivariate pattern confirms that K behaviour in inceptisol soil order is governed by continuous redistribution among functionally distinct soil pools.

Effect of potassium application on soil potassium fractions

The distribution of different K fractions under varying K application levels is presented in Fig. 3. Potassium application significantly

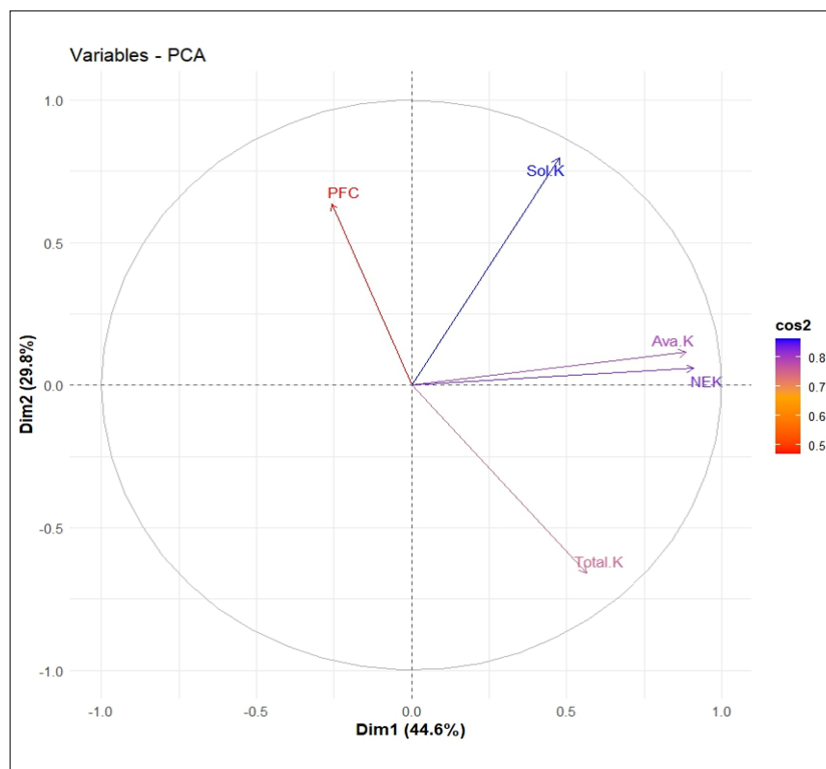


Fig. 2. The principal component analysis (PCA) of potassium (K) fraction revealed that the majority of the variability was explained by Dim1 (44.6 %) and Dim2 (29.8 %) while potassium fixation capacity (PFC) and total K had opposing associations with available forms; available K and non-exchangeable K were tightly related.

influenced the distribution of K among the different soil fractions ($p < 0.001$). A progressive increase in available K, water-soluble K, non-exchangeable K, total K and K fixation capacity was observed with increasing K application rates. The highest concentrations of available K, water-soluble K and non-exchangeable K were consistently recorded under the 100 mg K kg⁻¹ soil treatment, indicating that higher K inputs enhanced both the readily available and reserve K pools.

Similar observations were reported, which demonstrated that long-term K fertilisation modifies the distribution of K among different soil fractions and improves the K-supplying capacity of soils (35). Likewise, graded K application increased both labile and reserve K fractions through continuous redistribution among soil K pools (43).

The increase in water-soluble and available K immediately after K application resulted from the dissolution of KCl and the subsequent accumulation of K ions in the soil solution. As incubation progressed, part of the applied K was adsorbed onto exchange sites and gradually transformed into non-exchangeable forms through fixation within the interlayer spaces of clay minerals. These transformations established a dynamic equilibrium among K fractions, ensuring a continuous supply of K to the soil solution while simultaneously replenishing reserve pools.

Similar mechanisms were described, which reported that adsorption-desorption and fixation-release reactions regulate the equilibrium among soluble, exchangeable, non-exchangeable and mineral K forms (26). Comparable findings were reported, which observed continuous redistribution of K among different fractions during incubation, thereby sustaining K availability (28).

