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RESEARCH ARTICLE

Productivity and nutrient budgeting of rice-wheat cropping systems: Insights from 25 years of long-term fertilization in a *Vertisol* of subtropical India

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Abstract

The present study aimed to evaluate the nutrient budget, apparent nutrient balance and quantify nutrient depletion and build-up resulting from 25 years of long term fertilization in a *Vertisol* of Subtropical India. The 150 % NPK recorded maximum positive apparent nitrogen (N) (3038 kg ha^{-1}) and phosphorus (P) (1182 kg ha^{-1}) balance, while minimum was recorded with absolute control (-1604 kg ha^{-1}). The inclusion of green manure (GM) with 50 % NPK registered positive apparent N balance. The apparent P balance was positive with inclusion of P in fertilizer scheduling even under 50 % NPK and 50 % NPK + Blue green algae (BGA) treatments, indicating that 50 % P application fulfilled the crop P demand. The negative apparent K balance was recorded across almost all treatments with the average rate of -181 kg $ha^{-1}yr^{-1}$ indicating luxury consumption of K by crops than its supplementation. The soil available N was depleted in all the treatments, however, depletion was minimum under 150 % NPK (10 kg ha^{-1}) and 100 % NPK+FYM (13 kg ha^{-1}). There was build-up of soil available P over initial status in all the imposed treatments (from 5 to 18 kg ha^{-1}) even under sub-optimal dose of NPK, except in absolute control and 100 % N. However, a net negative soil available K was observed in almost all the treatments due to mining of soil K reserves to meet out crop demand. The findings underscore the critical necessity for strategic N and K fertilization in *Vertisol* under rice-wheat cropping system to sustain optimal nutrient equilibrium, managing soil fertility and maximize agronomic productivity.

Keywords: long term fertilizer experiment; nutrient budgeting; productivity; rice-wheat cropping system; subtropical climate; *Vertisol*

Introduction

Nutrient budgeting plays a crucial role in understanding the nutrition dynamics within agricultural systems and is critical for promoting sustainable farming practices. It involves accounting for the balance between nutrient inputs, nutrient uptake by crops and nutrient losses, aiming to ensure long-term soil fertility and crop productivity. Fertilizers have been pivotal in driving India's Green Revolution and ensuring food security (1). Fertilizer consumption in India is projected to reach 277 kg ha^{-1} by 2030, with the total demand expected to rise to 57 million metric tonnes (Mt) (2). Over the years, there has been a significant increase in both fertilizers use and food grain production. Total nutrient consumption of Nitrogen, Phosphorus and Potassium (NPK) rose from 12.54 Mt in 1990-91 to 29.84 Mt in 2022-23 (3), while food grain production surged from 176.39 Mt to 329.7 Mt during the same period. These trends clearly demonstrate a direct correlation between fertilizer consumption and food grain production, underscoring the critical role of fertilizers in meeting the nation's growing food demands.

The rice-wheat cropping system, a predominant agricultural practice in Subtropical India, relies heavily on the judicious application of fertilizers to meet the nutrient demands of these high-yielding crops. Over the years, extensive fertilizer application has been employed to maintain or increase crop yields. However, the long-term consequences of such practices on soil health and nutrient sustainability remain a subject of concern (4). The role of nitrogen (N), phosphorus (P) and potassium (K), the three macronutrients most limiting crop growth, is particularly significant in this context. However, the intensive nature of the rice-wheat system has led to concerns about nutrient depletion, particularly with the excessive use of nitrogen fertilizers. Moreover, imbalanced fertilization practices, often neglecting the importance of phosphorus and potassium, have further exacerbated nutrient deficiencies in these soils.

Over application of Nitrogen is prevalent in rice-wheat systems, as these crops are heavy N feeders. However, excess N is prone to losses via leaching, volatilization and denitrification, reducing N use efficiency and contributing to environmental pollution. Indian soils are inherently N-deficient due to subtropical climatic conditions that limit soil organic matter accumulation, the primary N source (5). In such regions, crop productivity relies heavily on external N inputs through fertilizers, manures, compost, crop residues and N-efficient technologies. Efficient use of N fertilizers and organic inputs is crucial in sustaining productivity while mitigating environmental impacts (5). The nutrient consumption ratio ($N:P_2O_5:K_2O$) remains imbalanced at 6.7:2.4:1 (2018-19), compared to the ideal 4:2:1. This imbalance is more pronounced in highly productive subtropical regions (6, 7).

Phosphorus is a major constraint for crop production in central Indian soils (8). As it is finite, non-renewable reserves are rapidly depleting and its deficiency is widespread due to intense cropping (9). Therefore, regular monitoring and assessment of phosphorus availability are essential for evaluating soil fertility and ensuring productivity in intensive cropping systems, particularly in black soils (10). A significant portion of applied phosphorus fertilizers is not absorbed by plants but is instead fixed in less available forms in the soil (11). The critical role of phosphorus in maintaining soil fertility and enhancing crop productivity is increasingly recognized, especially since Indian soils universally respond to phosphorus application (12).

Indian soils were once rich in potassium (K), but after the Green Revolution, there was a significant increase in productivity and production, which led to accelerated depletion of native K. As a result, crops began to show a response to applied K in several locations (13). On an average, a crop at a high productivity level removes nearly 100 kg of K from the soil. Continuous mining of K by crops and the removal of straw from fields have contributed to the decline in soil K status. Over the past fifty years, potassium fertilizer consumption in India has accounted for not more than 10 % of total NPK fertilizer consumption (14). Moreover, local fertilizer recommendations advocate for a balanced use of N, P and K. Majority of farmers usually go for application of only N or a combination of N and P, with little or no K fertilizer (15). It is often stated that Indian soils face a negative nutrient balance of 10-12 Mt annually, with potassium being the major contributor to this deficit. It is an established fact that the crop demands (particularly the cereal crops) for K are much more due to luxury consumption that resulted continuous mining of native K from soil and the exclusion of K from fertilization schedule accelerates this mining.

