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Optimised nutrient management for sustainable rice-wheat cropping systems: A five-year on-farm study in Trans-Gangetic Plains Region, India

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Abstract

The rice-wheat cropping system (RWCS), a cornerstone of food security in the Indo-Gangetic Plains (IGP), faces challenges from nutrient depletion and declining soil health due to intensive cultivation. To address this, a five-year on-farm study (2017–18 to 2021–22) was conducted across 24 farmers' fields in two blocks of Fatehabad district, Haryana, India. The primary objectives were to evaluate the impact of various nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) fertiliser combinations on grain yields, partial factor productivity (PFP), agronomic use efficiency (AUE), sustainable yield index (SYI) and economic viability of the RWCS. Seven fertiliser treatments were implemented as T_1-control (0-0-0), T_2-N alone, T_3-NP, T_4-NK, T_5-NPK, T_6-NPK + Zn and T_7-farmers' fertiliser management practice (FFMP). The highest grain yields were recorded with NPK + Zn treatment for rice (5142 kg ha^{-1}) and wheat (5706 kg ha^{-1}). The combined application of NP significantly enhanced rice grain yield by 105 % and wheat grain yield by 97 % over the control. Partial factor productivity of N increased with the combined application of N and P and with the further inclusion of K and Zn. The AUE of N in rice ranged from 14.76–21.20 kg grain kg^{-1} N, while in wheat it ranged from 15.75–29.83 kg grain kg^{-1} N. The SYI was highest with NPK + Zn (0.90). Economically, NPK + Zn (T_6) yielded the highest gross returns (₹293377 ha^{-1}) and net returns (₹199367 ha^{-1}). This study advocates for integrating macro- and micronutrients to enhance productivity, profitability and soil fertility in the RWCS.

Keywords: economics; fertilisation practices; on-farm experiment; productivity; rice-wheat cropping system

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Introduction

The rice-wheat cropping system (RWCS) is a predominant agricultural practice in the Indo-Gangetic Plains (IGP) and a cornerstone of food security for South Asia (1). This intensive system supports livelihoods but poses increasing sustainability challenges due to its high input demands and environmental impacts. The RWCS depletes 500–900 kg of nitrogen (N) + phosphorus pentoxide (P_2O_5) + potassium oxide (K_2O) ha^{-1} year^{1} and drains significant secondary and micronutrients like zinc (Zn) and sulphur (S) (2). Over decades, this has led to soil degradation, declining factor productivity and reduced responsiveness to fertilisers (3). This cropping system contributes nearly one-third of India's rice and 40 % of its wheat production and over 90 % of global rice is grown and consumed in Asia (1) However, escalating demands for food amid limited arable land and water resources have pushed the RWCS to ecological limits (4). Fertiliser-responsive high-yielding varieties (HYVs) have been widely adopted, yet soil nutrient exhaustion and fertiliser imbalance remain critical problems. Despite applying recommended doses, nutrient imbalances and declining nutrient-use efficiency are evident in RWCS, with a negative balance of N, P and Zn reported across regions (5). Enhancing productivity without increasing ecological footprints demands site-specific nutrient management (SSNM) and integrated nutrient management (INM) strategies that consider both macro and micronutrients (6). In the Trans-Gangetic Plains (TGP) and Upper Gangetic Plains (UGP), irrigation intensity is high, requiring 15–30 irrigations for rice and 3–6 for wheat (7). These nutrient-intensive crops depend heavily on external inputs, yet about 50.8 % of N in fertilised crops still comes from the soil.

Haryana, a key part of the IGP in Agro-Climatic Zone VI, has loamy soils ideal for agriculture but now faces issues of nutrient depletion and soil health decline, especially in high-temperature, sandy loam zones like Fatehabad district. This district features extreme weather patterns, with rainfall concentrated in monsoon months and temperatures ranging from below 0 °C to above 49 °C. A five-year on-farm participatory study (2017–18 to 2021–22) was conducted in two contrasting productivity blocks of Fatehabad-Ratia (high productivity) and Bhattu

(low productivity). A total of 24 farmers were involved to assess crop response to different N, phosphorus (P), potassium (K) and micronutrient management regimes. The participatory research approach ensures relevance, scalability and farmer ownership of innovations (8). Balanced fertilisation, especially when supplemented with micronutrients like Zn has been shown to increase yields, maintain soil health and improve nutrient use efficiency (4, 9). Well-designed fertilisation strategies can help restore the ecological balance of soils, enhance crop productivity and support sustainable intensification of RWCS under agro-ecological constraints.

The application of the recommended dose of fertilisers, supplemented with micronutrients, within an intensive RWCS is not only highly productive and profitable but also ensures stability over time and maintains soil fertility. This is of significant importance in the current context. Consequently, an on-farm experiment employing a farmer's participatory approach was designed to evaluate the response of plant nutrients in the RWCS. The objectives of this study are as follows: (i) to assess the response of major crops to nutrients within predominant cropping systems across different agro-ecosystems and (ii) to evaluate the effect of balanced fertilisation on system productivity, nutrient-use efficiency and economic returns in the RWCS.

Materials and Methods

Data source and study location

The data underpinning this investigation originated from on-farm experiments conducted between the agricultural years 2017–18 and 2021–22. These experiments focused on rice and wheat cultivation within two blocks (Ratia and Bhattu) of the Fatehabad district in Haryana state, India. The experimental framework was established under the auspices of the All India Coordinated Research Project (AICRP) on Integrated Farming Systems (IFS) On-Farm Research (OFR), coordinated by the Indian Council of Agricultural Research (ICAR)-Indian Institute of Farming Systems Research, Modipuram, Uttar Pradesh, India. Fatehabad, situated in the TGP, is characterised by a prevalent RWCS. The weather pattern shown in Fig. 1 reflects clear seasonal variation across the study period. Most of the rainfall occurred during the monsoon months, with the highest amount recorded in July (around 150 mm), followed by September (110 mm) and August (80 mm). In contrast, rainfall was very low from November to May, indicating dry conditions for a major part of the year. Temperature gradually increased from winter to summer, with maximum temperature rising from nearly 20 °C in January to about 42 °C during May–June and then declining afterwards. Minimum temperature also followed a similar trend, remaining low during winter (around 10 °C) and increasing to about 25–28 °C in summer. Relative humidity was higher during the rainy season (about 60–70 %) and dropped considerably during summer months, especially in April and May (around 30–40 %). These conditions indicate that the rice crops grown during the kharif season received sufficient rainfall and favourable humidity, whereas the wheat crop in the rabi season largely depended on irrigation due to limited rainfall. The hot and dry conditions before the monsoon may also have affected crop growth and nutrient availability, thereby influencing the response to different nutrient management practices.