Potassium fixation capacity also increased with increasing K application, indicating that soils receiving higher K inputs retained a greater proportion of the applied K within clay mineral structures. Although fixation temporarily reduced the proportion

of immediately available K, it contributed to the development of reserve K pools capable of gradually releasing K under conditions of depletion. This process enhances the K buffering capacity of the soil and supports long-term K availability.

Similar findings reported that non-exchangeable K serves as an important reserve capable of gradually replenishing plant-available K (39). Likewise, it was emphasised that reserve K plays a significant role in maintaining soil K availability and buffering capacity under agricultural production systems (32).

Overall, the results demonstrate that graded K application not only increased the readily available K fraction but also promoted the redistribution of K into reserve forms through adsorption, desorption, fixation and release processes. These transformations are fundamental for maintaining K equilibrium, enhancing fertiliser-use efficiency and sustaining long-term soil fertility. The present findings are consistent with those reported in earlier studies which emphasised that balanced K fertilisation improves K cycling, nutrient-use efficiency and sustainable soil fertility management (26, 35, 43).

Interaction effects (Potassium levels × Incubation periods)

The interaction between K application levels and incubation periods significantly influenced all K fractions ($P < 0.001$), indicating that K transformations were jointly regulated by the quantity of K applied and the duration of incubation. Soils receiving higher K application rates consistently exhibited greater concentrations of available K, water-soluble K, non-exchangeable K, total K and K fixation capacity throughout the incubation period than the control treatments, demonstrating a strong interaction between treatment level and incubation time.

Immediately after K application, a substantial proportion of the applied K remained in the soil solution, resulting in higher water-soluble and available K concentrations. During incubation, K was progressively redistributed among soluble, exchangeable, non-exchangeable and fixed forms through adsorption-desorption and