In the rice-wheat system, sub-optimal or excessive nutrient management leads to reduced yields, low nutrient use efficiency, nutrient mining and financial losses (16, 17). The quantification of nitrogen (N), phosphorus (P) and potassium (K) sinks and sources through N, P, K budgeting helps address nutrient losses and low N, P, K use efficiency (NUE) (18, 19). Long-term fertilizer experiments (LTFE) provide a unique platform to assess nutrient budgets by analyzing nutrient inputs and crop uptake data. This helps evaluate the balance between nutrient supply, actual crop demand and uptake, thereby assessing the long-term sustainability of nutrient management practices. Hence, the present study was undertaken with the objectives (i) to evaluate the crop productivity of rice and wheat (ii) to assess nutrient budgets and apparent balance that account for nutrient inputs and crop removal of RWCS (iii) to evaluate the net nutrient balance in the soil and (iv) to quantify nutrient depletion and build-up rate as influenced by 25 years of long-term fertilizer experiments in a *Vertisol* of sub-tropical climate of India.

Materials and Methods

Experimental site descriptions

The All India Coordinated Research Project (AICRP) on Long-Term Fertilizer Experiments (LTFE) was initiated in 1999 at the Instructional cum Research Farm of Indira Gandhi Agricultural University, Raipur, Chhattisgarh, India (21°40' N, 81°39' E, altitude 234 m above mean sea level). The experimental site is located in the eastern plateau agro-climatic zone, characterized by a sub-tropical climate. The region receives an average annual rainfall of 1190.9 mm, with the majority (88 %) occurring during the rainy season (mid-June to December) and the remaining 12 % during winter (December to February). Summer temperatures range from 30 °C to 42 °C, while winter temperatures vary between 0 °C and 25 °C. Additional climatic details during the experimental period are provided in Table 1. The soil at the experimental site belongs to the *Vertisol* soil order, specifically the *Typic Haplustert* suborder. These soils are classified as *Fine montmorillonitic, hyperthermic Chromusterts*. These soils are deep, loamy, neutral to slightly acidic and non-calcareous. The length of the growing period (LGP) is 150-180 days (20). The initial soil properties of the experimental site are outlined in Table 2.

Experimental design

The current experiment involved two annual crops: rice (June -October) and wheat (November-April). It included 10 fertilization treatments arranged in a randomized block design with four replications, using a plot size of 200 m^2 (20 m × 10 m). The treatments were as follows: no fertilizer or manure (control, T_1), 50 % NPK (T_2), 100 % NPK (NPK, T_3), 150 % NPK (T_4), 100 % NPK + Zn (NPK+ Zn, T_5), 100 % NP (NP, T_6), 100 % N (N, T_7), 100 % NPK + FYM (NPK+FYM, T_8), 50 % NPK+BGA (T_9) and 50 % NPK+GM (T_{10}). From 1999 to 2018, the recommended dose of fertilizer (RDF) was 100:26:33 kg NPK ha^{-1} for both crops. This was increased to 120:26:33 kg NPK ha^{-1} from 2019 onward. Fertilizers used as nutrient sources were urea for nitrogen (N), single super phosphate (SSP) for phosphorus (P) and muriate of potash (MOP) for potassium (K). Zinc sulfate ($ZnSO_4$) was applied at 10 kg ha^{-1} annually during rice transplanting. Farmyard manure (FYM) at 5 Mg ha^{-1} was incorporated into the soil annually in designated plots before rice transplanting through plowing. Blue-green algae (BGA) dry culture 10 kg ha^{-1} was applied one week after rice transplanting. A green manure (GM), using sunn hemp (*Crotalaria juncea*), was sown two months before rice transplanting and incorporated into the soil before flowering, followed by puddling. A net plot size of 5 m × 5 m was used for crop harvesting to minimize border effects and accurately estimate grain yields.

Crop management

The field was uniformly puddled and divided into replicated plots. From 1999 to 2018, the rice cultivar 'Mahamaya' was used, which was subsequently replaced with 'Rajeshwari'

Table 1. Mean climatic data during experimental period (1999-2023)

Months	Mean temperature (°C)	Rainfall (mm)	Mean RH (%)	Evaporation (mm day^{-1})	Sunshine (h)
Rice growing season					
July	28	348.5	81.6	114.7	2.9
August	28	311.0	84.2	98.0	2.9
September	28	223.7	81.5	99.2	4.9
October	27	41.8	71.7	104.2	7.3
November	23	7.1	63.4	90.3	8.0
Wheat growing season					
December	20	10.3	61.4	83.4	7.2
January	20	13.3	60.4	86.8	7.3
February	23	18.0	57.2	108.1	8.2
March	27	10.4	47.6	174.4	8.4
April	32	17.7	37.5	254.4	8.8

Source of data: Department of Agro-meteorology, IGKV Raipur

Table 2. Initial soil physico-chemical characteristics of long-term fertilizer experiments in a *Vertisol*

Soil characteristics	Values
Bulk density (Mg m^{-3})	1.37
Textural Class	Clayey
pH (soil: water, 1.25)	7.7
EC (dS m^{-1})	0.20
Soil organic carbon (g kg^{-1})	6.2
Sand (%)	20
Silt (%)	34
Clay (%)	46
CEC (cmol (p^{+}) kg^{-1})	38
Available N (kg ha^{-1})	236
Available P (kg ha^{-1})	16
Available K (kg ha^{-1})	474
DTPA Extract Zn (mg kg^{-1})	1.2

from 2019 onward. Rice seedlings, aged 20-22 days, were transplanted manually at a spacing of 20 cm × 10 cm at a depth of 3-4 cm. Throughout the growth period, a minimum water level of 1-2 cm was maintained in the plots until the crop attained physiological maturity. During the wet season, irrigation was provided as needed to ensure an adequate water supply. Rice was harvested manually at physiological maturity in the last week of October, leaving 5-6 cm of stubble above the soil surface. Following rice harvest, the soil was plowed twice annually, incorporating stubbles and roots, before sowing wheat in the second week of November. In this LTFE, wheat cultivars were updated over time-'Sujata' was grown from 1999 to 2001, followed by 'GW 273' from 2002 to 2018 and 'CG Amber' from 2019 to the present. A seed rate of 120 kg ha^{-1} was generally used for these varieties, with a spacing of 20 cm x 10 cm at 4-5 cm depth by hand each year. The crop was harvested manually at physiological maturity in mid of April at 5-6 cm above soil surface.The stubbles and roots of wheat were incorporated into the soil during land preparation for the following rice crop. Grain yields for both crops were air-dried and weighed after harvest. Full doses of phosphorus (P) and potassium (K) were applied at transplanting (rice) and sowing (wheat). Nitrogen (N) was applied in three split doses: one-third at transplanting/ sowing, one-third at the tillering stage and the remaining one -third at the panicle initiation stage for both crops. Weed management and plant protection measures were implemented as necessary to control weeds, diseases and pests. Rice (*Oryza sativa* L.) belongs to the family *Poaceae*, has a panicle-type inflorescence, produces a caryopsis-type fruit and is diploid with a ploidy level of 2n = 24. Wheat (*Triticum aestivum* L.) also belongs to the family *Poaceae*, has a spike-type inflorescence, produces a caryopsis-type fruit and is hexaploid with a ploidy level of 2n = 6x = 42.