Experimental design and treatments

The study strategically selected locations within the Ratia and Bhattu blocks to encompass variations in soil characteristics, prevailing climatic conditions and existing fertiliser application practices employed by local farmers. Experiments were carried out across these diverse productivity levels of the RWCS from 2017–18 to 2021–22. A total of 24 farmers' fields were chosen for evaluation, with four fields selected from each of six villages: Aharwan, Hamjapur and Bharpur in the high-productivity Ratia block and Banmandori, Pilimanmandori and Thuia in the low-productivity Bhattu block.

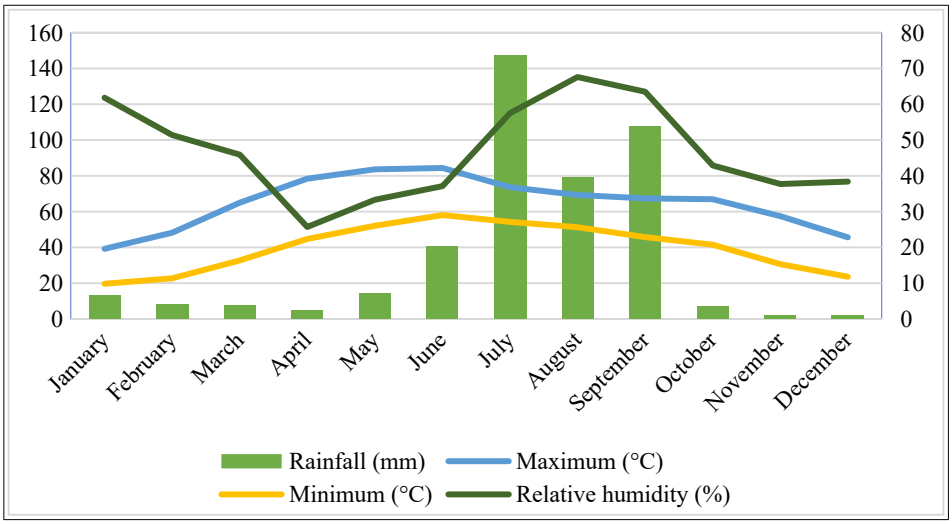

Fig. 1. Average weather data during 2017–18 to 2021–22.

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Within each selected farmer's field, seven fixed plots, each measuring 100 m², were demarcated. These plots were utilised to evaluate a set of seven distinct fertiliser treatments applied to both the rice and subsequent wheat crops. The fertiliser treatments comprised: T_1) control (no fertiliser application); T_2) N alone (150 kg N ha^{-1} for rice and wheat); T_3) NP (150 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} for rice and wheat); T_4) NK (150 kg N ha^{-1} + 60 kg K_2O ha^{-1} for rice, 150 kg N ha^{-1} + 30 kg K_2O ha^{-1} for wheat); T_5) NPK (150 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} + 60 kg K_2O ha^{-1} for rice, 150 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} + 30 kg K_2O ha^{-1} for wheat); T_6) NPK + Zn (150 kg N ha^{-1} + 60 kg P_2O_5 ha^{-1} + 60 kg K_2O ha^{-1} + 5.25 kg Zn ha^{-1} for rice and wheat) and T_7) farmers' fertiliser management practices (FFMP) (160 kg N ha^{-1} + 45 kg P_2O_5 ha^{-1} + 0 kg K_2O ha^{-1} for rice, 155 kg N ha^{-1} + 40 kg P_2O_5 ha^{-1} + 0 kg K_2O ha^{-1} for wheat).

Fertiliser application and crop management

The recommended rates of NPK and Zn were applied according to the treatment specifications for both rice and wheat crops, except for the absolute control (T_1) where no nutrients were applied. The fertilisers used were diammonium phosphate (DAP) containing 16 % P_2O_5, muriate of potash (MOP) containing 60 % K_2O and Zn was applied through zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$, 21 % Zn) at a rate equivalent to 25 kg $ZnSO_4$ ha^{-1} (5.25 kg Zn ha^{-1}). In the rice crop, the full doses of P, K and Zn, along with half of the N dose, were applied as basal during transplanting. The remaining half of the N was applied at the panicle initiation stage. For the subsequent wheat crop, the full doses of P, K and Zn, along with one-third of the N dose, were applied as basal at the time of sowing. The remaining N was applied in two equal splits at the crown root initiation (CRI) stage and at anthesis. Apart from the imposed fertiliser treatments, the participating farmers managed their respective fields using their customary cultural practices and available resources for both rice and wheat cultivation. The rice variety PB-1121 and the wheat variety WH-1105 were consistently used across all experimental plots.

Soil analysis

Before the start of on-farm trials in kharif, 2017, soil samples were collected from the plough layer (0–15 cm) at ten random points in each of the 24 farmer fields. Composite samples were homogenised, sieved (100 mm mesh) and subsampled for analysis. Organic carbon (OC) was estimated by the Walkley and Black method (10), available N by the alkaline potassium permanganate ($KMnO_4$) method (11), available P using 0.5 M sodium bicarbonate ($NaHCO_3$) (pH 8.5) (12) and available K with 1 M ammonium acetate (NH_4OAc) (pH 7.0) (13).

Yield and assessment

Grain and straw yields of rice and wheat were recorded at harvest from each treatment plot and expressed in kilograms per hectare (kg ha^{-1}). Rice equivalent yield (REY) was used to assess system productivity, allowing direct comparison of total productivity across treatments based on the economic value of crops. Rice equivalent yield was calculated using the following formula:

$$REY = Yrb + (Yw \times Pw / Pr)$$

Where,

Yr = rice grain yield (kg ha^{-1}),

Yw = wheat grain yield (kg ha^{-1}),

Pw = minimum support price (MSP) of wheat ₹ kg^{-1}),

Pr = MSP of rice (₹ kg^{-1}).