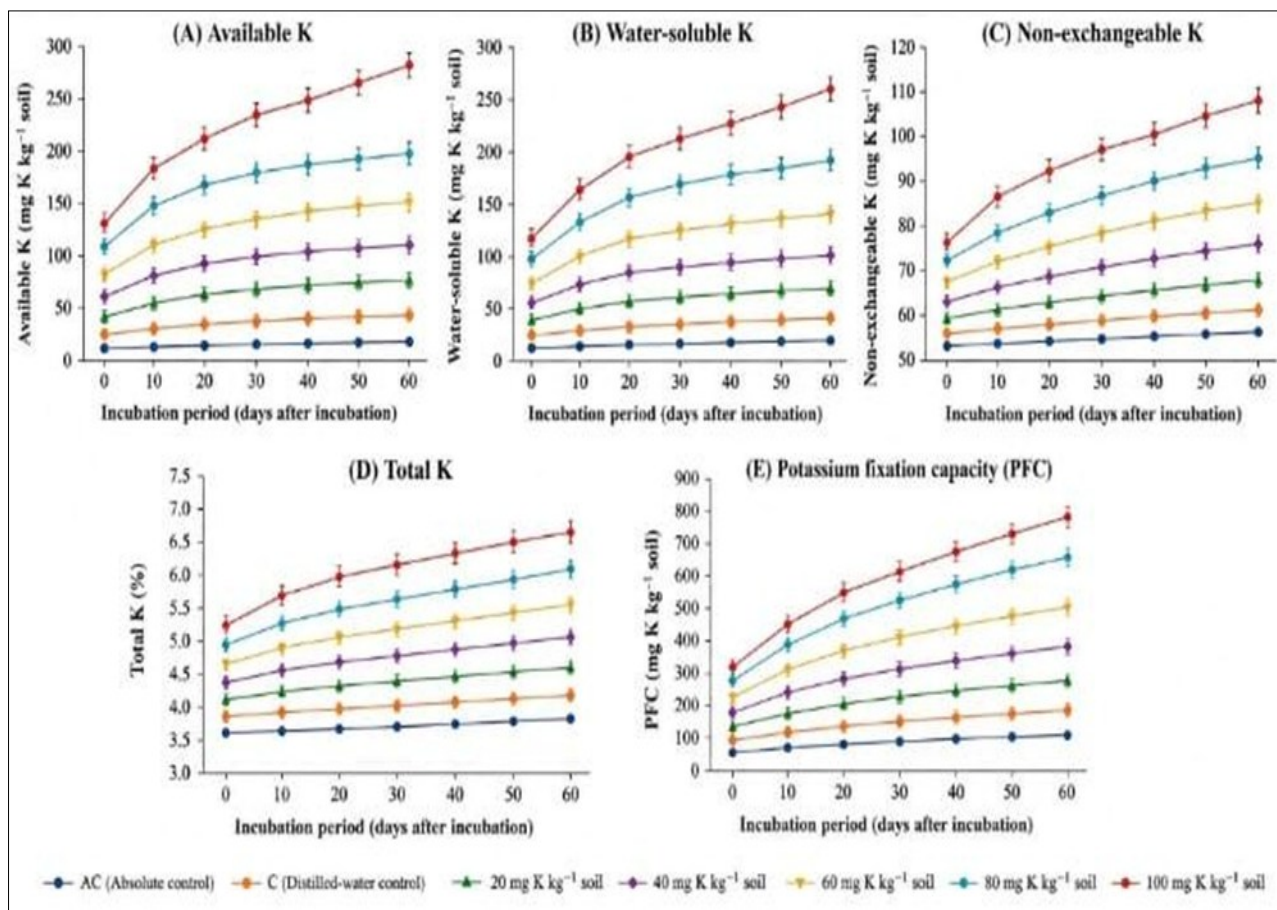


Fig. 3. Effect of graded potassium (K) application on available K (Ava K), water-soluble K (Sol K), non-exchangeable K (NEK), total K (TK) and K fixation capacity (PFC) in an inceptisol during incubation. Values are presented as mean $\pm$ SEM ($n = 3$). The corresponding SEM values were ± 3.55 mg K kg⁻¹ for available K, ± 2.53 mg K kg⁻¹ for water-soluble K, ± 0.93 mg K kg⁻¹ for non-exchangeable K, ± 0.061 % for total K and ± 1.077 mg K kg⁻¹ for K fixation capacity. Error bars represent the standard error of the mean (SEM).

fixation-release reactions. A portion of the applied K was retained on exchange sites, whereas another fraction became fixed within the interlayer spaces of clay minerals, leading to a gradual increase in non-exchangeable K. Simultaneously, reserve K was released to replenish the available K pool, thereby maintaining K equilibrium throughout the incubation period.

Similar K transformation mechanisms were reported, highlighting the importance of reversible K exchange processes in regulating soil K dynamics (26, 44).

The highest concentrations of available K, water-soluble K and non-exchangeable K were consistently recorded under the 100 mg K kg⁻¹ soil treatment throughout the incubation period, indicating that higher K application enhanced both the immediately available and reserve K pools. In contrast, the absolute control and distilled-water control maintained the lowest K concentrations because no external K source was supplied.

Comparable findings were reported, which demonstrated that appropriate K fertilisation improves K availability and the quantity-intensity relationship in agricultural soils (45). Similar observations were also reported, where balanced K application promoted redistribution among different K fractions and enhanced the K-supplying capacity of soils (26).

Overall, the significant interaction between K application level and incubation period demonstrates that K dynamics are highly time-dependent and strongly influenced by fertiliser application rate. The continuous redistribution of K among different soil fractions maintained K buffering capacity, improved nutrient-use efficiency and ensured a sustained supply of K throughout the

incubation period. These findings are consistent with those reported in earlier studies which emphasised that soil physicochemical properties, mineralogical composition and K application rate collectively regulate K transformations and long-term K availability (41, 45). Therefore, both K application rate and incubation duration should be considered when developing efficient K management strategies for sustaining soil fertility and crop productivity. The results have important implications for K management in inceptisols. Since K application increased both readily available and reserve K pools, balanced K fertilisation should be adopted to sustain K availability throughout the crop-growing period. Periodic soil testing combined with appropriate K fertilisation can improve fertiliser-use efficiency while minimising depletion of reserve K in inceptisol soils. Similar recommendations have been proposed for intensively cultivated inceptisols under long-term cropping systems (31, 32, 46).

