



RESEARCH COMMUNICATION

Dynamics of soil potassium fractions under long-term manuring and fertilisation in a finger millet-maize cropping sequence in an inceptisol

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Abstract

A long-term fertiliser experiment (LTFE) initiated during 1972 was evaluated after 51 yr (118th crop; 2024–25) at Tamil Nadu Agricultural University, Coimbatore, India, to quantify changes in soil potassium (K) fractions, K depletion dynamics and yield sustainability of finger millet grown on an Inceptisol. The experiment comprised ten fertiliser treatments, including control, nitrogen (N) alone, nitrogen and phosphorus (NP), recommended dose of NPK (100 % NPK), higher NPK levels and integrated nutrient management (INM) with farmyard manure (100 % NPK + FYM), arranged in a randomised block design with four replications. Surface soil (0–15 cm) samples were analysed for water-soluble K (WSK), exchangeable K (exch. K), non-exchangeable K (NEK), lattice K, total K and available K using standard procedures. Integrated nutrient management (100 % NPK + FYM) maintained significantly higher available K and exchangeable K compared with sole chemical fertilisation, whereas continuous K omission treatments showed substantial depletion of labile K pools, indicating progressive mining of native reserves. Lattice K constituted the dominant fraction, followed by NEK, exch. K and WSK. Available K showed strong positive associations with grain and straw yield. The sustainable yield index (SYI) was highest under integrated fertilisation, reflecting greater yield stability over time. Net change analysis showed a negative K balance under omission treatments and improved K retention under balanced fertilisation. The results demonstrated that long-term balanced fertilisation combined with organic manure is essential for sustaining soil K fractions, preventing reserve depletion and maintaining productivity in intensive cropping systems on inceptisol.

Keywords: finger millet; integrated nutrient management; long-term fertiliser experiment; potassium fractions; sustainable yield index

Introduction

Potassium (K) is an essential nutrient that plays a vital role in plant physiological functions such as enzyme activation, osmotic regulation, protein, starch synthesis and translocation of photosynthates, which ultimately contribute to crop productivity and sustainability (1, 2). Despite its importance, K often receives less attention compared to N and P, especially in Indian agriculture, where skewed fertiliser consumption ratios have favoured N and P over K, leading to imbalanced nutrient inputs (3). This results in depletion of soil K reserves globally, as well as in India. The continuous mining of native soil K has led to negative K balances in many croplands, causing declines in soil fertility and crop yields (4).

Soil K exists in dynamic equilibrium among four main fractions: WSK, exch. K, NEK and lattice K, which are integral parts of primary K-bearing minerals such as mica and illite (5). Among these, WSK and exch-K are the primary pools immediately available to

plants and microbes, whereas NEK and lattice K act as reservoirs that replenish available K over time through weathering and dynamic soil chemical processes (6). The dynamics of these K pools depend on soil physicochemical properties, mineralogy, cropping intensity and nutrient management strategy (7).

Long-term intensive cropping without adequate K replenishment leads to depletion of readily available K pools, forcing plants to rely increasingly on NEK reserves (8). This mining of K can result in diminished nutrient supply, lower yields and irreversible soil degradation. Long-term studies have demonstrated significant shifts among K fractions under different fertilisation regimes, showing that balanced fertilisation and organic amendments improve K availability while maintaining reserve pool stability (9). Long-term studies emphasise that K fertilisation strategies consider the contribution of soil native K pools, especially the NEK fraction, which plays a buffering role during periods of low K input (10). Monitoring temporal changes in K fractions helps in identifying early signs of

nutrient mining and guides site-specific, long-term nutrient management strategies. Such insights are particularly critical in intensive cropping systems where soil K dynamics directly influence nutrient sustainability and are indispensable for developing efficient fertilisation strategies (11).

The objective of this study is to elucidate the impact of long-term nutrient management on changes in K fractions in an irrigated Inceptisol under a finger millet–maize cropping system after 51 yr and the relationship of these fractions with yield. The changes in the available K, K fractions and yield of the 118th crop of finger millet are discussed in this paper. The goal is to generate insights that can guide sustainable K fertilisation practices to maintain soil fertility and crop productivity in tropical semi-arid conditions.

Materials and Methods

Site description

The experiment was conducted as part of an LTFE that was initiated in 1972 under the ICAR–All India Coordinated Research Project (AICRP) on Soil Science and is currently maintained by the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University (TNAU), Coimbatore. The cropping sequence being followed is finger millet–maize sequence (since 2000–2001). The experimental site is located at 11° N latitude and 77° E longitude, with an elevation of 426.7 m above mean sea level. The soil at the site is classified as an Inceptisol (*Vertic Ustropept*) and is characterised as a calcareous mixed black soil with a sandy clay loam texture, belonging to the Periyanaickenpalayam soil series. Coimbatore has a tropical climate, marked by hot and humid summers and relatively cool winters. The average annual temperature at the site during the

study period (2024–2025) is about 36.5 °C (maximum) and 27.0 °C (minimum). Annual rainfall during the study period was 674.2 mm, with an average relative humidity of 46 %. Initial soil physicochemical properties of the experiment were given in Table 1. The experimental trial has followed different cropping sequences over time and the sequence adopted from 2000 to date has been finger millet - maize (Table 2).