This approach standardises yields across the RWCS by converting wheat yield into rice equivalents based on prevailing market prices.

Partial factor productivity analysis

Partial factor productivity (PFP) of N, P and K was calculated to assess nutrient use efficiency under different fertiliser regimes in the RWCS. Partial factor productivity is defined as the ratio of crop grain yield to the amount of nutrient applied and was calculated separately for each nutrient using the following formula:

$$PFPX = Y / Fx$$

Where,

PFPX = partial factor productivity of nutrient x (kg grain per kg nutrient applied),

Y = grain yield (kg ha^{-1})

F = quantity of nutrient x (N, P, or K) applied (kg ha^{-1})

Partial factor productivity was computed for both rice and wheat crops for each nutrient where applicable. Treatments without a specific nutrient input were excluded from PFP calculations for that nutrient. The PFP values provided insights into the efficiency of nutrient use and the potential synergistic effects of balanced fertilisation, including secondary nutrient (Zn) addition and the FFMP.

Agronomic use efficiency

Agronomic use efficiency (AUE) was calculated to assess the effectiveness of applied NPK in increasing crop yield in the RWCS. Agronomic use efficiency was expressed as the additional grain yield obtained per unit of nutrient applied and calculated separately for each nutrient and crop using the following formula:

$$AUEx = Yt - Y_0/F_x$$

Where,

AUE_x = agronomic use efficiency of nutrient x (kg grain increases per kg nutrient applied),

Y_t = grain yield in the fertilised treatment (kg ha^{-1}),

Y_0 = grain yield in the control (T_1) treatment (kg ha^{-1}),

F_x= amount of nutrient x applied (kg ha^{-1})

Agronomic use efficiency was calculated for N, P and K wherever the respective nutrient was applied. Treatments that did not include a specific nutrient were excluded from the AUE calculation for that nutrient. This analysis provided insight into the yield response per unit of nutrient input, highlighting the benefits of balanced

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and INM, including secondary nutrient (Zn) addition and farmers' fertiliser practices.

Sustainable yield index

Sustainable yield index (SYI) was calculated to assess the stability of system productivity over the study period. It was computed using the following formula:

$$SYI = (\bar{Y} - SD) / Y$$

Where, $\bar{Y}$ is the mean yield over the five years (2017–18 to 2021–22), SD is the standard deviation of yield and Y_{max} is the maximum yield recorded during the study period.

Sustainable yield index was calculated based on system productivity expressed as REY to allow comparison across treatments in the RWCS.

Economic analysis

The economic performance of the RWCS under different fertiliser treatments was evaluated by calculating gross returns, cost of cultivation, net returns and benefit-cost (B : C) ratio based on pooled data from 2017–18 to 2021–22. Gross returns (₹ ha^{-1}) were calculated by multiplying the grain yield of rice and wheat by their respective MSP for each year.

Cost of cultivation (₹ ha^{-1})) included all variable and fixed inputs such as seeds, fertilisers, labour, irrigation, plant protection and machinery use, based on prevailing local rates.

Net returns (₹ ha^{-1}) were computed as follows:

Net returns = gross returns - cost of cultivation

B : C ratio was calculated as follows:

B : C ratio = Gross returns / cost of cultivation

Gross returns were worked out using the grain yield of rice and wheat with reference to the MSP applicable during the study period (2017–18 to 2021–22). The calculations were based on the prices of the respective years and no correction for inflation was made. The cost of cultivation covered all expenses on inputs such as fertilisers (including Zn where applied), labour, irrigation and other field operations followed by farmers. Net returns were obtained by deducting the cost of cultivation from gross returns and the B : C ratio was calculated accordingly. The economic evaluation considered grain yield only, while the value of straw was not considered. This economic evaluation provided insight into the profitability and economic efficiency of integrated and balanced nutrient management practices compared to the control and farmers' practice.

Statistical analysis

The study followed a randomised block design (RBD), with individual farmer fields serving as replications within each location. Descriptive statistics were calculated to assess variability in measured parameters within and across locations, using the standard error of the mean. Treatment effects on crop yield and soil parameters were analysed through analysis of variance (ANOVA) using SAS software (version 11.0). Fisher's *F*-test was applied at a significance level of $p \leq 0.05$ to determine differences among treatments and locations. Where significant treatment × location interactions were detected, mean comparisons were performed using the least significant difference (LSD) test at the 5 % level. In addition, stepwise multiple regression analysis was employed to identify the most influential soil variables (N, P, K and OC) affecting crop yield under zero external input conditions.

The experiment was arranged in a RBD, where each farmer's field was taken as a replication. In every field, seven plots of 100 m^2 were prepared and observations were recorded from these plots, which served as the experimental units. The study was conducted for five years (2017–18 to 2021–22). Data from all years were combined and analysed together to obtain overall treatment effects. The trials were carried out in six villages under two blocks, Ratia and Bhattu, representing different productivity conditions. These location differences were not considered separately in the statistical analysis. Variation among farmer fields was considered by treating each field as an independent replication. The data were analysed using ANOVA in SAS (version 11.0). Differences among treatment means were tested using the LSD at the 5 % level of significance. Coefficient of variation (CV) was calculated to assess the variability in yield data across replications. No data transformation or outlier removal was performed, as the observed variation represents actual field conditions.