Soil sampling and analysis

Initial soil samples from the topsoil (0-15 cm) were collected in 1999, prior to the commencement of the experiment. After the 25th crop cycle, soil samples were collected using a post-hole auger from four different points in each replicated plot. The samples from each plot were thoroughly mixed to create a homogeneous composite sample. These samples were air-dried in the shade, homogenized, processed and sieved through a 2 mm mesh. The prepared samples were then transferred to the laboratory in clean cotton bags for analysis. Available nitrogen (N) was determined using the alkaline potassium permanganate ($KMnO_4$) method, where ammonia liberation was measured as described by Subbiah and Asija (21). Available phosphorus (P) was measured using the Olsen method, employing 0.5 M $NaHCO_3$ as an extractant (22). Available potassium (K) was quantified using the neutral ammonium acetate method and analyzed with a flame photometer (23).

Statistical analysis

Analysis of variance (ANOVA) was performed, followed by Tukey's HSD test at p=0.05 level of significance to determine the differences among treatments to quantify and evaluate the sources of variance for different parameters using R. Pearson's correlation matrix was carried out between nutrient applied, uptake and balance. Pearson's correlation matrix was also carried out between rice and wheat yield, apparent balance of N, P and K, soil organic carbon and soil nutrient status.

Results and Discussion

Crop productivity

Results of long-term fertilizer experiment after 25 cropping cycles of rice and wheat indicated that the mean yield of rice increased from its initial value in all treatments, even in the control plot (Table 3). Similar findings were also reported for wheat, except in the case of imbalanced fertilization (N treatment), which reduced the mean yield of wheat from its initial value. It was observed that the long-term application of a super optimal dose of fertilizer (150 % NPK) and integrated nutrients management (NPK+FYM) significantly increased the yield of both crops over the unfertilized control (Table 3). The 150 % NPK recorded significantly highest grain yield of 5.80 and 3.03 Mg ha^{-1} in rice and wheat, respectively which was closely followed the respective yields obtained in NPK+FYM (5.70 and 2.93 Mg ha^{-1} for rice and wheat, respectively) (4). The super optimal dose of NPK followed by integrated nutrient management, led to continuous increase in productivity of rice and wheat with time could be attributed to an increase in soil organic carbon (SOC), microbial activity, soil structure and consequential soil health (4, 24). Results also reflected that no crop response was observed for applied K, Zn and BGA as indicated by statistically at par yields with NPK & NP, NPK & NPK + Zn and 50 % NPK & 50 % NPK+BGA. The inclusion of green manure (GM) with 50 % NPK registered a significantly higher yield as compared to 50 % NPK alone.

Nutrient budgeting

Nitrogen (N)

Results from long-term fertilizer experiments indicated that over a total of 25 crop cycles of rice and wheat, the cumulative nitrogen (N) input (7800 kg ha^{-1}) and uptake (4762 kg ha^{-1}) was recorded as maximum under super optimal dose of NPK (150 %NPK) (Table 4). This increase in nutrient supply leads to a substantial positive apparent N balance of 3038 kg ha^{-1}. The apparent N balance under 100 % N (2437 kg ha^{-1}) was higher than that of the NPK+FYM treatment (1434 kg ha^{-1}). This might be attributed to sufficient N supply under 100 % N treatment as per crop requirement. However, the absence of P and K in this treatment declined crop yield compared to NPK+FYM resulting in lower N uptake and consequently, a higher N balance in the soil.

It was observed that the apparent N balance under NP treatment (1363 kg ha^{-1}) was slightly higher than that of NPK treatment (1250 kg ha^{-1}), which may be attributed to slightly higher yield under NPK treatment, however, the yield was at par with NP treatment. This also indicates no crop response was observed to applied K fertilizer. The absolute control treatment exhibited maximum negative apparent N balance of -1604 kg ha^{-1}, followed by 50 % NPK along with BGA (-325 kg ha^{-1}), 50 % NPK (-223 kg ha^{-1}) and indicated the profound impact of the continuous absence of N fertilization and suboptimal fertilization on apparent nitrogen (N) availability in rice-wheat system. However, inclusion of green manure (GM) with 50 % NPK registered positive apparent N balance demonstrating the positive impact of GM in replenishing soil nutrients. The observation is further validated by correlation study. The amount of N applied was significant positive correlated with N uptake ($R^2 = 0.83$, $p < 0.05$) and N balance ($R^2 = 0.92$, $p < 0.05$) (Fig. 1a). The correlation results revealed that N balance in soil is directly depend on N applied to soil.

The net N loss from rice -wheat system was observed under absolute control treatment (64.17 kg ha^{-1}yr^{-1}), followed by 50 % NPK+BGA (13.02 kg ha^{-1}yr^{-1}) and 50 % NPK (8.93 kg ha^{-1} yr^{-1}) (Table 4). The accumulation/gain of N by the rice wheat system was varied from 21.72 to 121.51 kg ha^{-1}yr^{-1} with N fertilization either through inorganic alone or in combination with organics (FYM, BGA, GM). The accumulation/gain of N was maximum under 150 % NPK (121.51 kg ha^{-1}yr^{-1}), followed by 100 % N (97.48 kg ha^{-1}yr^{-1}), NPK+FYM (57.35 kg ha^{-1}yr^{-1}) and by NP (54.52 kg ha^{-1}yr^{-1}). The rate of apparent N balance either positive or negative depends on the amount of N applied to soil, crop productivity and nutrient uptake. The negative apparent nitrogen (N) balance observed under the absolute control and sub-optimal NPK application (50 % NPK) indicated that N is being removed from the system through crop uptake at a higher rate than it is being supplemented. This imbalance suggests insufficient N input to sustain the crop's nutrient demand. In contrast, a positive apparent N balance signifies that the N applied is adequate to meet the crop's requirements, resulting in a surplus in the system. This highlights the importance of optimal fertilization to maintain N balance and support sustainable crop productivity (25, 26). The significant positive correlation (Fig. 2). between rice ($R^2 = 0.69$, $p < 0.05$) and wheat ($R^2 = 0.70$, $p < 0.05$) yield with apparent N balanced further proved the importance of inclusion of balanced N in fertilization schedule.