Treatment details

In the long-term fertiliser experiment (LTFE), a total of ten treatments were evaluated (Table 3). Urea, single superphosphate (SSP) and muriate of potash (MOP) were used as nutrient sources, except in treatment nine, where diammonium phosphate (DAP) was applied as the P source. Each treatment was replicated four times in a randomised block design. Finger millet was raised as the test crop during the kharif season. The cultivar used throughout the experimental period was CO 15. Seeds were collected from the Department of Millets, Tamil Nadu Agricultural University, Coimbatore. Each experimental plot measured 20 × 10 m² and the treatments were arranged in a randomised block design with four replications. The crop was grown under irrigated conditions and irrigation was scheduled based on crop growth stages and soil moisture status. Irrigations were applied uniformly across all treatments to avoid moisture stress, following the recommended agronomic practices for finger millet in the region. Typically, irrigation was provided at critical growth stages such as establishment, tillering, flowering and grain filling to ensure optimum crop growth.

Collection and processing of soil samples

The 118th crop (finger millet) was raised during Kharif (June to September 2024). As per the treatment, 50 % N and the full P and K were applied basally, with the remaining nitrogen top-dressed in

Table 1. Initial physical, physicochemical and chemical properties of the experimental soil

	Parameter	Value
I.	Physical properties	
	Clay (%)	32.60
	Silt (%)	4.80
	Fine sand (%)	15.10
	Coarse sand (%)	39.40
	Textural class	Sandy clay loam
	Soil series	Periyanaickenpalayam
	Soil taxonomy	<i>Vertic Ustropept</i>
II.	Physico-chemical properties	
	Soil reaction (pH)	8.20
	Electrical conductivity (EC) (dS m ⁻¹)	0.20
	Cation exchange capacity (cmol (p ⁺) kg ⁻¹)	25.20
III.	Chemical properties	
	Organic carbon (g kg ⁻¹)	3.00
	Total nitrogen (mg kg ⁻¹)	428.00
	Total phosphorus (mg kg ⁻¹)	490.00
	Total potassium (mg kg ⁻¹)	3964.00
	Total calcium (%)	2.10
	Total magnesium (%)	1.00
	Available nitrogen (kg ha ⁻¹)	199
	Available phosphorus (kg ha ⁻¹)	12.30
	Available potassium (kg ha ⁻¹)	907
	Exchangeable calcium (cmol (p ⁺) kg ⁻¹)	10.60
	Exchangeable magnesium (cmol (p ⁺) kg ⁻¹)	6.50
	DTPA-Zn (mg kg ⁻¹)	2.58
	DTPA-Mn (mg kg ⁻¹)	2.74
	DTPA-Cu (mg kg ⁻¹)	0.42
	DTPA-Fe (mg kg ⁻¹)	2.74

Table 2. Cropping sequence followed over the years

S. No	Cropping Sequence	Period	
		From	To
1.	Finger Millet-Cowpea grain-Maize (up to 10 th cycle)	1972-73	1984-85
2.	Finger Millet-Maize- Cowpea grain (11 th to 14 th cycle)	1985-86	1989-90
3.	Finger Millet-Maize- Cowpea fodder (15 th to 25 th cycle)	1990-91	1999-2000
4.	Finger Millet- Maize (26 th cycle onwards)	2000-01	Till date

Table 3. Details of the treatments

Treatment No.	Treatment details	Finger millet (N:P ₂ O ₅ :K ₂ O kg ha ⁻¹)
T ₁	50 % NPK	45: 22.5: 8.75
T ₂	100 % NPK	90: 45: 17.5
T ₃	150 % NPK	135: 67.5: 26.25
T ₄	100 % NPK + Hand weeding	90:45:17.5
T ₅	100 % NPK + Zinc	90: 45: 17.5
T ₆	100 % NP	90: 45 :0
T ₇	100 % N	90:0:0
T ₈	100 % NPK + FYM	90:45:17.5 + FYM at 10 t ha ⁻¹
T ₉	100 % NPK (-) Sulphur	90:45:17.5
T ₁₀	Control (unfertilised and unmanured)	-

FYM= Farm yard manure

two splits at 25 and 45 days after transplanting (DAT). Cultural practices were followed in raising the crop, Crop Production Guide (2020). To evaluate long-term changes in soil properties, post-harvest soil samples were collected from 0-15 cm depth from each replicated plot of all treatments. The collected samples were air-dried, ground with a wooden pestle and mortar and sieved through a 2 mm mesh before analysis.

Soil analysis

Soil texture was determined following the International Pipette Method (12). Soil pH was assessed in a 1:2.5 soil-to-water extract, while electrical conductivity (EC) was measured using a conductometric method with the same soil-to-water ratio (13). Cation exchange capacity (CEC) was estimated with the neutral normal ammonium acetate (NH₄OAc) extraction method (14). Soil organic carbon (SOC) content was quantified by the wet chromic acid oxidation technique (15). Available N was analysed using the alkaline K permanganate extraction method and available P by Olsen's extraction method and available sulphur by the turbidimetric method (16–18). Exchangeable calcium and magnesium were both estimated using the Versenate titration method (13). Available micronutrients (Zn, Fe, Mn and Cu) were extracted with DTPA and estimated using Atomic Absorption Spectrophotometry (AAS) (19).