Results

Grain yield of both rice and wheat was found to be increased with the application of nutrients over the control (T_1). The highest grain yield of both crops was recorded with balanced fertilisation of NPK along with Zn (T_6: rice 5142 kg ha^{-1}, wheat 5706 kg ha^{-1}). Averaged grain yield showed that the application of N alone (T_2: rice 4176 kg ha^{-1}, wheat 3594 kg ha^{-1}) recorded ~55 % higher rice grain yield and 50 % higher wheat grain yield over the control (T_1: rice 1962 kg ha^{-1}, wheat 1231 kg ha^{-1}). Application of N and P (T_3: rice 4450 kg ha^{-1}, wheat 4798 kg ha^{-1}) also exerted a significant effect on the grain yield of both crops, improved the rice grain yield by 105 % and wheat grain yield by 97 % over the control, on average. Combined application of N with K (T_4: rice 4266 kg ha^{-1}, wheat 4567 kg ha^{-1}) followed similar yield pattern over the control; however, yield improvement could not keep pace with the combined application of N and P. The application of N with K increased the grain yield of rice and wheat by 80 and 73 % over the control respectively, on average. Similarly, the average yield advantage due to the combined application of NPK (T_5: rice 4711 kg ha^{-1}, wheat 5144 kg ha^{-1}) was 142 % in rice and 137 % in wheat over the control. Application of NPK with Zn (T_6: rice 5142 kg ha^{-1}, wheat 5706 kg ha^{-1}) over-yielded by about 160 % in rice and 152 % in wheat compared to the control. Farmers' practice (T_7: rice 4650 kg ha^{-1}, wheat 5087 kg ha^{-1}) also showed substantial yield improvements over the control. The higher variability observed in yield data is attributed to

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differences in soil properties and management practices across farmer fields under on-farm conditions.

The REY of the RWCS was significantly influenced by different fertiliser treatments (Table 1). The lowest REY (3241 kg ha^{-1}) was recorded under the control treatment (T_1). Application of N alone (T_2) significantly increased REY to 7909 kg ha^{-1}, showing a 144 % improvement over the control. When P was added along with N (T_3), the REY further increased to 9433 kg ha^{-1}, which is a 191 % increase over the control, highlighting the synergistic effect of N and P on REY. Application of N and K (T_4) resulted in a REY of 9009 kg ha^{-1}, showing a 178 % increase over the control. The highest REY was recorded under the NPK + Zn treatment (T_6), with a value of 11069 kg ha^{-1}, reflecting a 242 % increase over the control and confirming the beneficial effect of micronutrient (Zn) supplementation in enhancing productivity. The farmers' practice (T_7) yielded 9933 kg ha^{-1}, which was 206 % higher than the control, but still lower than the NPK + Zn treatment, indicating potential for further improvement with balanced fertilisation.

Yield gap between different nutrient management practices for rice and wheat

The study quantified the yield gaps observed between different nutrient management practices for both rice and wheat, as presented in Table 2, application of recommended fertiliser (RF) significantly increased grain yield compared to the unfertilised control. For rice, this yield gap amounted to 2754 kg ha^{-1}. For wheat, the yield gap was 3850 kg ha^{-1}, indicating a substantial positive response to RF in both crops, with wheat showing a larger absolute gain. The addition of $ZnSO_4$ to the FFMP further enhanced yields over RF alone. This led to an additional yield gain of 411 kg ha^{-1}for rice. In wheat, the increment in yield with FFMP + $ZnSO_4$ over RF was 551 kg ha^{-1}. A comparison between the RF practice and the FFMP revealed a yield gap of 182 kg ha^{-1} for rice, with RF producing higher yields. In contrast, for wheat, the yield gap between RF and FFMP was minimal, at only 14 kg ha^{-1}, suggesting that the farmer's current practices for wheat were very close to the RF application in terms of yield outcome. The most comprehensive nutrient management practice, FFMP + $ZnSO_4$ exhibited considerable yield advantages. For rice, the yield gap between FFMP + $ZnSO_4$ and farmer's practice (FP) was 592 kg ha^{-1}. For wheat, a similar trend was observed, with a yield gap of 566 kg ha^{-1}between FFMP + $ZnSO_4$ and FP. These findings indicate that integrating Zn into the RF regime offers substantial potential for increasing grain yields beyond current farmer practices in both crops.

Table 1. Influence of treatments on grain yield (kg ha^{-1}) and system productivity (kg ha^{-1}) of rice and wheat during the period 2017–18 to 2021–22 (mean values)

Crop/Treatment	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		Rice equivalent yield (kg ha^{-1})
	Rice	Wheat	Rice	Wheat	
T_1 (Control)	1962	1231	2625	1386	3241
T_2 (N)	4176	3594	5426	3790	7909
T_3 (N + P_2O_5)	4450	4798	5762	5024	9433
T_4 (N + K_2O)	4266	4567	5521	4763	9009
T_5 (N + P_2O_5 + K_2O)	4711	5144	6095	5390	10054
T_6 (N + P_2O_5 + K_2O + Zn)	5142	5706	6556	5965	11069
T_7 (fertiliser best management practices)	4650	5087	6093	5322	9933
SEm (±)	137.1	182.3	255.4	206.7	331.09
CD (p = 0.05)	427.6	571.4	789.4	665.6	1021.41
CV (%)	15.5	20.7	23.0	21.1	18.4

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc.

Table 2. Mean yield (kg ha^{-1}) gap between different nutrient management practices of rice-wheat cropping system under farmer nutrient managed condition (mean data for the period 2017–18 to 2021–22)

Crop	Yield gap between different nutrient management practices			
	Yield gap (kg ha^{-1})			
	Yield gap-1	Yield gap-2	Yield gap-3	Yield gap-4
	RF vs control	FFMP + $ZnSO_4$ vs RF	RF vs FFMP	FFMP + $ZnSO_4$ vs FP
Rice	2754	411	182	592
Wheat	3850	551	14	566

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RF: recommended fertiliser; FFMP: farmers' fertiliser management practices; $ZnSO_4$: zinc sulphate; FP: farmer's practice.

Partial factor productivity of nitrogen, phosphorus and potassium in rice-wheat cropping system under varied fertiliser regimes

The analysis presents the PFP of N under different fertiliser treatments in rice and wheat (Table 3). Under N alone (T_2), PFP_n was 27.84 and 23.96 kg grain kg^{-1} N in rice and wheat respectively. The addition of P (T_3) increased PFP_n to 29.67 and 31.99 kg grain kg^{-1} N, indicating increment of 6.6 and 33.5 %, while K application (T_4) improved it to 28.44 and 30.45 kg grain kg^{-1} N. The inclusion of Zn with NPK (T_6) further enhanced PFP_n to 34.28 and 38.04 kg grain kg^{-1} N, showing the highest increment of 23.1 and 58.8 %. Under FFMP; T_7, PFP_n was 29.06 and 32.82 kg grain kg^{-1} N in rice and wheat respectively.