Table 3. Grain yield of rice-wheat cropping systems as influenced by long term fertilizer experiments (1999-2023)

Treatment	Initial grain yield (Mg ha^{-1})		Mean (1999-2023) grain yield (Mg ha^{-1})	
	Rice	Wheat	Rice	Wheat
Control	2.07	1.06	2.28 ± 0.03f	1.08 ± 0.05g
50 % NPK	3.04	1.61	4.15 ± 0.04d	1.84 ± 0.03e
NPK	4.47	2.60	5.29 ± 0.04b	2.61 ± 0.08c
150 % NPK	4.88	2.48	5.80 ± 0.05a	3.03 ± 0.07a
NPK+Zn	4.47	2.32	5.22 ± 0.04b	2.97 ± 0.04c
NP	4.41	2.30	5.20 ± 0.03b	2.56 ± 0.04c
N	2.92	2.26	3.60 ± 0.07e	1.64 ± 0.04f
NPK+FYM	4.79	2.80	5.70 ± 0.05a	2.93 ± 0.02b
50 % NPK+BGA	3.16	2.12	4.14 ± 0.05d	1.91 ± 0.04e
50 % NPK+GM	3.88	1.96	4.77 ± 0.06c	2.12 ± 0.04d

Mean followed by similar letter within a column for a particular management practices and same row are not significant different ($p < 0.05$) according to Tukey's HSD test

Table 4. Nitrogen budgeting as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol*

Treatments	Applied	Uptake	Apparent balance	Apparent balance rate
	Cumulative of 25 years (1999 to 2023)			
	(kg ha^{-1})			(kg ha^{-1} yr^{-1})
Control	0	1604	-1604	-64.17
50 % NPK	2600	2823	-223	-8.93
NPK	5200	3950	1250	50.00
150 % NPK	7800	4762	3038	121.51
NPK+ Zn	5200	3921	1279	51.16
NP	5200	3837	1363	54.52
N	5200	2763	2437	97.48
NPK+FYM	5825	4391	1434	57.35
50 % NPK+BGA	2600	2925	-325	-13.02
50 % NPK+GM	3954	3411	543	21.72

The contribution of N through FYM and GM has also been considered

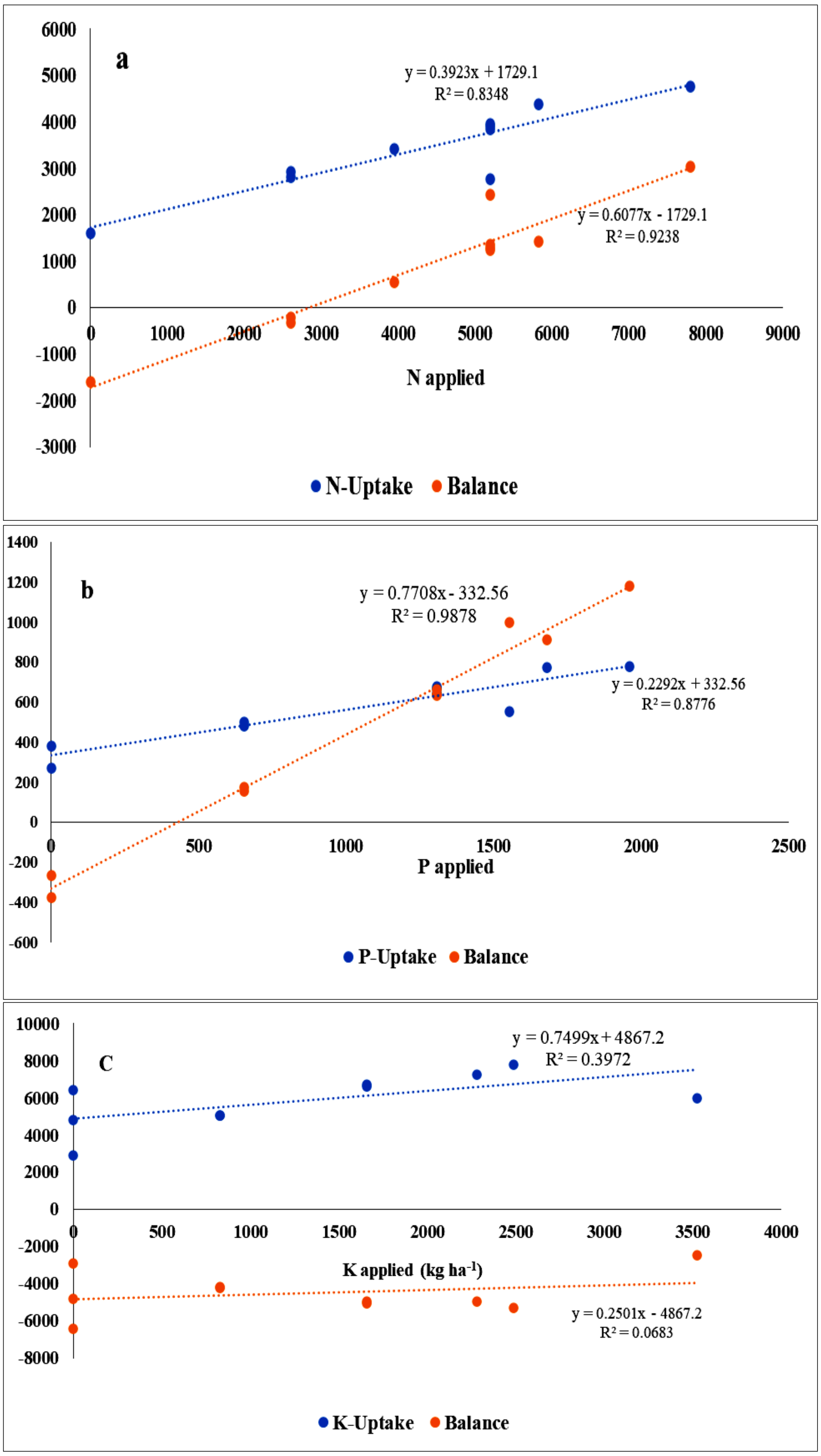

Fig. 1. Pearson's correlation matrix between amount of nutrient applied, uptake and apparent nutrient balance in soil. (a) N; (b) P; (c) K as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol*.