Available potassium and potassium fractions

Available K was estimated using the neutral normal NH₄OAc method (20). Potassium fractions in the soil were quantified using well-established laboratory protocols. WSK was extracted using a 1:10 soil-to-water suspension, Exch-K by extracting the soil with 1N ammonium acetate (NH₄OAc), while NEK was determined using a 1N nitric acid (HNO₃) extract (21). Total K was estimated by digesting the soil sample with a mixture of perchloric acid (HClO₄) and hydrofluoric acid (HF), based on the standard procedure (13). Lattice K was calculated by subtracting the combined amounts of WSK, Exch-K and NEK from total K (22, 23)

Depletion % of potassium

The potassium depleted from the soil was calculated by the formula (24):

$$\text{Depletion of K (\%)} = \frac{\text{Available K status of index year} - \text{Available K status of studied/experimental year}}{\text{Available K status of index year}} \times 100 \quad (\text{Eqn. 1})$$

Collection and processing of plant samples

During 2024, five plants in each plot, which were tagged for recording growth observations, were uprooted at harvest and thoroughly washed to remove any adhering dirt and soil particles. The samples

were air-dried initially and then dried in a hot air oven at 60 °C until they reached a constant weight. The oven-dried samples were powdered using a Willey mill and utilised for analysing the K content after digestion with tri acid (13). At harvest, the dry yield of grain and straw was recorded and expressed in kg ha⁻¹.

Potassium uptake

The K uptake was calculated by multiplying the nutrient content and total dry matter production (kg ha⁻¹).

$$\text{Potassium uptake (kg ha}^{-1}\text{)} = \frac{\text{K content (\%)} \times \text{Total dry matter production (kg ha}^{-1}\text{)}}{100} \quad (\text{Eqn. 2})$$

Sustainable yield index (SYI)

The LTF's effect on the crop yield was evaluated using SYI (25).

$$\text{SYI} = \frac{\hat{Y} - \sigma}{Y_{\max}} \quad (\text{Eqn. 3})$$

Where $\hat{Y}$ is the average yield of finger millet over the years, σ is the treatment standard deviation and $Y_{\max}$ is the maximum yield in the experiment throughout cultivation.

Statistical analysis

Analysis of variance (ANOVA) was conducted to evaluate the effects of continuous cropping and long-term nutrient management practices on soil and plant analysis. Statistical analyses were performed using KAU-GRAPES (26). Treatment differences were assessed via the LSD test at $p = 0.05$ significance level (27). Additionally, R software was employed for correlation analysis.

Results

Distribution of potassium forms

Soil available K at 0–15 cm depth varied significantly among treatments after 51 yr of continuous fertilisation. The highest available K was recorded under (100 % NPK + FYM), representing a 46.19 % increase over the control (CK). The 150 % NPK treatment ranked next, followed by 100 % NPK, whereas K omission treatments (100 % N and 100 % NP) maintained values closer to the control, indicating progressive depletion under imbalanced fertilisation (Table 4). A similar trend was observed for water-soluble K (WSK), with 100 % NPK + FYM recording the highest concentration, followed by 150 % NPK and 100 % NPK. Treatments with omission of K input showed comparatively lower WSK, reflecting reduced labile K pools. Exch. K exhibited patterns consistent with available K, with INM significantly enhancing the exchangeable fraction compared to sole chemical fertilisation and omission treatments.

Table 4. Effect of long-term fertilisation on water-soluble, exchangeable, non-exchangeable, lattice and total potassium finger millet crop of an inceptisol

Treatments		Available K	WSK	Exch. K	NEK	Lattice-K	Total K
		(mg kg ⁻¹)					
T ₁	50 % NPK	280 (7.43)	22.55 (10.00)	257.9 (7.44)	228.9 (6.98)	2183 (5.44)	2692 (5.78)
T ₂	100 % NPK	313 (19.84)	24.27 (18.39)	288.5 (20.21)	242.5 (13.34)	2290 (10.61)	2845 (11.79)
T ₃	150 % NPK	361 (38.45)	28.80 (40.49)	332.6 (38.57)	277.8 (29.79)	2540 (22.70)	3179 (24.91)
T ₄	100 % NPK + HW	312 (19.54)	25.00 (21.95)	287.0 (19.59)	249.2 (16.47)	2325 (12.31)	2886 (13.40)
T ₅	100 % NPK + Zn	309 (18.43)	25.60 (24.88)	283.5 (18.13)	255.0 (19.18)	2377 (14.82)	2941 (15.56)
T ₆	100 % NP	292 (11.97)	21.85 (6.59)	270.4 (12.66)	224.0 (4.67)	2145 (3.61)	2661 (4.56)
T ₇	100 % N	279 (6.94)	21.53 (5.02)	257.6 (7.33)	221.2 (3.36)	2130 (2.88)	2630 (3.34)
T ₈	100 % NPK + FYM	382 (46.19)	29.54 (44.10)	352.0 (46.68)	282.0 (31.77)	2546 (23.02)	3210 (26.13)
T ₉	100 % NPK (-S)	308 (18.01)	23.31 (13.71)	284.7 (18.62)	234.4 (9.55)	2213 (6.89)	2755 (8.25)
T ₁₀	Control	261	20.50	240.0	214.0	2070	2545
SEd		4.14	0.33	3.94	3.66	27.82	39.15
CD ($p = 0.05$)		8.48	0.67	8.08	7.51	57.08	80.34

