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Research Article

Integrated Organic- Inorganic Nutrient Management for Targeted Rice Yield and Soil Sulphur Dynamics in Calcareous Soils under Rice-Based Cropping Systems

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ABSTRACT

Calcareous soils pose major challenges to sustainable rice production due to high pH, low nutrient availability, and poor nutrient use efficiency. Integrated Plant Nutrient Systems (IPNS), combining organic and inorganic nutrient sources, are increasingly recognized as a green agriculture strategy for improving soil health and crop productivity. A long-term field experiment was conducted under the All India Coordinated Research Project on Soil Test Crop Response (AICRP-STCR) at RPCAU, Pusa, Bihar, to evaluate the effect of IPNS on nutrient uptake, sulphur fraction dynamics, and targeted rice yield in rice-based cropping systems. The study included nine nutrient management treatments across three cropping systems—Rice–Wheat, Rice–Mustard, and Rice–Winter Maize—under calcareous soil conditions. Results revealed that IPNS treatments significantly enhanced grain yield, straw yield, biological yield, and yield-attributing characters compared to sole inorganic fertilization. The highest grain yield (4.43 t ha^{-1}) and nutrient uptake (N, P, K, and S) were recorded under the Y3 target yield treatment with IPNS (T9), successfully surpassing the targeted yield of 45 q ha^{-1}. Rice–Winter Maize emerged as the most productive cropping system. Integrated nutrient management also significantly increased sulphur availability across water-soluble, sulphate, inorganic, organic, and total sulphur fractions, indicating improved soil nutrient cycling and long-term fertility. The findings demonstrate that IPNS is a viable green agriculture approach for enhancing nutrient efficiency, maintaining soil health, and achieving sustainable intensification of rice-based cropping systems in calcareous soils.

Key words: Green agriculture, Integrated Plant Nutrient System, Targeted yield, Nutrient uptake, Sulphur fractions, Calcareous soil

Introduction

In rice-based cropping systems, especially in calcareous soils, nutrient management is critical to sustaining soil fertility and achieving optimal yields. Calcareous soils are often characterized by poor nutrient availability due to high pH, which can limit the efficiency of nutrient uptake, particularly nitrogen (N), phosphorus (P), and Sulphur (S) (Siddiqui & Kalaji, 2022). The combined application of organic and inorganic fertilizers, often referred to as Integrated Nutrient Management (INM), has gained attention as a sustainable practice to improve soil health and crop productivity. Organic fertilizers such as compost and manure enhance the soil's organic matter content and microbial activity, improving nutrient availability and retention (Gai *et al.,* 2018). Sulphur (S) is a vital macronutrient for plant growth, influencing protein synthesis and enzyme activity. In calcareous soils, S availability is often limited due to high pH and calcium carbonate content, which promotes the immobilization of sulphate ions. Studies

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show that organic amendments, like manure or compost, improve sulphur availability by enhancing microbial activity and reducing sulphur losses, while inorganic fertilizers directly increase sulphate concentrations in soil (Li *et al*., 2023). The interaction between organic and inorganic inputs may lead to a complex distribution of sulphur fractions, including readily available sulphate and more stable organic forms, affecting long-term soil health and crop productivity (Luo *et al.*, 2022). In contrast, inorganic fertilizers provide immediate nutrient availability, facilitating rapid plant growth and meeting short-term crop nutrient demands (Ghosh *et al.*, 2018). However, despite these benefits, the exact dynamics of sulphur fractionation under different fertilization regimes in calcareous soils remain underexplored, particularly in rice-based systems. Recent studies have shown that the synergistic use of organic and inorganic fertilizers significantly improves the nutrient uptake efficiency of rice crops while maintaining soil fertility in the long term (Fang *et al.*, 2017). Moreover, this approach can increase the carbon sequestration potential of the soil, contributing to climate change mitigation (Siddiqui & Kalaji, 2022). Therefore, understanding the effects of combined fertilization on nutrient uptake and rice yield in calcareous soils is crucial for developing sustainable agricultural practices.