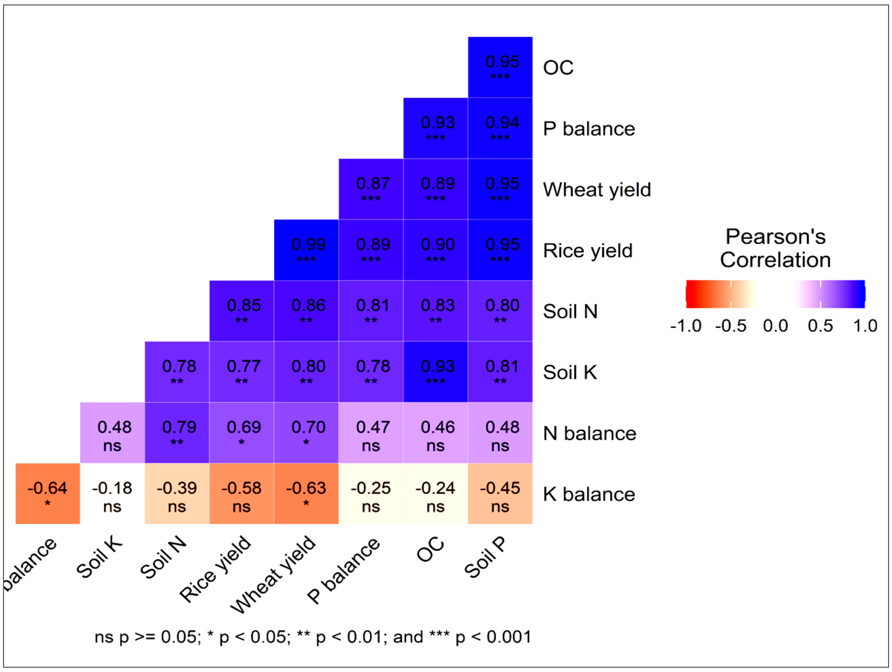

Fig. 2. Pearson's correlation matrix among rice and wheat yield, soil organic carbon, soil nutrient status and apparent balance of N, P and K as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol.*

Phosphorus (P)

The continuous cropping over 25 successive crop cycles of rice and wheat indicated that the continuous application of super-optimal fertilizer dose (150 % NPK) resulted in the highest cumulative phosphorus (P) input (1962 kg ha^{-1}) and uptake (780 kg ha^{-1}), leading to a substantial positive apparent P balance of 1182 kg ha^{-1} (Table 5). It was observed that the P input and uptake under NPK+FYM was higher than that of 50 % NPK+GM treatment, however, the apparent P balance was vice versa. The application of 5 t ha^{-1} FYM with balanced fertilization maximized crop productivity led to better P availability and uptake by crops, while the higher positive apparent P balance under 50 % NPK+GM treatment could be due to the nutrient mobilizing effects of GM, which improves availability of native P to crops and efficiency leading to higher positive apparent P balance. In contrast to N, a positive apparent P balance was observed under the 50 % NPK (173 kg ha^{-1}) and 50 % NPK + BGA (155 kg ha^{-1}) treatments. This might be due to that the amount of P applied was higher than that of plant uptake. This indicates that 50 % P application in these treatments fulfilled the crop's P demand. This findings is validated by soil test value, which show an increase in available soil P from 16 kg ha^{-1} to 21 kg ha^{-1} (Fig. 3b), indicating a net accumulation in the soil due to surplus P remaining after crop uptake. Furthermore, correlation analysis (Fig. 1b) revealed that soil-applied P exhibited a stronger positive relationship with the apparent P balance ($R^2 = 0.98$, $p < 0.05$) compared to P uptake ($R^2 = 0.87$, $p < 0.05$) providing the additional evidence in support of the observed trends.

The continuous absence of P fertilization in the absolute control and 100 % N treatment led to gradual depletion of soil P, resulted in a negative apparent P balance in rice-wheat system (26, 28). The maximum net P loss from rice -wheat system was -15.2 kg $ha^{-1}yr^{-1}$ under alone N treatment (100 % N), followed by absolute control (-10.7 kg $ha^{-1}yr^{-1}$) for rest of all other treatment net accumulation/gain of P was observed by rice-wheat system which was varied from 6.2 to 47.3 kg $ha^{-1}yr^{-1}$. The net accumulation/gain of P was recorded maximum under 150 % NPK (47.3 kg $ha^{-1}yr^{-1}$), followed by NPK+FYM (36.5 kg $ha^{-1}yr^{-1}$), NP (26.6 kg $ha^{-1}yr^{-1}$) and NPK (25.6 kg $ha^{-1}yr^{-1}$). The negative apparent P balance might be due to continuous cropping without P fertilization, while the positive apparent P balance may be attributed to

Table 5. Phosphorus budgeting as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol*

Treatments	Applied	Uptake	Apparent balance	Apparent balance rate
	Cumulative of 25 years (1999 to 2023)			
	(kg ha^{-1})			(kg $ha^{-1}yr^{-1}$)
Control	0	267	-267	-10.7
50 % NPK	654	481	173	6.9
NPK	1308	667	641	25.6
150 % NPK	1962	780	1182	47.3
NPK+Zn	1308	675	633	25.3
NP	1308	644	664	26.6
N	0	379	-379	-15.2
NPK+FYM	1682	771	912	36.5
50 % NPK+BGA	654	499	155	6.2
50 % NPK+GM	1553	554	999	40.0

The contribution of P through FYM and GM has also been considered inclusion of adequate P doses in the fertilization schedule either through inorganic alone or in combination with organics (11, 25, 26). The significant positive correlation (Fig. 2) between rice ($R^2 = 0.89$, $p < 0.05$) and wheat yield ($R^2 = 0.87$, $p < 0.05$) with apparent P balanced further proved the importance of inclusion of balanced P in fertilization schedule.