Available K= Available potassium WSK= Water soluble potassium, Exch-K= Exchangeable potassium, NEK= Non exchangeable potassium, Lattice K= Lattice potassium

Non-exchangeable K (NEK) ranged from 214.0 to 282.0 mg kg⁻¹ and followed the order: 100 % NPK + FYM > 150 % NPK > 100 % NPK > 100 % NP > 100 % N > CK. Lattice K, the most stable fraction, constituted the dominant K pool and varied from 2070 mg kg⁻¹ in CK to 2546 mg kg⁻¹ under 100 % NPK + FYM. Omission treatments recorded lattice K values close to the control, suggesting limited replenishment of reserve pools. Total K reflected cumulative treatment effects, with 100 % NPK + FYM recording the highest value, followed by 150 % NPK and 100 % NPK. Compared to nutrient omission treatments, balanced fertilisation, particularly when combined with FYM, significantly improved all K fractions, showing the long-term role of INM in sustaining soil K reserves under intensive cropping.

Percentage contribution of different forms of potassium to total potassium

The percentage contribution of different K forms to total soil K under long-term fertilisation in finger millet after 51 yr at 0-15 cm depth revealed consistent patterns across treatments. The data for the percentage contribution of different forms of K to total K are presented in (Fig. 1). Available K contributed approximately 10.24 % (CK) to 11.89 % (100 % NPK + FYM) of total K after 51 yr. The contribution of WSK to total K showed 0.81 % CK to 0.92 % under 100 % NPK + FYM. Exchangeable- K accounted 9.43 % CK to 10.97 % (100 % NPK + FYM), while NEK 8.41 % (CK) to 8.78 % (100 % NPK + FYM) to total K. Lattice K showed the highest percentage contribution to total K from 79.33 to 81.35 % in 100 % NPK + FYM and CK, respectively.

Depletion and net change of potassium

The 100 % NPK + FYM treatment recorded the lowest available K depletion (15.86 %) and the lowest net K loss (-144 kg ha⁻¹). Among

the mineral fertiliser treatments, 150 % NPK performed best, reducing depletion of 20.32 % after 51 yr and curbing net K loss of -184 kg ha⁻¹. Treatments, 100 % NPK and 100 % NPK + HW, showed slightly lower depletion (31.03 and 31.20 %) and K losses of (-281 to -283 kg ha⁻¹). Control showed the greatest decline, with available K depletion of 42.55 % after 51 yr, accompanied by the highest net K loss of (-386 kg ha⁻¹) (Fig. 2).

Potassium uptake and yield

Long-term fertilisation showed significant variation in finger millet yield along with K uptake after 51 yr of continuous cropping (Table 5). Straw yield of finger millet ranged from 2002 kg ha⁻¹ in the unfertilized CK to a maximum of 5033 kg ha⁻¹ (151.40 % increase over CK) under 100 % NPK + FYM treatment. Grain yield mirrored this trend, increasing from 1319 kg ha⁻¹ in CK to 2730 kg ha⁻¹ (106.97 % increase) in 100 % NPK + FYM. The 150 % NPK treatment also recorded notable increases, with straw and grain yields at 4633 kg ha⁻¹ (131.42 %) and 2519 kg ha⁻¹ (90.98 %), respectively. Lower fertilisation levels, such as 50 % NPK and treatments with omission of nutrients (e.g., 100 % N and 100 % NP), produced significantly lower yields. The 50 % NPK treatment showed a straw yield of 3398 kg ha⁻¹ and a grain yield of 2045 kg ha⁻¹. The 100 % NP treatment shows a straw yield of 3257 kg ha⁻¹ and a grain yield of 2121 kg ha⁻¹. The 100 % N treatment had the lowest yield of 2821 kg ha⁻¹ for straw and 1508 kg ha⁻¹ for grain.

Potassium uptake results closely followed yield trends. Total K uptake was highest in the 100 % NPK + FYM treatment with 97.17 kg ha⁻¹ (248.78 % increase over CK), indicating efficient nutrient use facilitated by organic matter addition. Treatments like 150 % NPK and 100 % NPK + Zn also recorded high K uptakes, e.g., total K uptake of 86.20 kg ha⁻¹ (209.40 %) and 80.67 kg ha⁻¹

Table 5. Effect of long-term fertilisation on potassium uptake, yield and SYI in a finger millet crop of an inceptisol