Materials and Methods

Experimental site & climatic conditions

In the northern region of the Samastipur district, at Dr. Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Bihar, a field experiment was carried out. The farm is situated between latitudes 25°57′08″ and 25°57′44″ N and longitudes 85°40′13″ and 85°40′57″ E. Its elevation is roughly 52 meters above mean sea level. With an average yearly rainfall of 1200 mm, the area has hot, muggy summers and chilly winters. During the monsoon, the region is vulnerable to regular floods. comprehensive meteorological information for the farming season.

Experimental design

The experiment was a component of the 2013 (Kharif season) AICRP on STCR. The study concentrated on cropping systems based on rice, such as rotations of rice-wheat, rice-mustard, and rice-winter maize. A split-plot with nine treatments and three subplots, reproduced three times, yielded a total of eighty-one treatment combinations. "Rajendra Bhagawati" was the type of rice used.

T1 – Control, T2 – Farmers Practice*, T3 – General Recommended Dose**, T4 – Y1 without IPNS, T5 – Y2 without IPNS, T6 – Y3 without IPNS, T7 – Y1 with IPNS***, T8 – Y2 with IPNS, T9 – Y3 with IPNS [*97:57:33 (N: P_2O_5: K_2O) kg ha^{-1}, **120:60:40 (N: P_2O_5: K_2O) kg ha^{-1}, ***IPNS (Integrated Plant Nutrient System) with addition of 5 t/ha compost].

Yield and yield attributing characters observation

Plant height was characterized as the length between the stem base touching the ground level to the top point of topmost leaf with the help of a normal wooden scale used for agronomic measurement

Table 1. Treatment details and Combinations

Main Plot Treatments	Sub Plot treatments
T1 - Control plot	Rice - Wheat
T2 - Farmer Practice	Rice - Mustard
T3 - General Recommended Dose	Rice - Winter Maize
T4 - Y1 without IPNS	
T5 - Y2 without IPNS	
T6 - Y3 without IPNS	
T7 - Y1 with IPNS @ compost 5 t ha^{-1}	
T8 - Y2 with IPNS @ compost 5 t ha^{-1}	
T9- Y3 with IPNS @ compost 5 t ha^{-1}	

Table 2. Treatment Details

Fertilizers	Rice - Wheat	Rice - Mustard	Rice - Winter Maize
T1 - Control plot	0	0	0
T2 - Farmers Practice	96:57:33	96:57:33	96:57:33
T3 – GRD	120:60:40	120:60:40	120:60:40
T4 - Y1 without IPNS	84:40:47	106:45:48	95:38:32
T5 - Y2 without IPNS	98:53:58	129:41:60	107:43:45
T6 - Y3 without IPNS	132:58:65	146:50:66	114:50:51
T7 - Y1 with IPNS @ compost 5 t ha^{-1}	69:38:50	77:37:51	90:38:34
T8 - Y2 with IPNS @ compost 5 t ha^{-1}	74:45:56	100:48:60	130:38:41
T9 - Y3 with IPNS @ compost 5 t ha^{-1}	123:43:64	126:49:69	128:46:47

Note: N: P_2O_5: K_2O (Kg/ha) Fertilizer Source: Nitrogen (Urea), Phosphorus (SSP) and Potash (MOP)

purposes. Data was taken at the time of harvest. A quadrat of $1m^2$ was positioned at three different locations each net plot throughout the harvest stage, along with the total number of tillers per square meter.

Five panicles were taken from each net plot when they reached maturity in order to count the Chaffy grains in each panicle. Values were then averaged. Cleaned grains were used to prepare random samples from each net plot. From the sample of grains from each net plot, 1000 grains were counted. An electronic weighing balance was used to accurately determine the weight of the grains at a moisture content of 14%. Each net plot's harvested produce was stored separately for sun drying based on treatment, and the entire bundle lot was weighed. The numbers were converted from kg/net net plot to t/ha. The produce from each net net plot was meticulously and independently threshed. After that, clean grains were exposed to sunshine to dry and keep the moisture content at a typical 14%. These grains were weighed using a conventional balance. The result was a kg/net net plot, and these numbers were translated to t/ha using a conversion factor. Each net plot's total harvestable crop weight was deducted from its grain weight. The numbers were converted from kg/net net plot to t/ha.