Potassium (K)

Data emanated from present long-term fertilizer experiment on nutrient input and output illustrated that the cumulative apparent K balance over 25 cropping cycles of rice and wheat was negative in all the nutrient management treatments even under recommended dose of K in the fertilization schedule (Table 6). The negative apparent K balance was recorded maximum under 100 % NP treatment (-6417 kg ha^{-1}) followed by 150 % NPK (-5316 kg ha^{-1}), NPK+FYM (-4972 kg ha^{-1}) and by NPK treatment (-4953 kg ha^{-1}). The optimal dose of N and P enhanced the crop growth and yield. However, the exclusion of K from the fertilization schedule accelerates the mining of reserve K from soil. This results in higher negative apparent K balanced under 100%NP treatment. The high crop productivity under super optimal dose of NPK (150 % NPK), NPK+FYM and NPK treatment is responsible for more negative apparent K balance under rice-wheat system (13, 29, 30).

The net loss of K from rice -wheat system varied from -99 to -257 kg ha^{-1} yr^{-1} with an average loss of -181 kg ha^{-1} yr^{-1} at normal to good productivity level. Among them, the minimum loss was observed under 50 % NPK+GM treatment (-99 kg ha^{-1}yr^{-1}), which might be attributed to nutrient mobilization effects of green manure which enhance the release of native soil K and its availability to crops, resulting in a minimum negative apparent K balance in the rice-wheat cropping system. Although the maximum net loss of K was recorded under 100 % NP treatment (-257 kg ha^{-1} yr^{-1}), followed by 150 % NPK (-203 kg ha^{-1}yr^{-1}). It was observed that the soil apparent K balance was highly negative even with the application of a super-optimal dose of NPK and under balanced fertilization along with FYM. It indicates that the K removal by crops far exceeded than that of its supplementation from K fertilization. The present findings are supported by the correlation study (Fig. 1c) which shows that the amount of K applied was poorly correlated with K uptake ($R^2 = 0.39$, $p < 0.05$) and very poor correlation between apparent K balance ($R^2 = 0.0.06$, $p < 0 .05$). These results suggest that the amount of K applied was inadequate to fulfill crop requirements, resulting in depletion of native soil K reserves. This trend is further supported by broader regional studies, which report that the majority of Indian soils exhibit a negative K balance (25, 28, 30).

Nutrient balance sheet

The available N in soil after 25 crop cycle of rice and wheat decreased across all the treatments over initial soil status (236 kg ha^{-1}) in *Vertisol* of sub-tropical India (Fig. 3a). The maximum depletion of available N was observed under absolute control treatment (-119 kg ha^{-1}) followed by 50 % NPK (-93 kg ha^{-1}) and by 50 % NPK+BGA treatment (-89 kg ha^{-1}) due to exclusion of N fertilizer in fertilization schedule and suboptimal nutrient supply than that of crop requirement. As a result, plants uptake N from the soil reserves, leading to a net negative N balance in the soil (26). A strong positive correlation ($R^2 = 0.83$, $p < 0.05$; Fig. 2) between SOC (Fig. 4) and soil N supports the observed trends indicating that after 25 crop cycles of rice–wheat, soil N decreased in those treatments where SOC declined from its initial status. Over time, a negative N balance may lead to reduced soil fertility and hinder crop productivity. This also indicates the importance of N fertilization on net N balance to soil (25). However, the minimum depletion of available N was recorded under 150 % NPK (10 kg ha^{-1}), which was closely followed by 100 % NPK+FYM (10 kg ha^{-1}). In the subtropical climate of India, where nutrient mineralization rate is very high, the super optimal dose of inorganic fertilizer (150 %NPK) followed by integrated nutrient management (NPK+FYM), effectively supplied almost sufficient nutrients to meet the crop's requirements. As a results N loss from soil were minimized (28, 31).

The long-term fertilizer experiment after 25 cropping cycles indicated that in contrast to available N, there was build -up of available P in soil from its initial status (16 kg ha^{-1}) with phosphorus (P) fertilization either through inorganic alone or in combination with organics, except where P was not applied in fertilization schedule in *Vertisol* of sub-tropical India (Fig. 3b). The build-up of soil P ranged from 5 to 18 kg ha^{-1} and the maximum accumulation was observed under 150 % NPK (18 kg ha^{-1}) closely followed by NPK+FYM (17 kg ha^{-1}). The minimum build-up of available P was recorded under both 50 % NPK and 50 % NPK+BGA treatment (5 kg ha^{-1}). The depletion of soil available P was recorded maximum (-7 kg ha^{-1}) under unfertilized control and 100 % N treatments. It was also observed that the net gain of soil P did not differ significantly among the NPK (11 kg ha^{-1}), NP treatments (11 kg ha^{-1}) and NPK+ Zn (10 kg ha^{-1}) treatments. This result may be attributed to crop yields were at par within these treatments and no significant crop response was observed due to applied K and Zn (7, 13). The build-up of soil available P under super-optimal dose of NPK followed by balanced fertilization with FYM indicated that the P fertilization in these treatments was higher than that of crop requirement. As a result, after crop uptake, the excess P from the applied fertilizer contributed to build up of available P in soils. The strong positive correlation ($R^2 = 0.94$, $p < 0.05$) between apparent P balance and available soil P support the observation (Fig. 2). It was also noted that the suboptimal dose of NPK (50 % NPK) provide an adequate amount of P to meet crop requirements and was higher than crop uptake leading to a build-up available P in soils. This indicates that even with reduced fertilization, the application of 50 % NPK can effectively sustain crop growth and improve soil P availability (7, 25, 26, 28). The decline in soil P under absolute control and alone N treatment, due to exclusion of P fertilizer in fertilization schedule, led to a reduction in soil fertility, which in turn hindered crop productivity.