Treatments		Grain K uptake	Straw K uptake	Total K uptake	Grain yield	Straw yield	SYI
		(kg ha ⁻¹)					
T ₁	50 % NPK	20.72 (88.54)	36.53 (116.41)	57.24 (105.46)	2045 (55.04)	3398 (69.73)	0.553
T ₂	100 % NPK	25.33 (130.48)	51.07 (202.55)	76.40 (174.23)	2226 (68.76)	4245 (112.04)	0.660
T ₃	150 % NPK	29.17 (165.42)	57.03 (237.86)	86.20 (209.40)	2519 (90.98)	4633 (131.42)	0.673
T ₄	100 % NPK + HW	22.65 (106.10)	48.38 (186.61)	71.04 (154.99)	2139 (62.17)	4059 (102.75)	0.631
T ₅	100 % NPK + Zn	25.35 (130.66)	55.32 (227.73)	80.67 (189.55)	2332 (76.80)	4568 (128.17)	0.568
T ₆	100 % NP	20.98 (90.90)	33.97 (101.24)	54.95 (97.24)	2121 (60.80)	3257 (62.69)	0.591
T ₇	100 % N	14.19 (29.12)	28.83 (70.79)	43.02 (54.41)	1508 (14.33)	2821 (40.91)	0.491
T ₈	100 % NPK + FYM	32.95 (199.82)	64.22 (280.45)	97.17 (248.78)	2730 (106.97)	5033 (151.40)	0.680
T ₉	100 % NPK (-S)	22.64 (106.01)	50.52 (199.29)	73.16 (162.60)	2204 (67.10)	4179 (108.74)	0.683
T ₁₀	Control	10.99	16.88	27.86	1319	2002	0.524
SEd		0.344	0.779	0.951	43.4	54	0.007
CD ($p = 0.05$)		0.705	1.598	1.950	89.3	110	0.014

K= Potassium, SYI= Sustainable yield index

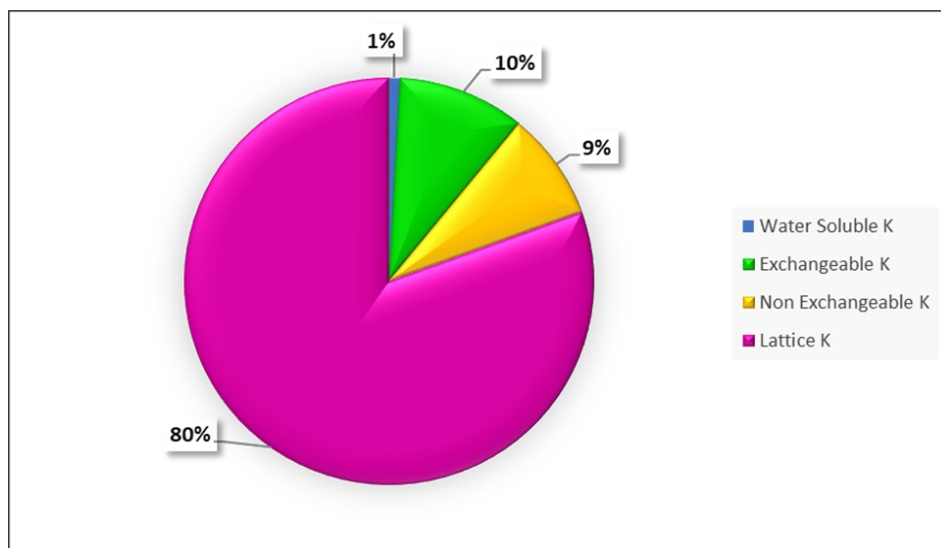


Fig. 1. Percentage contribution of different potassium fractions to total potassium in post-harvest finger millet-maize soil (0–15 cm depth) after 51 yr of long-term fertilisation in an Inceptisol.

