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Soil potassium fractions and crop yield as influenced by inorganic fertilisers, crop residues and green manuring under rice-wheat cropping system in calcareous soil

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Abstract

Soil potassium (K) occurs in multiple fractions, but the effects of integrated nutrient management (INM) on K dynamics remain poorly characterised in calcareous alluvial soils of the middle Indo-Gangetic Plains (IGP). A field experiment was conducted in an ongoing rice–wheat cropping system (RWCS) at Dr Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Bihar, to evaluate eight nutrient management treatments involving nitrogen, phosphorus and potassium (NPK) fertilisation, cereal residue recycling, green manuring and Pusa Decomposer (PD) application on soil K fractions and crop productivity. Treatments combining cereal residue and green manure with residue decomposer (T_5) recorded the highest water-soluble potassium (WSK) (7.26 mg kg^{-1}), exchangeable potassium (EK) (64.39 mg kg^{-1}), 1 hr tetraphenylboron-extractable potassium (TBK) (2002.96 mg kg^{-1}) and 1 hr non-exchangeable potassium extracted using sodium tetraphenylboron (NEK_{NaTPB}) (1931.31 mg kg^{-1}). Residue decomposer application enhanced labile and kinetically accessible K within corresponding treatment pairs. At the same time, 168 hr non-exchangeable potassium (NEK), lattice potassium (LK) and total potassium (TK) remained statistically unchanged, indicating limited alteration of stable K reserves over four years. Rice and wheat grain and straw yields were highest under treatments receiving greater proportions of inorganic N and P (T_1, T_6 and T_7), whereas T_4 and T_5 produced lower yields despite higher labile K. Labile K fractions were positively inter-correlated, with the strongest association between 1 hr TBK and 1 hr NEK (r = 0.82, $p \leq 0.001$), whereas soil K fractions showed weak and non-significant relationships with crop yield. However, nutrient management enhanced labile K pools without significantly altering stable K reserves or explaining yield variation. Recycling cereal residue with a decomposer, together with 25 % substitution of fertiliser N, may sustain rice–wheat productivity while improving labile K availability in calcareous soil.

Keywords: calcareous soil; green manuring; integrated nutrient management; sodium tetraphenylboron-extractable potassium; potassium fractions; rice-wheat cropping system

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1. Introduction

Potassium (K) is an essential macronutrient governing plant enzyme activation, osmoregulation and photosynthate translocation, making it indispensable for productivity in intensive cereal-based cropping systems (1). In the rice–wheat cropping system (RWCS) of the Indo-Gangetic Plains (IGP), K removal by high-yielding varieties often exceeds fertiliser replenishment. This drives progressive mining of native K reserves and threatens long-term soil fertility (2). The problem is compounded by the long-standing perception that the alluvial soils of the region are inherently K-rich because of their micaceous minerals. This perception has historically discouraged adequate K fertilisation relative to actual crop demand (3, 4).

Unlike nitrogen (N) and phosphorus (P), soil K exists across several operationally distinct fractions: water-soluble potassium (WSK), exchangeable potassium (EK), non-exchangeable potassium (NEK) and lattice or structural potassium (LK), each differing markedly in availability, mobility and rate of replenishment (5). While WSK and EK together form the immediately plant-available pool, the non-exchangeable fraction held at the wedge and interlayer positions of 2 : 1 clay minerals such as illite and mica functions as a critical buffering reservoir, capable of sustaining crop K uptake once the labile pools are depleted (6). Conventional soil testing commonly relies on neutral ammonium acetate (NH_4OAc)-extractable K as an indicator of readily available (water-soluble and exchangeable) K, but this measurement does not capture the contribution of non-exchangeable K reserves to crop K supply. Kinetic K fractions obtained from time-dependent extraction can be more sensitive than single-point measurements to changes in K-supplying capacity under different nutrient management practices (7). However, this relationship remains inadequately understood in the calcareous alluvial soils of the middle IGP, where several soil properties may constrain K availability and release kinetics. High pH and free calcium carbonate ($CaCO_3$) maintain a calcium ion (Ca^{2+}) and magnesium ion (Mg^{2+})-dominated exchange complex, so K^+ must compete with divalent cations and its activity relative to them stays low (8). Calcium ion can displace K^+ from outer exchange sites, giving an initial rapid release, which is followed by a slower, diffusion-controlled release of NEK (9). The clay fraction is dominated by micaceous and illitic minerals, which hold most of the reserve K in interlayer and edge sites and release it slowly as solution K falls (10). The combined effect of these properties on K supply under integrated nutrient management (INM) has not been characterised in these soils.

Many long-term K-fractionation studies have been conducted on non-calcareous soils such as Alfisols, red soils and Mollisols (5, 6, 11, 12), whereas the calcareous soils of Bihar, which are moderately to strongly alkaline with low organic carbon, may behave differently (8, 13). Such soils are widespread across the middle IGP. However, systematic investigation is scarce for continuous RWCS in this region. In particular, little is known about how different combinations of inorganic K, cereal residue recycling, green manuring and residue decomposer application influence the sequential K pools, from the labile WSK fraction to the structural LK reserve.

Sole reliance on inorganic fertilisation, despite its demonstrated short-term yield benefits, has increasingly been questioned for its limited capacity to sustain long-term soil K balance and build the NEK reserve (14). Integrated nutrient management, combining chemical fertilisers with organic amendments such as crop residues and green manures, offers a promising alternative. Cereal residues are relatively rich in K, which occurs mainly in soluble, non-structural forms within plant tissues. Consequently, much of this K is released rapidly during residue decomposition, unlike mineral K, which equilibrates more gradually with the soil exchange complex (14). Green manuring with leguminous biomass such as *Sesbania aculeata* (Willd.) Pers. (Dhaincha) can contribute K and organic inputs and has been reported to improve soil organic carbon (SOC), microbial activity and cation-exchange capacity (2). However, residue decomposition under field conditions is often slow and incomplete, particularly under submerged rice culture or under high-pH soil conditions, limiting the synchrony between K release and crop demand. Microbial residue decomposers, such as the Pusa Decomposer (PD), have been proposed to accelerate this breakdown and associated nutrient mineralisation, yet their specific influence on soil K fractionation remains largely unexplored (15). Moreover, crop yield under a given nutrient regime is influenced not only by soil K availability but also by K release dynamics and the overall balance of other essential nutrients, particularly N and P.