Long-term fertilization over 25 crop cycles of rice and wheat showed that the available K in the soil decreased in all treatments compared to the initial soil K status (474 kg ha^{-1}), irrespective of the inclusion of K in the fertilization schedule, in a *Vertisol* of sub-tropical India (Fig. 3c). The soil available K was decreased maximum under absolute control treatment (-193 kg ha^{-1}) followed by 100 % NP (-192 kg ha^{-1}) and by 100 % N treatment (-191 kg ha^{-1}) might be attributed to continuous cropping without K fertilization, leads to mining of soil reserves K to meet crop requirements, resulting in a net

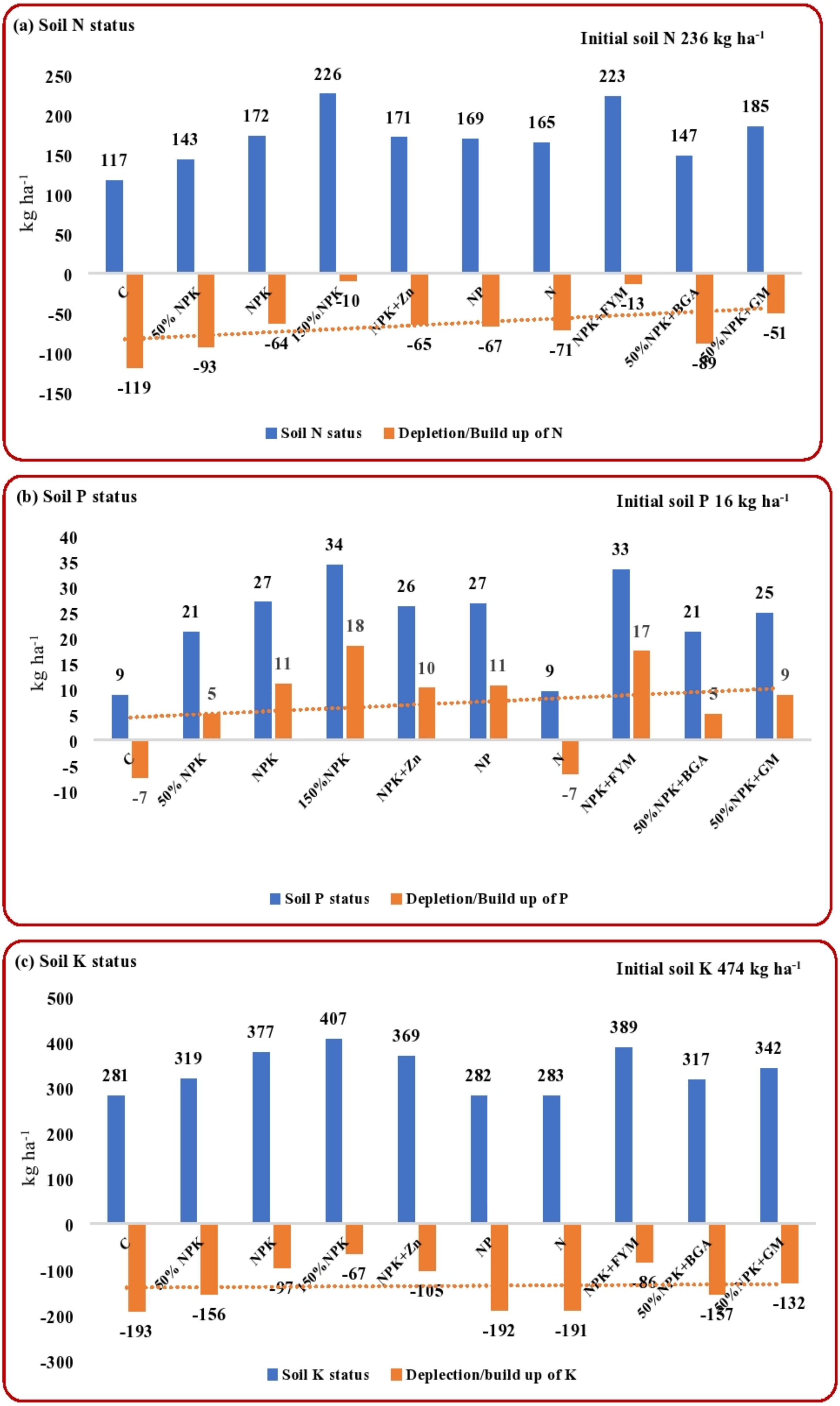

Fig. 3. Impact of long-term fertilizer experiments (1999-2023) on current soil nutrient status. (a) Available N; (b) Available P; (c) Available K and their depletion and build up under rice-wheat cropping systems in a *Vertisol* of sub-tropical India.

Table 6. Potassium budgeting as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol*

Treatments	Applied	Uptake	Apparent balance	Apparent balance rate
	Cumulative of 25 years (1999 to 2023)			
	(kg ha^{-1})			(kg ha^{-1} yr^{-1})
Control	0	2910	-2910	-116
50 % NPK	830	5060	-4230	-169
NPK	1660	6613	-4953	-198
150 % NPK	2490	7806	-5316	-213
NPK+Zn	1660	6741	-5081	-203
NP	0	6417	-6417	-257
N	0	4797	-4797	-192
NPK+FYM	2283	7255	-4972	-199
50 % NPK+BGA	830	5038	-4208	-168
50 % NPK+GM	3527	5994	-2467	-99