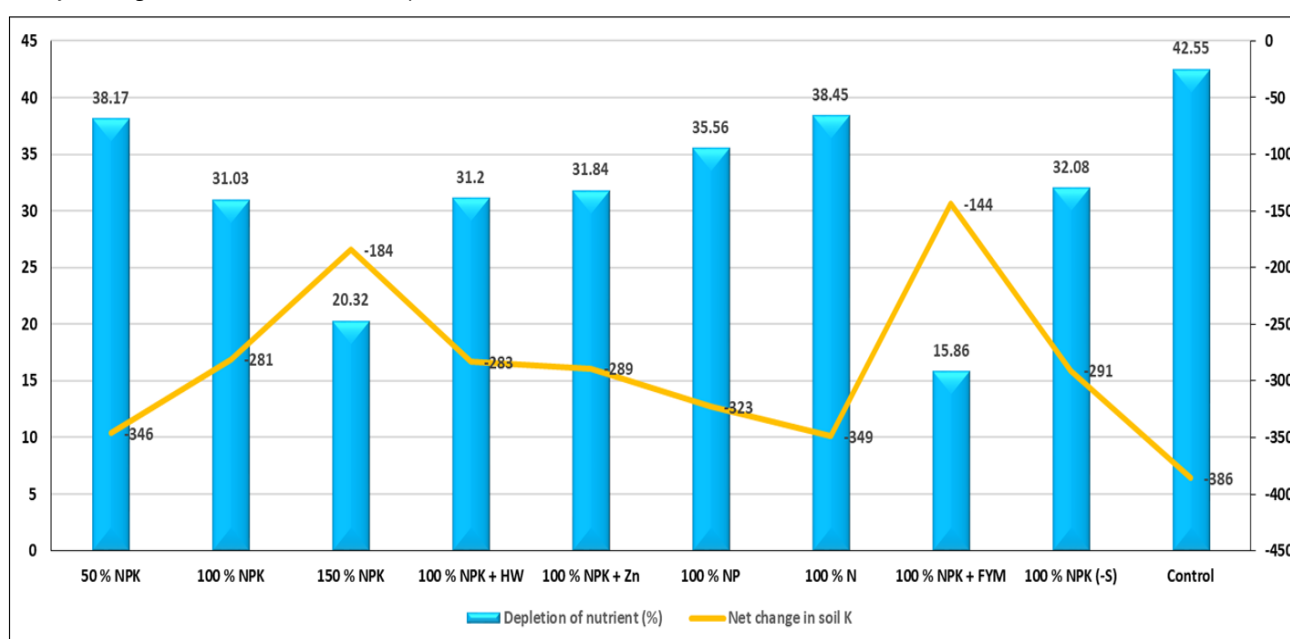


Fig. 2. Depletion of available potassium and net change in potassium status of finger millet soil after 51 yr of long-term fertilisation in an Inceptisol.

(189.55 %), respectively, showing the importance of high and balanced nutrient input, including micronutrients, for optimum growth. The 50 % NPK and nutrient-limited treatments showed inferior K uptake that correlated with their lower yield performance. 50 % NPK had a total K uptake of 57.24 kg ha⁻¹ (105.46 % increase relative to CK) after 51 yr, indicating possible soil nutrient depletion and diminishing returns under reduced fertiliser input.

Sustainable yield index

The SYI varied from 0.491 under 100 % N to 0.683 with 100 % NPK (-S), showing the differences in yield stability across treatments. Integrated and elevated nutrient applications yielded higher SYI values, such as 0.680 for 100 % NPK + FYM and 0.673 for 150 % NPK, showing more reliable and consistent crop performance. Treatments including 100 % NPK (0.660) and 100 % NPK + HW (0.631) also showed reasonable yield stability. Conversely, nutrient-deficient treatments like the control (0.524) and 100 % N (0.491) exhibited lower SYI, showing instability from imbalance treatments.

Correlation among different forms of soil potassium with potassium uptake and crop yield

Correlation analysis among different soil K fractions after 51 yr indicated strong and significant positive relationships across all components (Fig. 3). Available K exhibited strong and significant positive correlations with WSK, exch. K, NEK, lattice K and total K ($r = 0.952\text{--}1.000$, $p < 0.01$), indicating the dynamic equilibrium among different K fractions in the soil. The near-perfect association between available K and exchangeable K suggested that the exchangeable pool constituted the primary contributor to plant-available K under long-term fertilisation. Significant correlations between available K and NEK further indicated the buffering role of reserve pools in sustaining K supply under continuous cropping. Grain and straw yields were positively and significantly correlated with available K and exchangeable K, demonstrating that yield performance was closely linked to the size of labile K pools. Similar strong associations between soil K fractions and crop yield under long-term fertiliser experiments have been reported in earlier studies, where exchangeable and non-exchangeable K fractions were shown to regulate K availability under intensive cultivation systems.