The combined application of P with N (T_3) resulted in a PFP_p of 74.17 and 123.03 kg grain kg^{-1} P in rice and wheat respectively. The addition of K along with N and P (T_5) further improved PFP_p to 78.52 kg grain kg^{-1} P in rice and 131.90 kg grain kg^{-1} P in wheat, representing increases of 5.9 and 7.2 % over NP application. A greater enhancement was observed with the inclusion of Zn along with NPK (T_6), where PFP_p increased to 85.70 and 146.31 kg grain kg^{-1} P in rice and wheat, reflecting gains of 9.1 and 10.9 % over NPK. Under FFMP (T_7), PFP_p was 103.33 kg grain kg^{-1} P in rice and 127.18 kg grain kg^{-1} P in wheat.

The PFPk for applied K with N (T_4) was 71.10 kg grain kg^{-1}K in rice and 152.23 kg grain kg^{-1}K in wheat. The combined application of NP and K (T_5) generally increased PFPk. For rice, PFPk was 78.52 kg grain kg^{-1}K, an approximate 10.4 % increase over K with N. For wheat, PFPk reached 171.47 kg grain kg^{-1}K, an approximate 12.6 % increase over K with N. The inclusion of Zn (T_6) with NPK also influenced PFPk. For rice, PFPk was 85.70 kg grain kg^{-1}K, an approximate 9.1 % increase over K with NPK. For wheat, PFPk was 190.20 kg grain kg^{-1} K, an approximate 10.9 % increase over K with NPK.

Agronomic use efficiency of nitrogen, phosphorus and potassium in rice-wheat cropping system

The AUE of NPK for rice-wheat varied across different fertiliser treatments (Table 4). In rice, the AUE of N ranged from 14.76 kg grain kg^{-1} N in the N only treatment (T_2) to 21.20 kg^{-1}N in the treatment combining N, P, K and Zn (T_6). Wheat showed a similar trend, with AUEn increasing from 15.75 kg grain kg^{-1} N (T_2) to 29.83 kg grain kg^{-1} N under T_6. Fertiliser best management practices (T_7) resulted in intermediate efficiencies of 16.80 for rice and 24.88 for wheat. These results highlight the positive effect of balanced nutrient application and micronutrient supplementation on nitrogen use efficiency (NUE) in both crops.

Agronomic use efficiency of P was higher in rice compared to wheat across treatments involving P application. In rice, AUEp ranged from 41.47 kg grain kg^{-1}P in the N + P treatment (T_3) to 59.73 kg grain kg^{-1}P in the FP (T_7). Wheat showed an increase in AUEp from 59.45 kg grain kg^{-1}P in T_3 to 74.58 kg grain kg^{-1}P in both T_6 and T_7 treatments. This indicates that P uptake and utilisation are enhanced with INM and real-world farmer practices.

Agronomic use efficiency of K was observed only in treatments where K was applied (T_4, T_5 and T_6). In rice, AUEk ranged from 38.40 kg grain kg^{-1}K in the N + K treatment (T_4) to 53.00 kg grain kg^{-1}K in the N + P + K + Zn treatment (T_6). In wheat, potassium use efficiency (KUE) was markedly higher, ranging from 111.20 kg grain kg^{-1}K (T_4) to 149.17 kg grain kg^{-1}K (T_6).

Sustainable yield index

The SYI was calculated based on five-year pooled data using REY as an indicator of system productivity (Table 5). Sustainable yield index varied significantly ($p < 0.05$) among the nutrient management treatments under the RWCS (Table 5). Among all treatments, T_6 (N + P_2O_5 + K_2O + Zn) recorded the highest SYI of 0.90, indicating its superior sustainability and productivity. This was followed by T_5 (0.83) and T_7 (fertiliser best management practice, 0.82), showing their effectiveness in maintaining stable yields. The lowest SYI (0.1) was observed under T_1 (control), which was significantly lower by 28.1 % and 71.0 % compared to T_3 (0.769) and T_6 (0.900) respectively. Compared to T_6, the SYI in T_1 was significantly reduced by approximately 79.0 %, highlighting the impact of unbalanced nutrient application. Treatments receiving partial or unbalanced fertilisation such as T_2 (0.61) and T_4 (0.74) showed intermediate SYI values, indicating that N alone or in combination with K_2O was not sufficient to achieve high yield stability.

Table 3. Partial factor productivity of nitrogen, phosphorus and potassium (kg grain per kg nutrient applied) of rice and wheat in rice-wheat cropping system (mean data for the period 2017–18 to 2021–22)

Treatment	PFP-N (kg grain kg^{-1} N)		PFP-P (kg grain kg^{-1} P)		PFP-K (kg grain kg^{-1} K)	
	Rice	Wheat	Rice	Wheat	Rice	Wheat
T_1 (Control)	-	-	-	-	-	-
T_2 (N)	27.84	23.96	-	-	-	-
T_3 (N + P_2O_5)	29.67	31.99	74.17	123.03	-	-
T_4 (N + K_2O)	28.44	30.45	-	-	71.10	152.23
T_5 (N + P_2O_5 + K_2O)	31.41	34.29	78.52	131.90	78.52	171.47
T_6 (N + P_2O_5 + K_2O + Zn)	34.28	38.04	85.70	146.31	85.70	190.20

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T_7 (fertiliser best management practices)	29.06	32.82	103.33	127.18	-	-

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc; PFP: partial factor productivity.