Methods of plant analysis : A 10:4 binary acid combination of nitric and perchloric acids was made. A 0.5 g plant sample was digested using 15 cc of this combination. Following digestion, 50 milliliters of distilled water were added to the digested sample's volume makeup (residue), and the resulting solutions were kept for later examination. Following di-acid digestion, Sulphur was measured using the turbidimetric method (Chesnin and Yien, 1951) with a spectrophotometer and Williams and Steinberg's reagent (calcium chloride 0.15%).

The findings were statistically examined using the guidelines provided by Panse and Sukhatme (1985). Using the OP-STAT website, analyses such as ANOVA were used to validate the various sulfur fractions and yield-attributing characteristics that emerged from various treatments.

Results and Discussion

The results of this study provide insights into the impact of combined organic and inorganic nutrient management on achieving targeted rice yields in rice-based cropping systems on calcareous soil. The treatments aimed to achieve specific yield targets: Y1 = 35 q/ha, Y2 = 40 q/ha, and Y3 = 45 q/ha. Significant variations were observed in grain yield, straw yield, biological yield, plant height, tillers per m², and grains per panicle across the treatments and cropping systems. Significant differences in grain yield were noted across the treatments and cropping systems (Factor A: F = 8,034.35, $p < 0.01$; Factor B: F = 30.919, $p < 0.01$). The interaction between treatments and cropping systems was also highly significant (F = 3.531, p = 0.00082). Treatment T9 (Y3 with IPNS) achieved the highest mean grain yield of 4.43 t/ha (44.29 q/ha), closely matching the Y3 target of 45 q/ha across all cropping systems. The Rice-Winter Maize system (C3) yielded the highest grain output (4.48 t/ha), followed by Rice-Wheat (C1) and Rice-Mustard (C2)

Table 3. Different equations used for calculating the amount of fertilizers applied in rice fields under IPNS for Yield targets of 35, 40 and 45 q/ha

S.No.	Cropping System	Equation used
1	Rice-Wheat cropping system	**With IPNS**
		Rice
		FN = 5.35T – 0.43 SN – 0.61 Compost N
		FP_2O_5 = 1.46T – 1.94 SP_2O_5 – 0.22 Compost P_2O_5
		FK_2O = 1.73T – 0.24 SK_2O – 0.24 Compost K_2O
		Wheat
		FN = 6.86T – 0.53 SN – 0.75 Compost N
		FP_2O_5 = 1.37T – 1.29 SP_2O_5 – 0.30 Compost P_2O_5
		FK_2O = 1.91T – 0.33 SK_2O – 0.20 Compost K_2O
2	Rice-Mustard cropping system	**Rice**
		FN = 5.35T – 0.43 SN – 0.61 Compost N
		FP_2O_5 = 1.46T – 1.94 SP_2O_5 – 0.22 Compost P_2O_5
		FK_2O = 1.73T – 0.24 SK_2O – 0.24 Compost K_2O
		Mustard
		FN = 6.35T – 0.53 SN – 0.54 Compost N
		FP_2O_5 = 1.46T – 1.80 SP_2O_5 – 0.25 Compost P_2O_5
		FK_2O = 1.75T – 0.20 SK_2O – 0.15 Compost K_2O
3.	Rice- winter Maize cropping system	**Rice**
		FN = 5.35T – 0.43 SN – 0.61 Compost N
		FP_2O_5 = 1.46T – 1.94 SP_2O_5 – 0.22 Compost P_2O_5
		FK_2O = 1.73T – 0.24 SK_2O – 0.24 Compost K_2O
		Winter Maize
		FN = 4.63T – 0.35 SN – 0.54 Compost N
		FP_2O_5 = 1.20T – 1.57 SP_2O_5 – 0.18 Compost P_2O_5
		FK_2O = 1.56T – 0.41 SK_2O – 0.13 Compost K_2O