Against this background, the present study was undertaken in an ongoing field experiment on calcareous soil at Pusa, Bihar, to evaluate the effect of inorganic fertilisers, cereal residue recycling, green manuring and residue decomposer application on soil K fractions and crop productivity under a continuous RWCS. The specific objectives were: (i) to quantify treatment effects on different soil K fractions; (ii) to evaluate the impact of inorganic and organic sources on crop yield; and (iii) to examine the relationship between these soil K parameters and rice–wheat yield components. We hypothesised that organic inputs, particularly when combined with a residue decomposer, would increase WSK, EK and kinetically accessible K more than sole mineral fertilisation, whereas LK and TK, which are closely tied to soil mineralogy, would show little response over the short term. We further hypothesised that INM would alter rice and wheat yields and that any association between soil K fractions and yield would differ among K pools and management regimes instead of being uniformly positive.

2. Materials and Methods

Experimental site and location

The study was conducted in an ongoing field experiment established in kharif 2021 at Pusa Farm, Dr Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Bihar, in highly calcareous soil. The experimental soil was sandy loam in texture. The experimental site is located at 25°58’52.32” N latitude and 85°40’30.16” E longitude, with an altitude of 52 m above mean sea level (AMSL). The initial soil of the experimental site was alkaline in nature, with a pH of 8.3 and had an electrical conductivity (EC) of 0.48 dS m^{-1} at 25 °C, indicating non-saline conditions. The SOC content was 0.41 %. The experimental soil was low in available N (127.9 kg N ha^{-1}) and P (17.8 kg phosphorus pentoxide (P_2O_5) ha^{-1}) but was medium in available K (134.27 kg potassium oxide (K_2O) ha^{-1}).

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Experimental details

The experiment comprised 8 treatments laid out in a randomised block design (RBD) with 3 replications, giving 24 plots in total. Blocks were established to account for spatial heterogeneity in the field. Each plot measured 4 × 3 m (12 m²), so the plots covered 288 m² in total, excluding bunds and channels. Rice (cv. Rajendra Bhagwati) and wheat (cv. DBW-252) were grown in rotation throughout the experimental period. Fertiliser N, P_2O_5 and K_2O were applied to both rice and wheat crops according to the respective treatment levels, using urea, single superphosphate (SSP) and muriate of potash (MOP), with 120 : 60 : 40 kg ha^{-1} N, P_2O_5 and K_2O representing the 100 % recommended dose of fertilisers (RDF). The experimental treatment details are presented in Table 1.

Table 1. Treatment details of different nutrient management practices under the rice–wheat cropping system (RWCS)

Treatments	Treatment details
T_1:	100 % RDF
T_2:	50 % RDF + 50 % N (CR)
T_3:	T_2 + RD
T_4:	50 % N (CR) + 50 % N (GM)
T_5:	T_4 + RD
T_6:	75 % RDF + 25 % N (CR)
T_7:	T_6 + RD
T_8:	Absolute control

CR: cereal residue; GM: green manure (*Sesbania aculeata*); RD: residue decomposer (Pusa Decomposer); RDF: recommended dose of fertilisers; N: nitrogen.

Rice was established by transplanting seedlings at a spacing of 20 × 15 cm, whereas wheat was grown under line sowing/direct-seeded conditions with 20 cm spacing between rows. Dhaincha (*S. aculeata*) seed, obtained from the Directorate of Seed, RPCAU, Pusa, Bihar, was broadcast at 40 kg ha^{-1} in a separate nursery field to raise green manure. The harvested green biomass was chopped into approximately 5 cm pieces and incorporated into the soil before rice transplanting and wheat sowing. Rice and wheat residues were collected, chopped into 5 cm pieces and recycled in the next crop. Rice residue was applied as surface mulch in wheat. Wheat residue was incorporated into the soil before the following rice crop. The application rates of rice and wheat residues and green manure (*S. aculeata*) were determined according to their mean N concentration and the N requirement of each treatment. The four-year average nutrient composition of the organic materials is presented in Table 2, while the cumulative quantities of wheat residue, rice residue and green manure incorporated or returned under each treatment during the four rice–wheat cycles are given in Table 3. The corresponding cumulative amounts of N, P and K contributed by these organic sources over the experimental period are presented in Table 4. The cereal residue decomposer used in the study was PD, developed by the Division of Microbiology, ICAR–Indian Agricultural Research Institute (IARI), New Delhi. The decomposer was prepared and applied according to the prescribed All India Coordinated Research Project (AICRP) formulation protocol. During the cropping period, hand weeding was carried out as and when required to maintain effective weed control. In the rabi wheat crop, broad-leaved weeds, including *Chenopodium album* L., were controlled with 2,4-D ethyl ester (38 % EC; Weedmar 38, Dhanuka Agritech Ltd.) applied post-emergence at 0.8 kg a.i. ha^{-1} (product rate 2.1 L ha^{-1}) in 500 L ha^{-1} of water at 30–35 days after sowing, using a knapsack sprayer with a flat-fan nozzle. The same herbicide, dose, spray volume and timing were applied to all plots, so weed management did not differ among treatments.

Table 2. Four-year average nutrient concentration of cereal residues and green manure used in the experiment

Source	N (%)	P (%)	K (%)
Cereal residue (Wheat)	0.50	0.11	1.11
Cereal residue (Rice)	0.60	0.13	1.49
Green manure (*Sesbania aculeata*)	2.70	0.20	1.40

N: nitrogen; P: phosphorus; K: potassium.