X-ray diffraction (XRD) analysis of soil mineralogy

The X-ray diffraction (XRD) pattern of the experimental soil is presented in Fig. 4. The diffractogram exhibited a prominent diffraction peak at $2\theta = 26.36^\circ$ ($d = 3.381$ Å), indicating quartz as a major crystalline phase. Additional diffraction peaks were observed at 20.59° , 36.30° , 42.21° , 45.64° , 49.92° , 59.71° , 67.90° and 90.62° , confirming the presence of other crystalline mineral phases within the soil matrix. The well-defined diffraction pattern indicates that the soil possesses crystalline minerals that contribute to its physicochemical characteristics, particularly nutrient retention and cation exchange processes. Similar observations have been reported, which demonstrated that soil mineralogy significantly

influences K availability and fixation by regulating clay mineral properties and cation exchange characteristics (32).

The mineralogical composition of the soil provides a mechanistic explanation for the observed K transformations during incubation. The presence of clay-associated minerals supports K retention through interlayer fixation and exchange processes, contributing to the development of non-exchangeable K pools and enhancing soil buffering capacity. These characteristics explain the strong coupling observed between soil mineralogy and K fraction dynamics.

Therefore clay mineralogy and the location of charge within clay minerals strongly influence K fixation, release and overall K availability in soils (32, 47). Similarly, it was emphasised that soil minerals act as long-term reservoirs of K and regulate the gradual replenishment of K in the soil solution, thereby sustaining crop nutrition (48).

The XRD pattern obtained in the present study provides complementary evidence for interpreting the observed K transformations during incubation. The presence of crystalline mineral phases supports the significant increase in non-exchangeable K and K fixation capacity following graded K application, indicating enhanced interaction between applied K and soil mineral surfaces. These findings agree with the observations of an earlier study, which reported that soil mineralogy is a major factor controlling K retention and release and highlighted the importance of mineral-bound K in maintaining long-term K availability and soil fertility (49, 50). The mineralogical characteristics observed in the present inceptisol also support previous reports indicating that clay mineralogy strongly regulates K fixation and release. The presence of K bearing clay minerals enhances K buffering capacity by facilitating reversible fixation and release processes, thereby sustaining long-term K availability in inceptisol soils (51, 52)

Conclusion

The present incubation study demonstrated that graded K application significantly influenced the distribution and transformation of K fractions in an inceptisol. Potassium levels, incubation periods and their interaction exhibited highly significant effects ($p < 0.001$) on all K fractions and K fixation capacity. Application of K up to 100 mg K kg^{-1} soil markedly increased available K ($77.49\text{--}759.93 \text{ mg K kg}^{-1}$), water-soluble K ($92.32\text{--}292.33 \text{ mg K kg}^{-1}$) and non-exchangeable K ($68.60\text{--}109.60 \text{ mg K kg}^{-1}$), indicating enhanced development of both labile and reserve K pools.

Available K increased markedly with K application, reaching maximum values at 100 ppm K . A significant positive relationship between available and non-exchangeable K ($r = 0.69$) and PCA explaining 74.4 % of total variability highlighted the interconnected nature of soil K pools.

Overall, the findings demonstrate that K dynamics in the experimental inceptisol are governed by continuous redistribution among water-soluble, exchangeable, non-exchangeable and mineral K pools. These results are consistent with previous studies on inceptisols, indicating that soil mineralogy and K fertilisation jointly regulate K availability and fertiliser-use efficiency. Future research should validate these findings under long-term field conditions across diverse cropping systems and agro-climatic regions. Integrating soil mineralogy, crop K uptake and long-term K fertilisation studies will facilitate the development of site-specific K management strategies for sustainable crop production in inceptisol soils.