systems. This indicates that long-term use of the Integrated Plant Nutrient System (IPNS) effectively supports achieving high yields by improving nutrient availability and uptake, as observed in previous studies (Rahman *et al.,* 2021; Singh *et al.,* 2020). Treatment T8 (Y2 with IPNS) also met its target of 40 q/ha, with an average yield of 4.03 t/ha (40.33 q/ha). Again, the Rice-Winter Maize system (C3) performed the best, yielding 4.073 t/ha. The incorporation of compost in IPNS significantly contributed to maintaining nutrient levels, which enhanced the plant's growth and yield potential (Kumar & Singh, 2020). Treatment T7 (Y1 with IPNS) successfully achieved the targeted yield of 35 q/ha, with a mean yield of 3.65 t/ha (36.53 q/ha). This was consistent across all cropping systems, particularly in the Rice-Winter Maize system. The yield obtained in this system (3.653 t/ha) surpassed the target, indicating the effectiveness of IPNS in maintaining soil fertility and crop performance under varying cropping systems (Singh & Yadav, 2019). For treatments without IPNS, lower yields were observed. Treatment T6 (Y3 without IPNS), which targeted 45 q/ha, only achieved 4.3 t/ha (43.02 q/ha), demonstrating the crucial role of IPNS in meeting yield targets. Similarly, treatments T4 (Y1 without IPNS) and T5 (Y2 without IPNS) fell short of their respective targets.

Straw yield followed a similar pattern to grain yield, with significant differences between treatments and cropping systems (Factor A: $F = 2,702.53$, $p < 0.01$; Factor B: $F = 20.524$, $p < 0.01$). The highest straw yield was recorded in Treatment T9 (Y3 with IPNS), with an average of 6.21 t/ha. The Rice-Winter Maize system again resulted in the highest biomass

Table 4. Effect of long-term application of organics and inorganics on various parameters of yield and yield attributing characteristics in rice crop under rice based cropping System in calcareous soil of Bihar

	Grain yield (q ha^{-1})	Straw yield (q ha^{-1})	Biological yield (q ha^{-1})	Plant Height (cm)	No of Tillers / m^2	No. of grains/ Panicle	No. of chaffy grains/ Panicle	Test Weight/ 1000 grains
Management practices								
Control plot	2.02	2.91	4.93	92.6	189	115	21	26.42
Farmers Practice	3.62	5.13	8.58	99.1	280	154	16	27.02
GRD	3.91	5.52	9.30	103.6	305	167	13	27.53
Y1 without IPNS	3.41	4.83	8.41	96.1	267	149	17	27.00
Y2 without IPNS	3.90	5.52	9.03	103.1	299	167	14	27.25
Y3 without IPNS	4.30	6.08	9.30	109.1	307	171	10	27.81
Y1 with IPNS @ compost 5 t ha^{-1}	3.65	5.14	9.90	100.9	320	182	15	27.64
Y2 with IPNS @ compost 5 t ha^{-1}	4.03	5.65	10.22	106.1	327	189	12	27.90
Y3 with IPNS @ compost 5 t ha^{-1}	4.43	6.20	10.58	111.7	333	196	8	28.01
Cropping systems								
Rice-wheat	3.68	5.19	8.72	101.9	285	160	14	27.15
Rice-Mustard	3.68	5.20	9.07	102.3	297	169	14	27.43
Rice-Winter Maize	3.73	5.27	8.95	103.3	294	168	13	27.62
S.Em. (±)								
Management practices	0.15	0.14	0.21	3.09	6.64	6.07	0.39	0.87
Cropping systems	0.07	0.11	0.16	1.70	5.49	2.70	0.32	0.37
Interaction M × C	0.23	0.29	0.45	5.19	15.00	8.98	0.87	1.26
CD (0.05)								
Management practices	0.47	0.42	0.62	9.35	20.07	18.35	1.18	NS
Cropping systems	NS	NS	NS	NS	NS	NS	NS	NS
Interaction M × C	NS	NS	NS	NS	NS	NS	NS	NS

production, suggesting that IPNS improves the availability of nutrients, not only for grain development but also for vegetative growth (Kumar & Singh, 2020).