Table 3. Cumulative amount of added organic sources over four years

Treatments	Wheat residue (t)	Rice residue (t)	Green manure (dry matter, t)	Total organic material (t)
T_1: 100 % RDF	-	-	-	-
T_2: 50 % RDF + 50 % N (CR)	48.5	40.0	-	88.5
T_3: T_2 + RD	48.5	40.0	-	88.5
T_4: 50 % N (CR) + 50 % N (GM)	48.5	40.0	17.8	106.3
T_5: T_4 + RD	48.5	40.0	17.8	106.3
T_6: 75 % RDF + 25 % N (CR)	24.2	20.0	-	44.2
T_7: T_6 + RD	24.2	20.0	-	44.2
T_8: Absolute control	-	-	-	-

CR: cereal residue; GM: green manure (*Sesbania aculeata*); RD: residue decomposer (Pusa decomposer); RDF: recommended dose of fertilisers.

Table 4. Cumulative nutrient inputs through organic sources over four years

Treatments	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
T_1: 100 % RDF	-	-	-
T_2: 50 % RDF + 50 % N (CR)	482.5	105.3	1,134.3
T_3: T_2 + RD	482.5	105.3	1,134.3
T_4: 50 % N (CR) + 50 % N (GM)	963.9	141.0	1,383.9
T_5: T_4 + RD	963.9	141.0	1,383.9
T_6: 75 % RDF + 25 % N (CR)	241.2	52.7	567.2
T_7: T_6 + RD	241.2	52.7	567.2
T_8: Absolute control	-	-	-

CR: cereal residue; GM: green manure (*Sesbania aculeata*); RD: residue decomposer (Pusa decomposer); RDF: recommended dose of fertilisers; N: nitrogen; P: phosphorus; K: potassium.

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Soil sampling and analysis

After completion of four rice–wheat cropping cycles, soil samples were collected from the 0–15 cm soil depth at the end of wheat harvest during 2024–25 using a soil auger. The samples were air-dried, gently ground and passed through a 2 mm sieve before analysis. Available K was determined by extraction with 1 N neutral NH_4OAc following the method described in (16). Total K was determined by wet digestion of soil samples with hydrofluoric acid (HF) and perchloric acid ($HClO_4$) (17). Water soluble potassium was determined in a 1 : 5 soil-to-water suspension by shaking for 2 hr followed by 16 hr of equilibration (18). Exchangeable potassium was calculated as the difference between NH_4OAc-extractable K (available K) and WSK (19). Sodium tetraphenylborate (NaTPB)-extractable K (TBK) was determined at two extraction intervals, i.e., 1 and 168 hr, to characterise kinetically distinct fractions of soil K release. The 1 hr extraction was used to determine 1 hr TBK following the tetraphenylborate-based extraction procedure (20, 21), whereas the 168 hr extraction was conducted following the extraction period to determine 168 hr TBK (22). Sodium tetraphenylborate -extractable non-exchangeable K was calculated by subtracting NH_4OAc-extractable K from the corresponding TBK value. The K released at 1 hr after this subtraction was designated as 1 hr NEK_{NaTPB} and referred to as the plant-accessible NEK fraction following the interpretation reported in early results (21), whereas the corresponding value at 168 hr was designated as 168 hr NEK_{NaTPB} and referred to as potentially available illite-associated K following the interpretation reported in previous results (23). Lattice K was calculated as the difference between total K and the sum of water-soluble, exchangeable and 168 hr non-exchangeable K fractions (19). All K fractions were expressed as milligram per kilogram (mg kg^{-1}) soil.

Grain and straw yield

At physiological maturity, crops were harvested from the net plot area, sun-dried and threshed. The grains and straw were cleaned, weighed separately and the respective yields were expressed as quintals per hectare (q ha^{-1}).

Statistical analysis

Data from all observations were compiled and analysed by analysis of variance (ANOVA) appropriate to a randomised block design, using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) (24). Treatment effects were tested by the *F*-test and the critical difference (CD) at the 5 % probability level ($p \leq 0.05$) was used to identify significant differences among treatment means. Duncan's multiple range test (DMRT) was used to group treatment means into homogeneous subsets and to rank the treatments. Pearson's correlation coefficients were calculated among soil K fractions and yield components (n = 24) and the graphs and the correlation matrix were prepared in R version 4.6.1 (25).

3. Results

Potassium fractions

Water-soluble potassium

Water-soluble K differed significantly among treatments (Table 5). It ranged from 5.12 mg kg^{-1} in T_8 to 7.26 mg kg^{-1} in T_5 and T_5 was statistically at par with T_4 (6.53 mg kg^{-1}) and T_3 (6.41 mg kg^{-1}). T_5 was 41.8 % higher than T_8. In the pairs differing only in decomposer application (T_3 vs T_2, T_5 vs T_4, T_7 vs T_6), WSK was numerically higher with the decomposer, but the differences were not significant.

Table 5. Impact of different nutrient management practices on soil potassium fractions under rice-wheat cropping system (RWCS)