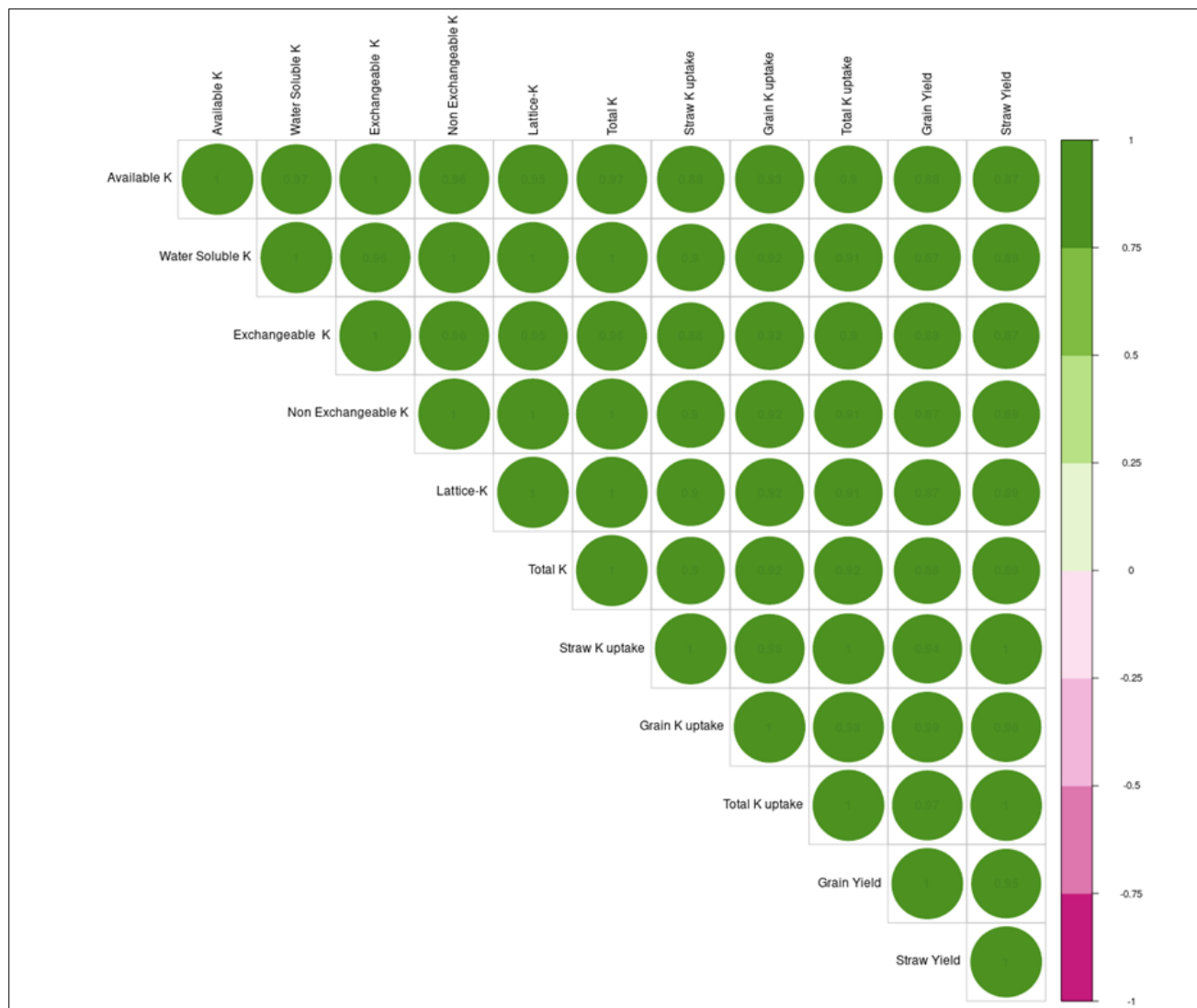


Fig. 3. Correlation among different soil potassium fractions after 51 yr of long-term fertilisation in a finger millet cropping system on an Inceptisol.

These relationships confirmed that balanced fertilisation not only enhanced individual K fractions but also strengthened the functional connectivity among soil K pools, thereby improving nutrient supply capacity and yield stability over time. The correlation pattern (ranging from 0.868 to 1.00) finally reflects the strong interconnections among soil K fractions and their association with plant K uptake and crop yield. Comparatively lower correlations (0.868–0.889) were observed between NEK and lattice K, with K uptake reflecting their slower release characteristics, while the high inter-pool correlations demonstrate strong K buffering under long-term intensive cropping in the Inceptisol.

Discussion

Changes in different potassium forms in soil

Available K in the surface (0–15 cm) layer showed significant variation among treatments after 51 yr of continuous fertilisation. The highest available K was recorded under 100 % NPK + FYM, reflecting the synergistic effect of balanced fertilisation and organic manure addition. The improvement under INM may be attributed to enhanced SOC, increased CEC and improved K cycling dynamics (6,9). Similar findings from LTFEs have been reported earlier (28, 29). In contrast, the lowest available K under control and K-omission treatments indicated progressive depletion of

labile K pools due to continuous crop removal without adequate replenishment (7).

Water-soluble K followed a similar trend, with higher values under 100 % NPK + FYM and 150 % NPK treatments. Organic inputs are known to enhance desorption and solubilization processes, thereby increasing K concentration in soil solution (30). Lower values in omission plots reflected depletion of readily available pools under sustained cropping pressure (31). Exchangeable K, representing the immediately plant-available fraction, was highest under integrated and balanced fertilisation treatments and declined in omission plots. Continuous cropping without K addition accelerates depletion of this buffering pool, particularly in soils with moderate K reserves (32). The exchangeable pool is replenished from non-exchangeable forms; however, prolonged nutrient imbalance weakens this equilibrium (33).

Non-exchangeable K (NEK) was also highest in 100 % NPK + FYM, suggesting enhanced mineral weathering and partial reversibility of K fixation under integrated nutrient management (24). Although higher fertiliser rates (150 % NPK) maintained NEK levels, the biological contribution of FYM appeared more effective in sustaining reserve pools. In K-omission treatments, NEK values approached those of control, indicating gradual mining of reserve fractions (34). Lattice K constituted the largest proportion of total K and exhibited comparatively smaller variation among treatments.

However, slightly higher values under integrated treatments suggested improved stabilisation and reduced mineral depletion (24). Since lattice K replenishes other fractions through slow weathering, its maintenance is critical for sustaining long-term K supply (6). Total K reflected cumulative changes across all fractions and was highest under 100 % NPK + FYM, followed by 150 % NPK. Balanced fertilisation helped conserve soil K reserves, whereas omission treatments led to gradual depletion over time. Across treatments, the dominance order of K fractions (lattice K > NEK > exchangeable K > WSK) remained consistent, confirming the dynamic equilibrium among soil K pools under long-term nutrient management (35). Farmyard manure enhances K availability by boosting microbial activity, releasing organic acids that mobilise K from minerals and improving SOC and CEC for better K retention (28, 30). While 150 % NPK maintains K levels through continuous high input and exchange site saturation, integrated use of NPK + FYM is more effective for sustaining long-term soil health, K dynamics and yield stability (28, 29).