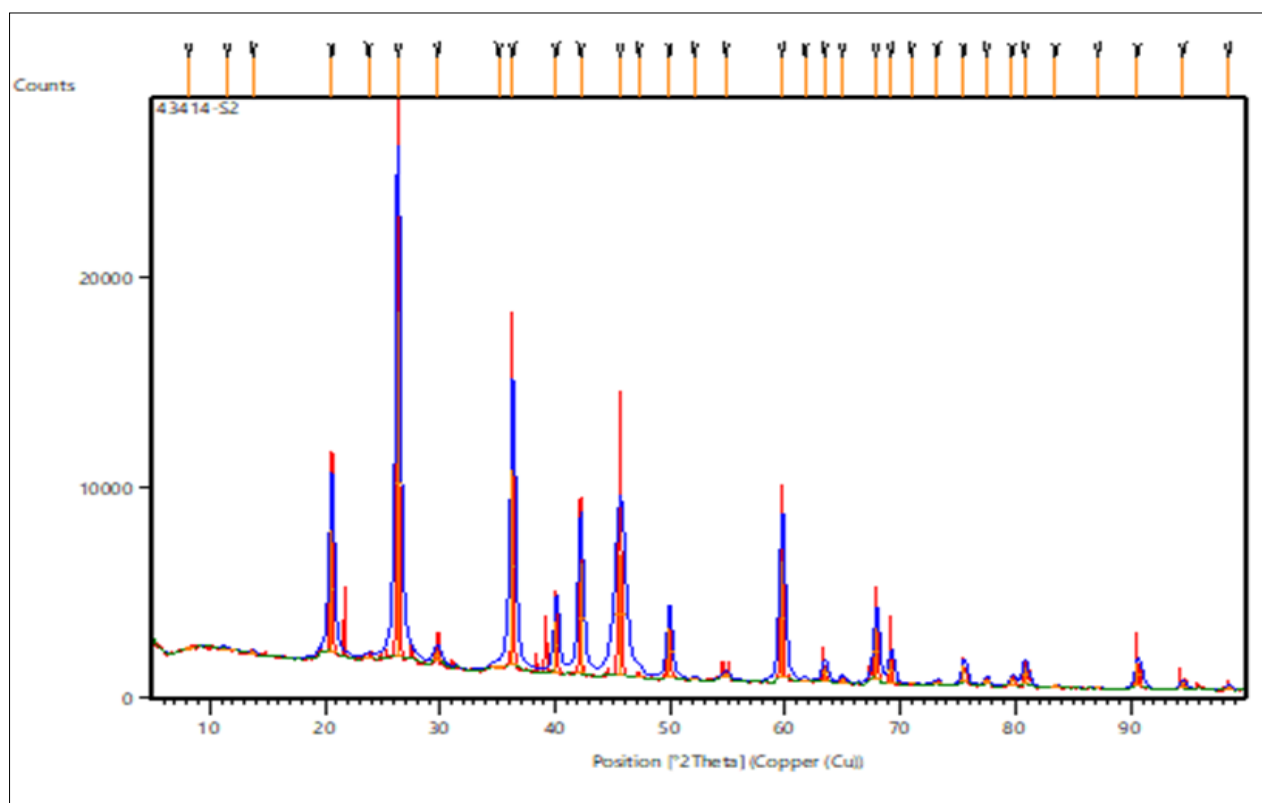


Fig. 4. X-ray diffraction (XRD) pattern of the experimental inceptisol used in the incubation study. The diffractogram was recorded using Cu K α radiation over a scanning range of $5\text{--}100^\circ$ (2θ). A prominent diffraction peak occurred at $2\theta = 26.36^\circ$ ($d = 3.381 \text{ \AA}$) corresponding to quartz, together with several additional diffraction peaks representing the crystalline mineral phases present in the soil.

Acknowledgements

The authors express their sincere gratitude to the Department of Soil Science, SRM College of Agricultural Sciences, SRM Institute of Science and Technology (SRMIST), Chengalpattu, Tamil Nadu, for providing essential facilities and continuous support for this research. The authors also thank the Nanotechnology Research Centre (NRC), SRMIST, for providing the necessary research facilities.

Authors' contributions

NVN conceived and designed the study, conducted the laboratory experiment, collected and analysed the data, performed the statistical analysis, interpreted the results, prepared the figures and tables and drafted the manuscript. RAS supervised the research, contributed to the study design, guided the interpretation of results and critically revised the manuscript. MJM contributed to the experimental methodology, data interpretation and critical revision of the manuscript. RA provided technical guidance, contributed to data interpretation and critically reviewed the manuscript. VS assisted in laboratory experimentation, sample processing and data compilation. TV assisted in laboratory analyses, data validation and manuscript editing. All authors 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

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, improving grammar and readability and formatting sections of the manuscript. After using this tool, the authors carefully reviewed, revised and verified the content and take full responsibility for the accuracy and integrity of the publication.

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