Treatments	WSK (mg kg^{-1})	EK (mg kg^{-1})	NaTPB-K (TBK) (mg kg^{-1})		NEK_{NaTPB} (mg kg^{-1})		LK (mg kg^{-1})	Total K (mg kg^{-1})
			1 hr TBK	168 hr TBK	1 hr NEK_{NaTPB}	168 hr NEK_{NaTPB}		
T_1: 100 % RDF	5.46^{cd}	42.74^{de}	1188.09^{d}	4569.53^{a}	1139.89^{d}	4521.33^{a}	12315.75^{a}	16885.28^{a}
T_2: 50 % RDF + 50 % N (CR)	6.26^{bc}	55.79^{bc}	1644.95^{bc}	4845.04^{a}	1582.90^{bc}	4782.99^{a}	12490.80^{a}	17335.84^{a}
T_3: T_2 + RD	6.41^{abc}	58.98^{abc}	1695.27^{abc}	4890.38^{a}	1629.88^{bc}	4824.99^{a}	12535.60^{a}	17425.98^{a}
T_4: 50 % N (CR) + 50 % N (GM)	6.53^{ab}	61.92^{ab}	1833.08^{ab}	4922.96^{a}	1764.63^{ab}	4854.51^{a}	12580.25^{a}	17503.21^{a}
T_5: T_4 + RD	7.26^{a}	64.39^{a}	2002.96^{a}	4977.51^{a}	1931.31^{a}	4905.86^{a}	12625.50^{a}	17603.01^{a}
T_6: 75 % RDF + 25 % N (CR)	5.64^{bcd}	50.61^{cd}	1454.38^{cd}	4739.20^{a}	1398.13^{cd}	4682.95^{a}	12460.15^{a}	17199.35^{a}
T_7: T_6 + RD	5.67^{bcd}	53.05^{c}	1580.22^{bc}	4762.94^{a}	1521.50^{bc}	4704.22^{a}	12510.30^{a}	17273.24^{a}
T_8: absolute control	5.12^{d}	38.85^{e}	1268.67^{d}	4649.23^{a}	1224.70^{d}	4605.26^{a}	12420.45^{a}	17069.68^{a}

CR: cereal residue; GM: green manure; RD: residue decomposer; WSK: water-soluble potassium; EK: exchangeable potassium; TBK: $NaBPh_4$-extractable potassium (tetraphenylborate extraction); 1 hr NEK_{NaTPB}: plant accessible non-exchangeable potassium; 168 hr NEK_{NaTPB}: potentially available illite potassium; LK: lattice potassium; Total K: total potassium.

Means followed by the same letter do not differ significantly ($p \leq 0.05$) based on Duncan's multiple range test.

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Exchangeable potassium

Exchangeable K differed significantly among treatments, from 38.85 mg kg^{-1} in T_8 to 64.39 mg kg^{-1} in T_5 (Table 5). T5 was statistically at par with T_4 (61.92 mg kg^{-1}) and T_3 (58.98 mg kg^{-1}) and 65.7 % higher than T_8. EK in T_1 (42.74 mg kg^{-1}) was at par with T_6 but significantly lower than in T_2, T_3, T_4 and T_5. In the pairs differing only in decomposer application (T_3 vs T_2, T_5 vs T_4, T_7 vs T_6), EK was numerically higher with the decomposer (by 5.7 %, 4.0 % and 4.8 %), but the differences were not significant.

Sodium tetraphenylboron-extractable potassium

Sodium tetraphenylboron-extractable K (1 hr TBK) differed significantly among treatments, from 1188.09 mg kg^{-1} in T_1 to 2002.96 mg kg^{-1} in T_5 (Table 5). T_5 was statistically at par with T4 (1833.08 mg kg^{-1}) and T_3 (1695.27 mg kg^{-1}) and 57.9 % higher than T_8. T_1 and T_8 did not differ significantly. In the pairs differing only in decomposer application (T_3 vs T_2, T_5 vs T_4, T_7 vs T_6), 1 hr TBK was numerically higher with the decomposer, but the differences were not significant. The 168 hr TBK (4569.53 to 4977.51 mg kg^{-1}) did not differ significantly among treatments.

Non-exchangeable potassium

The 1 hr NEK differed significantly among treatments, from 1139.89 mg kg^{-1} in T_1 to 1931.31 mg kg^{-1} in T_5 (Table 5). T_5 was at par with T_4 (1764.63 mg kg^{-1}), significantly higher than all other treatments and 57.7 % higher than T_8. T_1 and T_8 did not differ significantly. The decomposer pairs (T_3 vs T_2, T_5 vs T_4, T_7 vs T_6) showed numerically higher 1 hr NEK with the decomposer (2.9 %, 9.4 % and 8.8 %), but the differences were not significant. The 168 hr NEK (4521.33 to 4905.86 mg kg^{-1}) did not differ significantly among treatments. NEK was calculated as TBK-(EK + WSK), so TBK and NEK are not independent.

Lattice potassium

The LK content ranged from 12315.75–12625.50 mg kg^{-1}, with all treatments belonging to the same statistical group (Table 5). Numerically, T_5 recorded the highest LK content (12625.50 mg kg^{-1}), followed by T_4 (12580.25 mg kg^{-1}) and T_3 (12535.60 mg kg^{-1}).

Total potassium

Total potassium content did not vary significantly among treatments (Table 5). The TK concentration ranged from 16885.28–17603.01 mg kg^{-1}, representing a relatively narrow numerical variation of approximately 4.3 %. T_5 recorded the highest numerical TK concentration (17603.01 mg kg^{-1}), whereas T_1 had the lowest numerical value (16885.28 mg kg^{-1}). Although numerical differences were observed among treatments, none of the treatments differed significantly from the others.

Yield

Rice grain and straw yield

The treatments significantly influenced the grain and straw yields of rice (Fig. 1a, b). Rice grain yield ranged from 29.1 q ha^{-1} in T_8 to 53.5 q ha^{-1} in T_7. The highest rice grain yield was recorded under T_7 (53.5 q ha^{-1}), which was statistically at par with T_1 (53.1 q ha^{-1}) and T_6 (46.7 q ha^{-1}). Compared with the absolute control (T_8), T_7 increased rice grain yield by 83.8 %, while T_1 and T_6 showed increases of 82.5 % and 60.5 %, respectively. Treatments T_3 (45.5 q ha^{-1}) and T_2 (44.2 q ha^{-1}) exhibited intermediate yields, whereas T_4 (37.6 q ha^{-1}) and T_5 (38.8 q ha^{-1}) recorded comparatively lower values.

Rice straw yield varied significantly from 36.7 q ha^{-1} in T8 to 65.2 q ha^{-1} in T_7. Treatment T_7 recorded the highest straw yield and was statistically at par with T_1 (64.7 q ha^{-1}) and T_6 (59.1 q ha^{-1}). Relative to T_8, the rice straw yield increased by 77.7 % in T_7, 76.3 % in T_1 and 61.0 % in T_6. The remaining treatments recorded intermediate straw yields, with T_4 (47.2 q ha^{-1}) showing the lowest value among the treated plots.