Table 4. Agronomic use efficiency of nitrogen, phosphorus and potassium for rice and wheat under different fertiliser treatments (mean data for the period 2017–18 to 2021–22)

Treatment	AUE of N (kg increased grain yield per kg N applied		AUE of P (kg increased grain yield per kg P applied		AUE of K (kg increased grain yield per kg applied	
	Rice	Wheat	Rice	Wheat	Rice	Wheat
T_1 (Control)	-	-	-	-	-	-
T_2 (N)	14.76	15.75	-	-	-	-
T_3 (N + P_2O_5)	16.59	23.78	41.47	59.45	-	-
T_4 (N + K_2O)	15.36	22.24	-	-	38.40	111.20
T_5 (N + P_2O_5 + K_2O)	18.33	26.09	45.82	65.22	45.82	130.43
T_6 (N + P_2O_5 + K_2O + Zn)	21.20	29.83	53.00	74.58	53.00	149.17
T_7 (fertiliser best management practices)	16.80	24.88	59.73	74.58	-	-

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc; AUE: agronomic use efficiency.

Table 5. Sustainable yield index of rice and wheat under different fertiliser treatments (mean data for the period 2017–18 to 2021–22)

Treatment	Mean yield (kg ha^{-1})	Standard deviation	Sustainable yield index
T_1 (Control)	1597	516	0.19
T_2 (N)	3885	411	0.61
T_3 (N + P_2O_5)	4624	248	0.70
T_4 (N + K_2O)	4417	213	0.72
T_5 (N + P_2O_5 + K_2O)	4928	217	0.83
T_6 (N + P_2O_5 + K_2O + Zn)	5424	282	0.90
T_7 (fertiliser best management practices)	4869	219	0.82

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc.

Economic analysis of fertiliser treatments in rice-wheat cropping system

The five years' average MSP was ₹17.85 Kg^{-1} for rice grains and ₹18.20 Kg^{-1} for wheat grain while the corresponding five-year average prices of rice straw and wheat straw were ₹1.0 kg^{-1} and ₹1.5 kg^{-1} respectively.

Economic evaluation of different nutrient management treatments showed clear variation in returns and profitability (Table 6). The lowest gross return was observed under the control (T_1) with ₹62130 ha^{-1}, while the highest was recorded in T_6 (NPK + Zn) with ₹211138 ha^{-1}. A similar trend was noted for net returns. The control treatment gave a marginal net return of ₹3215 ha^{-1}, whereas T_6 resulted in the highest net return of ₹117128 ha^{-1}. Treatments receiving balanced fertilisation (T_5 and T_6) and farmers' practice (T_7) also showed higher net returns compared to other treatments. The B : C ratio followed the same pattern. The lowest B : C ratio was recorded under control (1.05), indicating very low profitability. Among the treatments, T_6 recorded the highest B : C ratio (2.25), followed by T_7 (2.15), T_5 (2.08) and T_3 (2.06). Treatments with single or partial nutrient application (T_2 and T_4) showed comparatively lower returns than balanced fertilisation. Overall, mean data indicated that cost of cultivation, gross returns, net returns and B : C ratio was consistently higher with the balanced application of N, P, K along with Zn (T_6) over all other nutrient management practices, including the fertiliser best management practice (T_7). The results support the economic viability of INM in enhancing system profitability.

Changes in soil organic carbon and nutrient availability after five years of differential fertilisation under rice-wheat system

The composite soil sample (0–15 cm) collected prior to initiation of the long-term experiment from 24 farmers' fields in Fatehabad district revealed that the soils were alkaline in reaction (pH 8.2) and non-saline (electrical conductivity (EC) 0.52 dS m^{-1}) (Table 7). The OC content was low (0.33 %), as were the levels of available N (145 kg ha^{-1}) and available P (8.5 grain kg^{-1}).

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Available K was rated as medium (185 kg ha^{-1}), while the available Zn concentration was deficient at 0.35 mg kg^{-1}. The soil texture was sandy loam, representative of the region's coarse-textured alluvial soils. This initial characterisation highlighted multiple nutrient deficiencies (particularly N, P and Zn) and provided the basis for formulating the differential fertiliser treatments.

Table 6. Mean economics of rice-wheat cropping systems during 2017–18 to 2021–22

Treatment	Gross return (₹ ha^{-1})	Cost (₹ ha^{-1})	Net return (₹ ha^{-1})	B : C ratio
T_1 (Control)	62130	58915	3215	1.05
T_2 (N)	151063	80458	70605	1.88
T_3 (N + P_2O_5)	180054	87514	92540	2.06
T_4 (N + K_2O)	171933	84188	87745	2.04
T_5 (N + P_2O_5 + K_2O)	191892	92084	99,808	2.08
T_6 (N + P_2O_5 + K_2O + Zn)	211138	94010	117128	2.25
T_7 (fertiliser best management practices)	189668	88234	101434	2.15

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc; B : C ratio: benefit-cost ratio.

Table 7. Initial composite soil fertility status before initiation of long-term fertiliser treatments in the rice-wheat cropping system (0–15 cm soil depth)

Soil property	Unit	Value	Category
pH	-	8.2	Alkaline
Electrical conductivity (EC)	dS m^{-1}	0.52	Non-saline
Organic carbon (OC)	%	0.33	Low
Available nitrogen (N)	Kg ha^{-1}	145	Low
Available phosphorus (P_2O_5)	Kg ha^{-1}	8.5	Low
Available potassium (K_2O)	Kg ha^{-1}	185	Medium
Available zinc (Zn)	Mg kg^{-1}	0.35	Deficient

Five years of continuous application of different fertiliser treatments under the RWCS brought noticeable changes in soil fertility parameters (Table 8). The control (T_1) recorded comparatively lower OC (0.30 %), available N (130 kg ha^{-1}) and available P (7.5 kg ha^{-1}), indicating nutrient depletion in the absence of fertiliser application. Application of N alone (T_2) increased the available N content to 152 kg ha^{-1}, while the other soil properties showed only slight variation. Treatments receiving P (T_3 and T_5) showed higher available P levels (12.8 and 13.5 kg ha^{-1} respectively), suggesting the contribution of continuous P application. In a similar way, K applied treatments showed higher available K, with values of 210 kg ha^{-1} in T_4 (NK) and 215 kg ha^{-1} in T_5 (NPK). The highest Zn content in soil (0.62 mg kg^{-1}) was observed under T_6 (NPK + Zn), reflecting the direct addition of Zn. Organic carbon content was also comparatively higher in fertilised plots than in control, with the highest value in T_6 (0.36 %), followed by T_5 (0.35 %) and T_7 (0.34 %). Soil pH remained almost unchanged across treatments, varying between 8.0 and 8.2. Electrical conductivity ranged from 0.48–0.55 dS m^{-1}, indicating that fertiliser application did not lead to any salinity problem. Overall, the results indicate that balanced nutrient application, especially NPK along with Zn, helps in maintaining and improving soil fertility under the RWCS.