Depletion and net change of potassium

The K depletion percentage and net change in soil available K (0–15 cm) after 51 yr of continuous cropping emphasised the critical role of fertilisation strategies in maintaining soil K fertility. The soil K net change after 51 yr of long-term fertilisation indicates the sustained K depletion across all treatments, ascertaining the continuous removal of soil K by crops exceeding replenishment rates (36). The overall trend showed that long-term application of balanced and INM practices reduced the extent of K depletion and mitigated the negative net changes compared to unbalanced or no fertilisation (7). Organic manure application improved soil properties, increasing CEC, which facilitates the release of K from non-exchangeable pools. The highest depletion of soil available K was observed in the CK, which indicates the mining of native soil K reserves under continuous cultivation without replenishment (37).

Similarly, treatments with a lower level of K application (50 % NPK) or omission of K in the fertiliser schedule (100 % N or NP), also resulted in high K depletion (above 34 %), reflecting poor nutrient input relative to crop removal and continuous reliance on soil reserves (38). Conversely, 100 % NPK + FYM improved soil physical and biological properties, enhanced nutrient cycling and facilitated K release from non-exchangeable pools, reducing depletion and improving soil resilience (39). The 150 % NPK treatment also showed lower depletion and improved net K balance compared to standard or reduced fertiliser rates, confirming that higher K inputs can effectively compensate for crop K uptake (9). Treatments with micronutrient addition (100 % NPK + Zn) and 100 % NPK + HW showed intermediate improvements, reflecting the complex interactions of nutrient management components on soil K dynamics (40).

Potassium uptake and yield

Long-term fertilisation significantly influenced the finger millet grain and straw yields and K uptake in the finger millet crop. Treatments with balanced and higher fertiliser inputs, especially those integrating FYM, consistently showed higher K uptake & yield than lower or imbalanced nutrient regimes as well as the CK. The highest grain and straw yields were recorded under 100 % NPK + FYM, followed by 150 % NPK, demonstrating the beneficial synergy of balanced macronutrient supply with organic matter and micro nutrients in stimulating crop growth and productivity. These observations are consistent with earlier reports showing that INM

incorporating FYM with recommended NPK doses enhanced soil fertility, nutrient availability and yield stability in finger millet–maize rotations (41).

A decline in yield and K uptake was observed in treatments with reduced or imbalanced fertilisation (50 % NPK, 100 % NP and 100 % N) and the lowest values were recorded in the CK. Such findings are consistent with earlier reports indicating that nutrient deficiencies diminish root proliferation, nutrient absorption efficiency and hence crop yields. Potassium uptake by both grain and straw increased proportionally with fertiliser input levels and organic matter addition. This response shows the role of balanced K nutrition in supporting key physiological functions such as enzyme activation, osmoregulation and photosynthesis, which underpin yield formation in finger millet (42). Treatments supplemented with zinc (100 % NPK + Zn) exhibited improved yields and K uptake compared with 100 % NPK alone, indicating that micronutrients indirectly enhance K use efficiency through improved root and plant vigour (43).

Sustainable yield index

Long-term fertiliser treatments significantly influenced SYI, showing a nutrient management role in yield stability across cropping cycles. The highest SYI occurred with 100 % NPK + FYM, as FYM, along with NPK, boosts SOM, nutrient availability, soil aggregation and microbial activity for sustained productivity (44, 45). Treatments like 150 % NPK, 100 % NPK and 100 % NPK + HW also showed strong stability, showing benefits of balanced major nutrients and organic residues (46). In contrast, 100 % NPK + Zn, 100 % NP, 50 % NPK, 100 % N and control revealed declines from partial supply, N-only application, or no fertilisation, leading to imbalances and reduced fertility (47).

Correlation among different forms of soil potassium with potassium uptake and crop yield

Strong positive correlations ($r = 0.952$ – 1.000) among soil K fractions indicate a dynamic equilibrium and effective buffering capacity in long-term fertilised Inceptisol. Available K was closely linked with exchangeable K, showing that it was the main source of plant-available K, while its relation with NEK shows the role of reserve pools (48). Grain and straw yields showed significant association with labile K fractions, emphasising their importance in sustaining productivity under continuous cropping (49). Lower correlations (0.868–0.889) of NEK and lattice K with uptake reflect slower release, but strong inter-pool connectivity ensures stable K supply and yield resilience (48).

Conclusion

After 51 yr of finger millet cultivation in an Inceptisol, 100 % NPK + FYM maintained higher available, water-soluble, exchangeable, non-exchangeable, lattice and total K fractions than chemical alone (150 % NPK and 100 % NPK) or omission treatments (100 % NP and 100 % N). Potassium omission depleted labile pools, mining native reserves, while K fraction dominance stayed stable across treatments. Balanced fertilisation, especially with FYM, boosted grain/straw yields and SYI; net change analyses confirmed depletion risks from imbalances. These findings show INM (100 % NPK + FYM) sustains yields, restores K levels and prevents soil fertility drop in Inceptisols. Future research should examine K balances in varied crops and climate effects on K shifts.

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Authors' contributions

GRL, SM, GS, SK, BK¹ and BK² contributed to writing the original draft and resources collection contributed through scientific supervision, conceptual guidance and critical evaluation of the manuscript. All authors read and approved the final manuscript. [BK¹ stands for Balaji Kannan and BK² stands for Boomiraj Kovilpillai].

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

During the preparation of this work, the authors used Quill Bot and AI assistance to enhance the readability and flow of content after original drafting. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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