Wheat grain and straw yield

Wheat grain yield ranged from 26.5 q ha^{-1} in T_8 to 50.2 q ha^{-1} in T_7 (Fig. 1c). The maximum yield under T_7 (50.2 q ha^{-1}) was statistically comparable with T_1 (49.7 q ha^{-1}), whereas T_6 (44.6 q ha^{-1}) recorded a significantly lower yield. Compared with T_8, T_7 increased wheat grain yield by 89.4 %, followed by T_1 (87.5 %) and T_6 (68.3 %).

Wheat straw yield was highest under T_7 (68.9 q ha^{-1}), followed by T_1 (68.3 q ha^{-1}) and T_6 (65.1 q ha^{-1}), whereas the lowest value was recorded under T8 (37.1 q ha^{-1}). T_7 increased wheat straw yield by 85.7 % over T_8 and was statistically comparable with T_1 and T_6, whereas T_3 and T_2 recorded significantly lower straw yields than T_7 (Fig. 1d).

4. Discussion

Labile potassium pools

Water soluble potassium and EK were higher under T_4 and T_5, which received all their N through green manure and cereal residue, than under T_1 (100 % RDF) or T_8 (absolute control). Relative to T_8, T_5 increased WSK to 7.26 mg kg^{-1} (+41.8 %) and EK to 64.39 mg kg^{-1} (+65.7 %). This suggests that organic additions can quickly replenish the plant-available K pool. Treatments that recycled more plant biomass would be expected to return more K to the soil, while the chemical form of K in plant tissues facilitates its rapid release during residue decomposition. Most K in plant cells is present as K^+ in the vacuole and cytoplasm and, unlike N or P, is not bound in proteins or nucleic acids (26). When microbial decomposition ruptures cell membranes, K^+ may enter the soil solution directly, without enzymatic mineralisation. Together, a larger K return and a fast release route could explain the higher WSK and EK under T_4 and T_5. This pattern is consistent with reports of K enrichment from organic amendments in rice–wheat systems and INM in the IGP (1, 2, 14).

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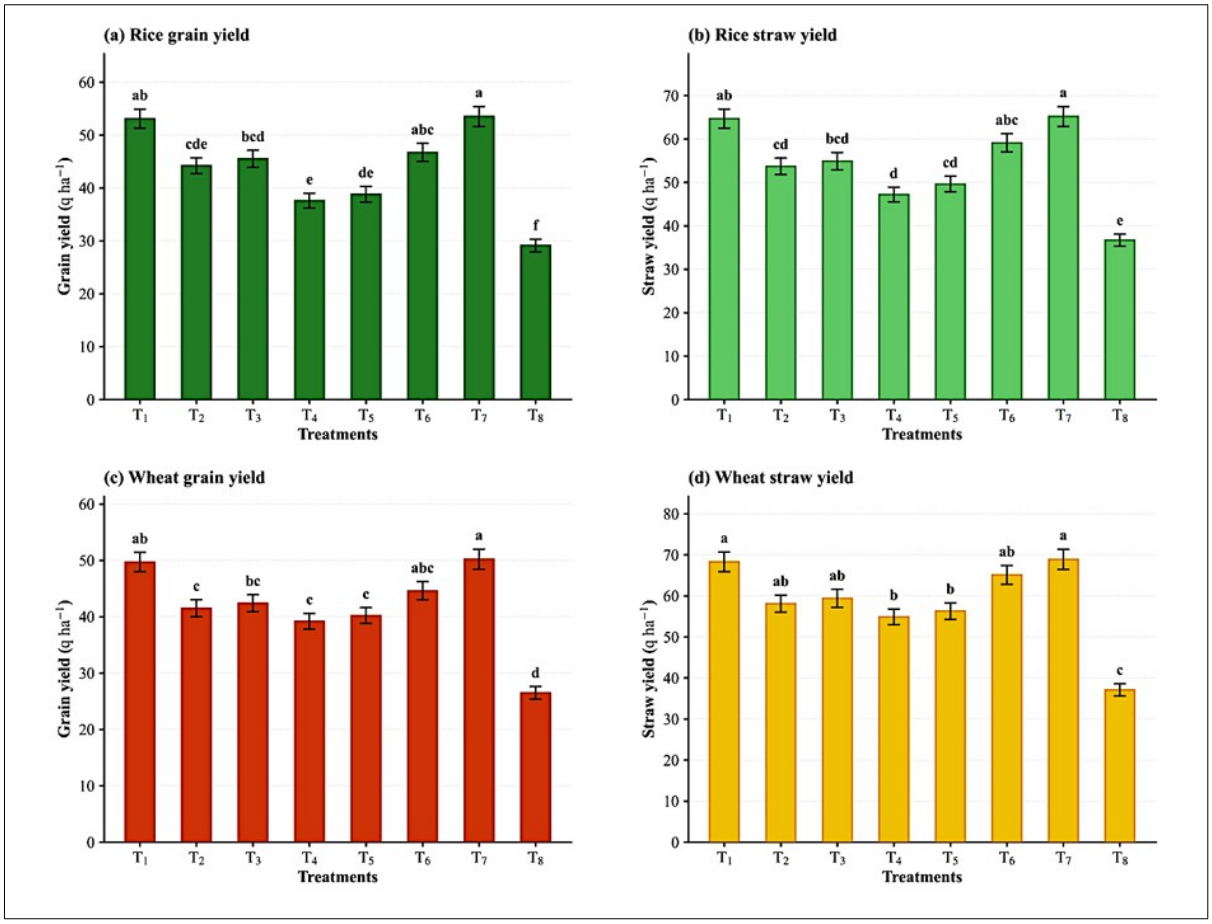


Fig. 1. Effect of different nutrient management practices. a: rice grain yield; b: rice straw yield; c: wheat grain yield; d: wheat straw yield.