Table 8. Changes in soil fertility parameters after five years of differential fertiliser application under a rice-wheat cropping system (0–15 cm soil depth)

Treatment	OC (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})	Available Zn (mg kg^{-1})	Soil pH	EC (dS m^{-1})
T_1 (Control)	0.30	130	7.5	178	0.32	8.2	0.48
T_2 (N)	0.31	152	7.2	175	0.34	8.1	0.50
T_3 (N + P_2O_5)	0.33	158	12.8	176	0.36	8.1	0.52
T_4 (N + K_2O)	0.32	154	7.0	210	0.34	8.1	0.51
T_5 (N + P_2O_5 + K_2O)	0.35	160	13.5	215	0.37	8.0	0.54

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T_6 (N + P_2O_5 + K_2O + Zn)	0.36	162	13.2	212	0.62	8.0	0.55
T_7 (fertiliser best management practices)	0.34	155	10.4	174	0.35	8.1	0.52
SEm (±)	0.006	4.5	0.8	6.2	0.03	0.04	0.01
CD (p = 0.05)	0.018	13.2	2.3	18.1	0.09	0.11	0.03

N: nitrogen; P_2O_5: phosphorus pentoxide; K_2O: potassium oxide; Zn: zinc; OC: organic carbon; EC: electrical conductivity.

Discussion

The results of this study clearly demonstrate the positive impact of nutrient application on the grain yield of both rice and wheat, corroborating findings from numerous studies highlighting the essential role of balanced fertilisation in enhancing crop productivity (14). The consistent superiority of the NPK + Zn treatment (T_6) in achieving the highest grain yields for both crops underscores the critical importance of not only macronutrients but also micronutrients like Zn in optimising plant growth and yield potential in intensive cropping systems. The superior performance under combined application of NPK and Zn may be explained by the interaction between Zn and N within the plant system. Zinc is involved in enzyme activation, protein synthesis and regulation of growth processes, which enhances NUE. At the same time, adequate N availability supports better uptake and internal movement of Zn. This interaction results in improved plant growth, higher biomass production and increased yield under balanced nutrient application, as also supported by previous findings (15). The substantial yield improvements observed with the application of N alone (T_2) compared to the control highlight the primary limitation imposed by N deficiency in these cropping systems. Nitrogen is a key component of essential plant structures and metabolic processes and its application invariably leads to significant biomass accumulation and yield enhancement (16). However, the fact that more balanced nutrient regimes (T_3, T_4, T_5, T_6 and T_7) consistently outperformed the sole application of N emphasises the synergistic effects of multiple nutrients in maximising yield potential. The comparable performance of the fertiliser best management practice (T_7) with the NPK treatment (T_5) suggests that local farmers are often utilising a relatively balanced nutrient application strategy, likely based on experience and available resources. However, the further significant yield increase observed with the inclusion of Zn in T_6 indicates that even well-established farmers' practices may benefit from the incorporation of micronutrient management based on soil testing and specific crop needs (17). The variability in yield response across different nutrient treatments underscores the complexity of nutrient interactions and the need for SSNM strategies. While the average data provides a general overview, understanding the location-specific responses, as indicated in the initial data (though not explicitly detailed in the final results), is crucial for developing tailored recommendations that optimise resource use efficiency and minimise environmental impacts (18). Future research should focus on delineating the specific soil characteristics and agro-climatic factors that contribute to the differential responses observed under various nutrient management regimes across different locations within the rice-wheat cropping zone. This will enable the development of more precise and sustainable nutrient management practices for enhanced productivity and soil health in the region (19).

The data clearly demonstrate that balanced nutrient management significantly improves PFP of NPK in the RWCS. The lowest PFP values under N-alone treatment align with recent studies emphasising that sole application of N limits crops nutrient use efficiency and yield potential (7, 9). The synergistic effect of applying P and K with N (T_5) substantially enhanced PFP-N by 12.8 % in rice and 43.1 % in wheat compared to N alone, confirming findings from recent research which highlight that balanced NPK fertilisation optimises nutrient uptake and utilisation, leading to better yield outcomes (20, 21). The higher PFP of P observed under farmers' practice in rice may be due to comparatively lower P application. Since PFP is expressed as yield per unit of nutrient applied, lower input levels tend to result in higher apparent efficiency. However, this does not necessarily indicate improved nutrient management, as reduced P application may limit yield potential and lead to depletion of soil P over time. Similar observations have been reported under low P input conditions. This is consistent with evidence that nutrients interact in soil-plant systems and that imbalanced nutrient supply can reduce the efficiency of applied fertilisers (22). The further increase in PFP values with the inclusion of Zn (T_6) underscores the vital role of micronutrients in enhancing nutrient use efficiency (23, 24). Recent studies also show that Zn application in rice-wheat systems improves crop resilience and nutrient use efficiency under varying agro ecological conditions (25). Regarding PFP-P and PFP-K, the improved values in treatments combining NPK and Zn corroborate recent findings that emphasise the importance of INM for optimising macronutrient use and sustaining soil fertility (26, 27). Balanced application not only enhances nutrient uptake but also reduces nutrient losses to the environment, supporting sustainable intensification goals (28). Overall, these findings align with the growing consensus in recent literature that INM involves balanced macro- and micronutrient application is essential to maximise nutrient use efficiency, enhance crop productivity and ensure sustainable RWCS (20, 23).