The contribution of K through FYM and GM has also been considered

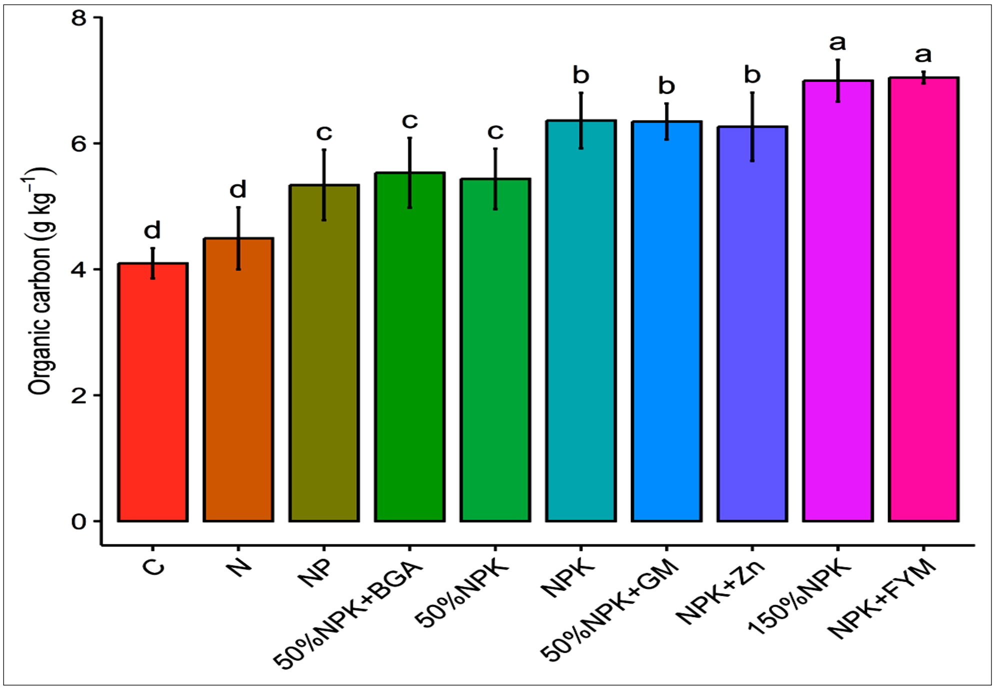

Fig. 4. Impact of long-term fertilizer experiments (1999-2023) on current soil organic carbon (g kg^{-1}) under rice-wheat cropping systems in a *Vertisol* of Sub-tropical India.

loss of K from soil. The depletion of soil available K to the extent of 150 kg ha^{-1} was observed under 50 % NPK, 50 % NPK+BGA and 50 % NPK+GM treatments. The available soil K decreased by nearly 100 kg ha^{-1} under balanced fertilization and with NPK+Zn treatment. Results indicated that in contrast to available P, the sub optimal doses of NPK, even the balanced fertilization unable to fulfil the luxury consumption of K by crops, resulting net negative K balance in soils. There was depletion of available K in soil to the extent of -67 kg ha^{-1} under 150 % NPK followed by -86 kg ha^{-1} under NPK+FYM treatment, revealed that the K removal by crops due to luxury consumption far surpassed its supplementation through super optimal doses of NPK and even by balanced fertilization with 5t ha^{-1} FYM per year. This imbalance led to accelerated mining of reserve K from soil. Results of long-term experiment indicate the importance of including K fertilizer in fertilization schedule to maintain soil reserve K consequently soil fertility and crop productivity (25, 26, 28, 30).

Depletion and build-up of available nutrients

The available N in soil decreased at rates ranging from -0.41 to -4.77 kg ha^{-1} yr^{-1} in different fertilization treatment (Table 7). The rate of depletion was maximum (-4.77 kg ha^{-1} yr^{-1}) under unfertilized control, while minimum reduction was observed under 150 % NPK (-0.41 kg ha^{-1} yr^{-1}) followed by NPK+FYM treatment (-0.53 kg ha^{-1} yr^{-1}). There was buildup of available P in soil varied from 0.20 to 0.73 kg ha^{-1} yr^{-1} by inclusion of P in fertilization schedule (Table 7). The maximum accumulation of available P was observed under 150 % NPK (0.73 kg ha^{-1} yr^{-1}) followed by closely by NPK+FYM (0.69 kg ha^{-1} yr^{-1}). The soil available P decreased with rate of -0.30 kg ha^{-1} yr^{-1} followed by -0.26 kg ha^{-1} yr^{-1}under absolute control and alone N treatment respectively. This decline is attributed to continuous cropping without P fertilization in *Vertisol* of rice-wheat cropping system. In contrast to available P, the available K in soil decreased in all the treatments with the rate of -2.66 to -7.71 kg ha^{-1} yr^{-1} irrespective of presence of K in Fertilization schedule (Table 7). The depletion of available K was recorded maximum under unfertilized control treatment (-7.71 kg ha^{-1} yr^{-1}), while minimum depletion was observed under 150 % NPK (-2.66 kg ha^{-1} yr^{-1}) followed by NPK+FYM treatment (-7.66 kg ha^{-1} yr^{-1}).

Table 7. Nutrient depletion and build-up rate as influenced by long term fertilizer experiments (1999-2023) under rice-wheat cropping systems in a *Vertisol*

Treatment	Nutrient depletion and build up rate ($kg\ ha^{-1}\ yr^{-1}$)		
	N	P	K
Control	-4.77	-0.30	-7.71
50 % NPK	-3.73	0.20	-6.22
NPK	-2.54	0.44	-3.87
150 % NPK	-0.41	0.73	-2.66
NPK+Zn	-2.60	0.40	-4.18
NP	-2.67	0.42	-7.68
N	-2.85	-0.26	-7.66
NPK+FYM	-0.53	0.69	-3.42
50 % NPK+BGA	-3.54	0.20	-6.26
50 % NPK+GM	-2.04	0.35	-5.26

Conclusion

The present study concluded that the soil available N and K decreased from their initial status in all the treatments even under balanced fertilization and INM treatment in *Vertisol* of subtropical India. However, the depletion of available N was negligible under 150 % NPK followed by INM treatments. Similarly, the decrease in soil available K was minimum under 150 % NPK followed by INM treatments. After 25 crop cycles of rice and wheat, the super optimal doses of NPK followed by INM (NPK+FYM) was emerged to be most sustainable practice to sustain the soil N and K status in *Vertisol* of subtropical India. The continuous cropping without NPK fertilization resulted in a negative balance in soils, leading to significant deterioration in soil fertility and reduced crop productivity in long run. The build-up of soil P was recorded to the extent of 5 to 18 kg ha^{-1} by inclusion of P fertilizer in fertilization schedule. The net gain of soil P was also observed under 50 % NPK treatments. Hence, based on soil analysis the accumulated P could be reutilized by curtaining the P dose up to 50 % in RDF or skipping the P application in subsequent *Rabi* crop. It will not only reduce the overuse of fertilizers but also substantially reduce huge amount of government subsidiary money on fertilizers in subtropical region of India. Curtailing excessive P application can mitigate environmental hazards and promoting sustainable agricultural.

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Authors' contributions

UK contributed to the conceptualization, methodology, original draft writing, data curation and formal analysis. VB was involved in conceptualization, methodology, data curation, supervision and writing, review and editing. RHW contributed to visualization, review and editing and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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