RDF: recommended dose of fertilisers; N: nitrogen; T_1: 100 % RDF; T_2: 50 % RDF + 50 % N (cereal residue); T_3: T_2 + residue decomposer; T_4: 50 % N (cereal residue) + 50 % N (green manure); T_5: T_4 + residue decomposer; T_6: 75 % RDF + 25 % N (cereal residue); T_7: T_6 + residue decomposer; T_8: absolute control.

Bars topped by the same letter do not differ significantly ($p \leq 0.05$) according to Duncan's Multiple Range Test.

The way K is retained after residue decomposition also needs attention in this calcareous soil. Such soils contain abundant exchangeable Ca^{2+} and Mg^{2+}, which compete strongly with K^+ for exchange sites and K released into solution may therefore move towards less accessible or fixed positions. Decomposing residues, however, produce humic and other polycarboxylic substances with carboxyl and phenolic groups. These can raise cation exchange capacity at higher pH and bind divalent cations, which may free negative sites to hold K^+ (27). This could explain why the gain in EK under T_5 (65.7 % over the absolute control) was larger than the gain in WSK (41.8 % over the absolute control: a larger share of the released K may have been held on exchange sites and not in the mobile, leaching-prone solution phase typical of free-draining calcareous alluvial soils).

T_2 and T_3 had higher WSK and EK than T_6 and T_7, even though T_6 and T_7 received a larger share of mineral RDF. T_2 and T_3 were designed to replace more crop N with residue than T_6 and T_7, so they presumably received more residue biomass and residue-derived K. Over four years, the amount of organic material recycled therefore appears to have influenced the labile K pool more than the proportion of mineral fertiliser. Within each matched pair, the decomposer treatments showed numerically higher WSK and EK than the corresponding treatments without the decomposer, although these pairwise differences were not statistically significant. The organic and mineral sources were the same within a pair, so the difference may reflect faster release of K already present in the residues, not extra K supply. A likely route is that the decomposer provides enzymes that degrade lignin, cellulose and hemicellulose, removing the cell-wall barriers that retain K within intact residue pieces (28).

Sodium tetraphenylboron-extractable and non-exchangeable potassium

Treatment effects were confined to the rapidly releasable component of soil K. They were significant for 1 hr TBK and 1 hr NEK but were absent at 168 hr. The 1 hr extraction is considered to release K associated with frayed-edge and wedge-zone positions at the periphery of partially weathered mica and illite particles (21). These positions lie between fully exchangeable planar sites and fully occluded interlayer sites and they respond to short-term changes in solution K concentration (10). The separation among treatments at this interval was pronounced. T_5 recorded 2002.96 and 1931.31 mg kg^{-1}

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for 1 hr TBK and 1 hr NEK, against 1188.09 and 1139.89 mg kg^{-1} in T_1. This suggests that treatments with greater K supply replenished the peripheral, kinetically accessible K pool. It agrees with the general observation that higher cumulative K input, whether from fertiliser, crop residues or manure, tends to produce larger short-term kinetic K fractions (5, 14).

T1 (100 % RDF) recorded the lowest numerical 1 hr TBK and 1 hr NEK of all 8 treatments, lower even than T_8. Sole mineral fertilisation supplies adequate N and P and supports the highest crop growth and hence K demand, among the fertilised treatments, but it supplies considerably less K than residue recycling. In that situation, sustained crop uptake may draw preferentially on the wedge-zone and frayed-edge reserve to bridge the gap between fertiliser-supplied K and crop demand, because this reserve is the most readily accessible source once the exchangeable pool has been depleted by root uptake (10). Under T_8, severely N- and P-limited growth probably kept K demand low, so this reserve may have remained comparatively undisturbed despite receiving no external K. The pattern therefore appears to reflect the combined influence of K supply and crop K demand over the experimental period.

The absence of a treatment effect at 168 hr suggests that the maximum operationally extractable NEK pool, which represents K held deeper in the interlayer and in ditrigonal cavities between opposing siloxane sheets, was relatively resistant to management over four years (29). This is consistent with the biphasic K release commonly reported for 2 : 1 clay minerals, where rapid release from external and wedge-zone sites is followed by much slower release from deeper interlayer positions. The slow phase is controlled mainly by diffusion along the mineral–solution concentration gradient and by the structure of the interlayers, which makes it less responsive to short- and medium-term differences in nutrient inputs (22, 23, 30). This is particularly relevant in a calcareous soil, where K may be strongly fixed in deeper interlayer sites, especially in the presence of mica or illite. The 168 hr fraction can therefore be regarded as a relatively stable, long-term potentially available NEK pool.

Lattice and total potassium

Lattice K and TK did not differ significantly among treatments. Lattice K ranged narrowly from 12315.75–12625.50 mg kg^{-1} and TK from 16885.28–17603.01 mg kg^{-1}, despite contrasting nutrient management. This stability is expected because lattice K is held within the crystal structure of primary K-bearing minerals such as feldspars and unweathered mica. It is released only through mineral weathering and structural alteration, which operate on pedogenic rather than agronomic timescales (31). This pool is therefore far less responsive to short-term management than the exchangeable and non-exchangeable fractions and it behaves as a slowly cycling reserve that needs long-term differential management before a change becomes measurable.

The results agree with long-term experiments in which labile K fractions responded readily to fertiliser and organic inputs while the mineral-associated K reserve changed slowly (32). In a 42-year fertilisation trial on a red soil, labile and non-exchangeable K shifted significantly while LK stayed comparatively stable and appreciable changes in the stable K pools became evident only under prolonged management (5). A seven-year rice–wheat experiment likewise showed that LK remained the dominant K fraction, although residue retention and green manuring eventually raised LK together with the other fractions (10). Sustained K inputs or continued K removal can eventually modify mineral-associated K reserves and the overall K-supplying capacity of a soil (11). The absence of a significant treatment effect on LK in this four-year study therefore does not mean that the pool is unaffected by management. It more likely indicates that the duration of contrasting management was too short to produce a detectable change in this large, slowly changing reservoir.