The AUE of N, P and K showed marked improvements with balanced fertilisation and micronutrient supplementation in the RWCS. The increase in AUE-N from N-alone treatment (T_2) to combined NPK + Zn (T_6) treatments for both rice and wheat indicate a synergistic effect of multi-nutrient

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application, enhancing N utilisation efficiency. This finding is consistent with earlier studies (7, 23), which reported that INM including micronutrients improves N uptake and crop productivity. Phosphorus use efficiency was notably higher in rice compared to wheat, with INM and farmer practices enhancing P uptake and utilisation. Balanced application of P with other nutrients optimises P availability and minimises fixation, improving its agronomic efficiency in cereal crops (20, 21). Potassium use efficiency was substantially higher in wheat than rice, showed that micronutrients like Zn enhance root development and enzymatic activities facilitating K uptake (24, 26). The pronounced response of wheat to K fertilisation suggests crop-specific nutrient dynamics that must be considered for efficient fertilisation strategies. Wheat exhibited a comparatively stronger response to K application than rice. This may be attributed to its higher requirement of K during the grain filling stage, where K plays a key role in assimilating translocation and maintenance of plant water balance. In the RWCS, a substantial portion of available K is removed by the preceding rice crop, resulting in reduced availability for wheat. Under such conditions, the response to applied K becomes more pronounced in wheat, as also observed in earlier studies. Overall, these results underscore the importance of balanced nutrient management, including macronutrients and micronutrients, to maximise fertiliser use efficiency, improve yields and support sustainable rice-wheat systems (27, 28).

The SYI differed significantly across nutrient treatments, with the highest value (0.90) under T_6 (N + P_2O_5 + K_2O + Zn), demonstrating superior yield stability and productivity. This aligns with studies showing that balanced nutrient application including micronutrients enhances sustainability in rice-wheat systems (23, 28). Treatments T_5 (NPK) and T_7 (fertiliser best management practice) showed good but slightly lower SYI values, indicating moderate yield stability. The control (T_1) had the lowest SYI (0.10), highlighting the adverse effects of nutrient deficiency on yield stability, consistent with earlier study (22). Partial fertilisation treatments (T_2 and T_4) showed intermediate SYI, underscoring that balanced fertilisation is necessary for consistent long-term yields (20). Overall, inclusion of all major nutrients plus Zn is critical for sustainable and stable rice-wheat production.

The economic analysis demonstrated that balanced fertilisation with micronutrient Zn (T_6) significantly enhanced profitability in the RWCS. Treatment T_6 recorded the highest gross returns (₹293377 ha^{-1}), net returns (₹199367 ha^{-1}) and B : C ratio (2.5), outperforming all other treatments including the fertiliser best management practice (T_7). This is consistent with recent findings that INM improves both yield and economic returns (23, 28). The 61 % higher net return of T_6 over farmer practice emphasises that investing in balanced nutrient management is economically justified and supports sustainable intensification (20). Overall, these results confirm that INM not only sustains higher productivity but also ensures better economic viability for farmers in rice-wheat systems.

The initial composite soil sample (0–15 cm) from 24 farmers' fields in Fatehabad confirmed an alkaline, non-saline sandy loam soil with low OC (0.33 %), N (145 kg ha^{-1}), P (8.5 kg ha^{-1}), medium K (185 kg ha^{-1}) and deficient Zn (0.35 mg kg^{-1}). This baseline aligns with recent soil surveys in Haryana's rice-wheat zones-Karnal district soils showed similar pH (~8.2), low OC (< 0.4 %) and deficient P and Zn (29, 30)-highlighting the broader regional fertility constraints. After five years, unfertilised control (T_1) plots exhibited declines in OC, N and P, indicating nutrient mining-a well-documented consequence of continuous cereal cropping without nutrient replenishment (31). In contrast, N-only (T_2) moderately increased available N, but failed to counteract P and K depletion. Treatments including P (T_3, T_5) significantly improved soil P levels, demonstrating positive residual effects (32). Likewise, K-based treatments (T_4, T_5) enhanced available K, consistent with fertiliser response patterns in continuous cropping systems (33). The superior result was obtained in treatment T_6 (balanced NPK + Zn), which not only elevated OC to 0.36 % but also doubled available Zn to 0.62 mg kg^{-1}, clearly underscoring the efficacy of micronutrient application (9, 34). Soil pH and EC remained within acceptable ranges (8.0–8.2; 0.48–0.55 dS m^{-1}), confirming that prolonged fertiliser use, including micronutrients, did not degrade soil health via acidification or salinity-findings which mirror regional data indicating stable chemical properties under balanced fertilisation (30).

Overall, these results reaffirm that INM (balanced NPK + Zn) is essential for maintaining and improving soil fertility under intensive rice-wheat systems in Haryana. Such strategies combat nutrient depletion (notably N, P, K and Zn), support OC accumulation and maintain soil physico-chemical stability critical for sustainable agronomic productivity (3, 35, 36).

Conclusion

This five-year field study in Trans-Gangetic Plains (TGP) Region of India rice-wheat system demonstrates that integrated nutrient management (INM) specifically the combined application of nitrogen (N), phosphorus (P), potassium (K) + zinc (Zn) (T_6) consistently maximised grain yield (up to 6.1 t ha^{-1} in rice, 5.4 t ha^{-1} in wheat), SYI = 0.90 and nutrient use efficiencies (PFP-N improved by 12.8 % in rice, 43.1 % in wheat over N-alone treatment). Treatment T_6 also recorded the highest net returns (₹199367 ha^{-1}) and benefit-cost (B : C) ratio (2.5), indicating strong economic feasibility. Soil analysis revealed that T_6 improved organic carbon (OC) (+ 0.03 %), available N (+ 17 kg ha^{-1}), P (+ 5.6 kg ha^{-1}), K (+ 14 kg ha^{-1}) and Zn (+ 0.27 mg kg^{-1}), while maintaining stable pH (8.0–8.2) and electrical conductivity (EC) (< 0.55 dS m^{-1}). Treatments omitting P, K, or Zn led to

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nutrient depletion and yield variability, reinforcing the need for balanced fertilisation. These findings advocate for INM integrating macro- and micronutrients to enhance productivity, profitability and soil fertility. Adoption of such strategies is essential for the long-term sustainability of the 10.8 M ha Indo-Gangetic rice-wheat belt under increasing climatic uncertainties.

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Authors' contributions

RSD, KC, K and RJ carried out the experiments and statistical analysis. RSD, R, RJ and DS contributed to manuscript preparation, while S, KC and DS assisted with manuscript editing. All authors 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

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