The non-significant variation in TK can be explained in the same way. Total K integrates readily cycling and structurally bound forms, so differences in management are expressed first in the exchangeable, non-exchangeable and other kinetically active pools and not in the TK inventory. Long-term rice–wheat studies support this, showing that management can substantially alter individual K fractions while LK remains a large proportion of TK (12).

Grain and straw yield

Yield trends differed from those of the K fractions. T_4 and T_5 had the highest WSK, EK and kinetic K fractions, yet their rice and wheat yields were lower than those of T_1, T_6 and T_7. Potassium availability therefore does not appear to have limited yield in these treatments. Because T_4 and T_5 received all their N from organic sources, slower and less synchronised N release relative to crop demand is a plausible explanation. Cereal residues generally have a high C : N ratio and can cause temporary microbial N immobilisation after incorporation (33). Microbes use available soil N for their own growth during decomposition and net N mineralisation begins only once the residue C : N ratio becomes sufficiently narrow (34). Green manure, with its lower C : N ratio, mineralises more readily and rapidly than cereal residue. The combined application of both in T_4 and T_5 nonetheless represents a wider average C : N input than mineral fertiliser and the resulting mineralisation–immobilisation dynamics may not have matched the sharp early-season N demand of rice and wheat during tillering and crown-root establishment.

This is consistent with a 15-year rice–wheat INM trial, in which organic sources with higher N concentration (green manure, farmyard manure and leguminous residue) sustained significantly higher straw yield than cereal-residue-based management with lower N concentration. That result links the N quality and release timing of the organic source to realised yield in RWCS (35). In this alkaline, calcareous soil, P availability may have added to the constraint, since phosphate released from organic

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mineralisation or applied as fertiliser is prone to fixation as poorly soluble calcium phosphates at high pH. That would further limit the P available for early crop establishment under treatments with organic sources only (36).

T_7 achieved yields statistically comparable to T_1 (100 % RDF). In this treatment, the 75 % RDF supplied readily available N and P at critical growth stages and the residue component supplemented it. This is consistent with the broader principle that INM meets the crop's immediate N requirement through inorganic fertiliser, while the accompanying organic inputs contribute to longer-term nutrient cycling and soil fertility. Such an approach also allows residues with a wide C : N ratio to be incorporated without greatly disrupting the match between nutrient release and crop demand (37). Partial substitution with a decomposer, as in T_7, may therefore enhance the K-supplying capacity of the soil while avoiding the yield reduction associated with complete replacement of mineral N by organic sources.

Correlation analysis

Pearson's correlation analysis was used to examine the relationships among soil K fractions and rice–wheat yield (Fig. 2). Water soluble K was positively correlated with EK and 1 hr TBK (r = 0.75 for both, p ≤0.001) and with 1 hr NEK (r = 0.67, p ≤0.001). Exchangable K was positively correlated with 1 hr TBK (r = 0.77, p ≤0.001) and 1 hr NEK (r = 0.72, p ≤0.001). The strongest association among the soil K variables was between 1 hr TBK and 1 hr NEK (r = 0.82, p ≤0.001), but this should be interpreted with caution because NEK is calculated as the difference between TBK and available K, so the two are analytically related. Correlations involving 168 hr TBK, 168 hr NEK, LK and TK were generally weak and mostly non-significant. The exceptions were the positive correlations between 168 hr NEK and LK (r = 0.46, p ≤0.05) and between 1 hr NEK and 168 hr NEK (r = 0.43, p ≤0.05). These relationships are consistent with a dynamic equilibrium among soil K pools, in which WSK and EK are replenished by K released from less available pools, depending on soil mineralogy and chemistry (38).

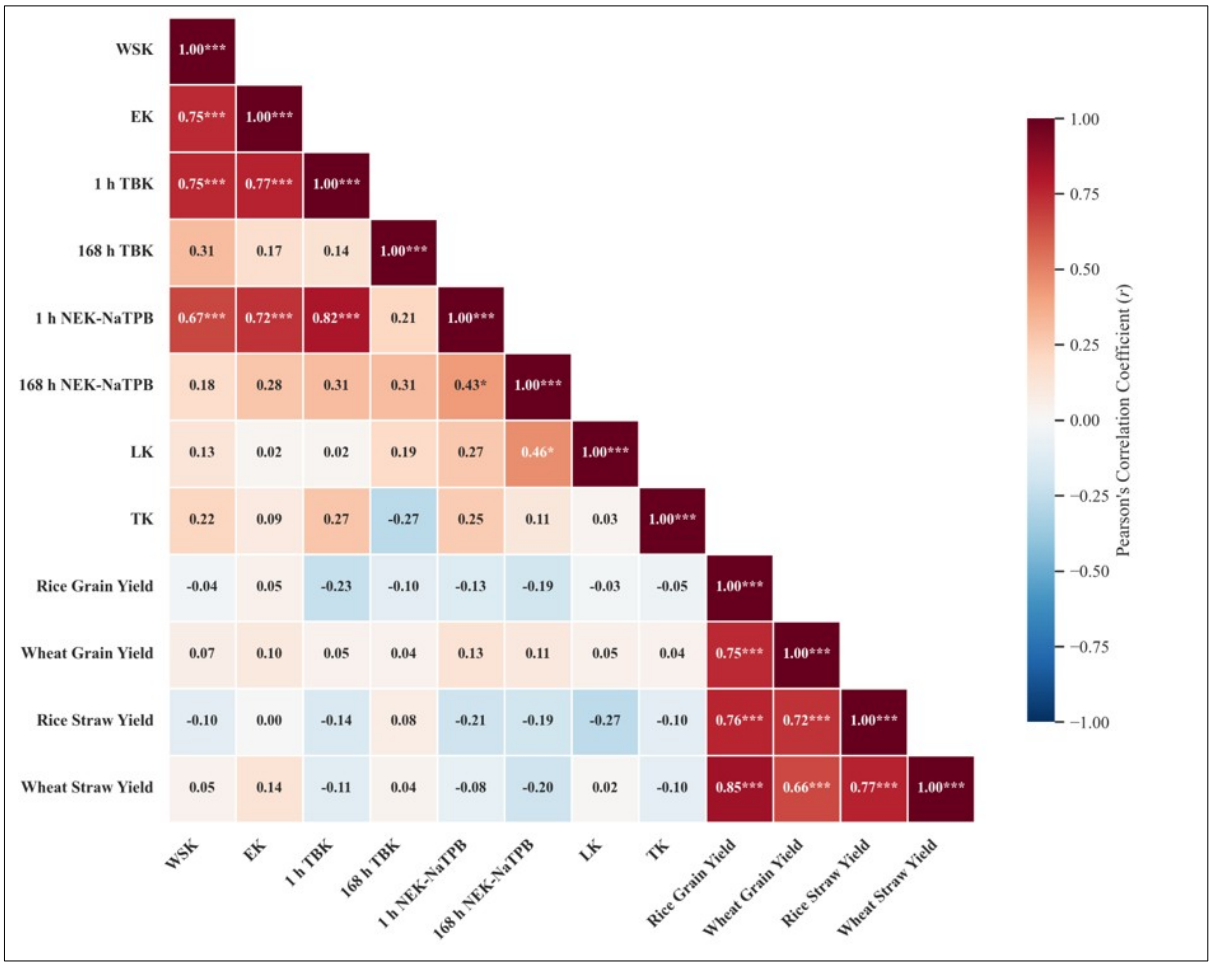


Fig. 2. Pearson correlation matrix among soil potassium fractions and rice-wheat yield (n = 24).

WSK: water-soluble potassium; EK: exchangeable potassium; 1 hr TBK: NaTPB-extractable potassium released after 1 hr; 168 hr TBK: cumulative NaTPB-extractable potassium released after 168 hr; 1 hr NEK: plant-accessible non-exchangeable potassium; 168 hr NEK: potentially available illite potassium; LK: lattice potassium; Total K: total potassium. Values represent Pearson's correlation coefficients (r). *, *** indicate significance at p ≤0.05 and p ≤0.001, respectively; values without asterisks are not significant (p > 0.05).

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The four yield components (rice grain, rice straw, wheat grain and wheat straw) were positively intercorrelated (r = 0.66–0.85, $p \leq 0.001$), indicating that grain and straw production responded similarly to the nutrient management treatments. The correlations between soil K fractions and yield, however, were weak and not significant. Rice grain yield showed no significant correlation with any K fraction (r = −0.23–0.05) and wheat grain yield was weakly correlated with them (r = 0.04–0.13). Rice straw yield showed weak negative correlations with several fractions, including LK (r = −0.27) and wheat straw yield ranged from r = −0.20–0.14. None of these was significant (p >0.05). The variation in yield across treatments could therefore not be explained by the measured soil K fractions alone. These weak relationships suggest that yield was influenced by factors beyond soil K status, such as the timing and supply of N and P, mineralisation and immobilisation of nutrients and how well nutrient release matched crop demand. Crop residues affect nutrient cycling through decomposition and temporary immobilisation of N and P (39) and combining organic sources with chemical fertilisers can alter nutrient availability and productivity RWCS (37). The higher K fractions under some treatments should therefore not be taken as evidence of greater immediate K availability or yield potential. Soil K fractions are better interpreted together with crop K uptake, K-release kinetics, K balance and the supply of other nutrients. This matters in intensive cropping, where continued removal without adequate K replenishment can shift the balance between readily available and reserve K pools (31).

The interpretations in this study should be viewed in light of certain limitations. K input, crop K uptake and K balance were not quantified and soil properties such as cation exchange capacity (CEC), humic fractions, mineralogy, residue C : N ratio and N and P mineralisation were not measured. The mechanisms discussed above are therefore hypotheses based on the treatment design and the literature. Longer-term studies including K budgets, X-ray diffraction (XRD) analysis and N and P dynamics are needed to confirm them.

5. Conclusion

Integrating cereal residue, green manure and the residue decomposer significantly increased labile and kinetically accessible soil potassium (K) compared with sole inorganic fertilisation. The decomposer consistently raised these fractions in every matched treatment pair. However, 168 hr tetraphenylboron-extractable potassium (TBK), 168 hr non exchangeable potassium (NEK), lattice potassium (LK) and total potassium (TK) were unchanged, suggesting that four years was too short to alter these slowly cycling reserves. Yields were highest where more nitrogen (N) and phosphorus (P) were supplied inorganically and no soil K fraction was significantly correlated with yield, so yield may have been influenced more by N and P supply than by soil K status. Applying 75 % recommended dose of fertilisers (RDF) with 25 % of fertiliser N substituted through cereal residue and the decomposer produced yields that were not significantly different from those under 100 % RDF under the present experimental conditions, while improving exchangeable potassium (EK), 1 hr TBK and 1 hr NEK. Based on these results, partial substitution of fertiliser N with cereal residue plus a residue decomposer may be suitable for rice–wheat systems on similar calcareous alluvial soils, subject to validation under longer-term and multi-location conditions. This practice produced yields that were not significantly different from those under 100 % RDF while improving the labile K status. Complete replacement of mineral N with organic sources is not advisable, as it lowered yields. Because the study covers four years at one site, multi-location, longer-term trials in the calcareous soils of the middle Indo-Gangetic Plains (IGP), with K budgets and mineralogical analysis, are needed to confirm the mechanisms underlying these K fraction responses before broader recommendations can be formulated.

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Authors' contributions

Conceptualisation was carried out by DN and SNS. The methodology was developed by DN, SNS and VK. Formal analysis and investigation were performed by DN, SNS and VK. The original draft was prepared by DN, SNS and VK. Resources were provided by SNS and VK. Supervision and data curation were undertaken by SNS, VK, SKS, D, HS and RS. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests 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 QuillBot for grammar correction and language editing to improve the clarity and readability of the manuscript. After

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using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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