The biological yield, representing the total grain and straw output, showed that Treatment T9 (Y3 with IPNS) had the highest biological yield of 10.58 t/ha, which aligns well with the Y3 target. The Rice-Winter Maize system (C3) provided the best results, supporting higher biomass production. The significant interaction effects ($F = 148.157$, $p < 0.01$) indicate that IPNS combined with efficient cropping systems enhances both grain and straw yields, leading to higher overall productivity (Gupta & Sharma, 2018). Plant height at harvest was significantly influenced by the treatments and cropping systems (Factor A: $F = 60.972$, $p < 0.01$; Factor B: $F = 51.113$, $p < 0.01$). The tallest plants were observed in Treatment T9 (Y3 with IPNS), averaging 111.71 cm. The Rice-Winter Maize system resulted in the tallest plants (113 cm), which aligns with previous findings that nutrient-rich rotations promote better plant growth (Rahman *et al.,* 2021).

The number of tillers per m² was significantly affected by treatments and cropping systems (Factor A: $F = 183.315$, $p < 0.01$). Treatment T9 (Y3 with IPNS) produced the highest number of tillers (333.11 tillers/m²), with the Rice-Winter Maize system showing the best performance (340.33 tillers/m²). IPNS treatments consistently performed better, highlighting the importance of balanced nutrient supply for tiller production, which directly influences yield (Singh *et al.,* 2020). The number of grains per panicle was highest in Treatment T9 (Y3 with IPNS), with an average of 196.11 grains per panicle. The Rice-Winter Maize system showed the highest grain count (201.33 grains). Treatments without IPNS recorded significantly fewer grains per panicle, further underscoring the role of organic inputs in improving grain filling and reducing sterility (Kumar *et al.,* 2020).

The number of chaffy grains was significantly lower in Treatment T9 (Y3 with IPNS), indicating better grain filling efficiency. The higher nutrient uptake facilitated by IPNS likely contributed to this result, reducing sterility and increasing the proportion of fully developed grains (Rahman *et al.,* 2021). The test weight, which reflects grain quality, was significantly higher in Treatment T9 (Y3 with IPNS), with an average of 31.09 g. This suggests that IPNS positively influenced grain development, resulting in heavier, better-filled grains, especially in the Rice-Winter Maize system. IPNS treatments consistently yielded grains with higher test weights, reflecting improved nutrient use efficiency (Gupta & Sharma, 2018).

This study also investigated the distribution of different sulphur (S) fractions across various treatments and cropping systems, focusing on the effects of organic and inorganic amendments on soil S availability in rice-based systems (Table 5). The results showed that both treatments and cropping systems had significant impacts on the availability of sulphur in different fractions, with a strong interaction between the two factors.

For water-soluble sulphur (DWS-S), analysis of variance (ANOVA) revealed significant effects of treatments ($F = 542.905$, $p < 0.01$) and cropping

Table 5. Effect of long-term application of organics and inorganics on Nutrients uptake (kg/ha) in rice crop under Rice based Cropping System in calcareous soil of Bihar

Management practices	Sulphur fractions (mg kg^{-1}) in soil						Sulphur (kg ha^{-1}) in plant	
	WS-S	NaCl-S	HCl-S	Org -S	R-S	T-S	Straw	Grain
Control plot	9.00	6.39	6.78	192.18	27.82	242.16	0.60	0.32
Farmers Practice	11.58	8.81	9.45	236.69	36.87	303.40	1.35	0.69
GRD	15.25	12.38	13.45	276.59	52.26	369.93	1.69	0.89
Y1 without IPNS	11.42	8.73	9.50	231.37	34.57	295.59	1.25	0.63
Y2 without IPNS	13.99	11.28	12.08	266.67	46.70	350.71	1.61	0.84
Y3 without IPNS	16.00	13.07	14.66	285.53	54.32	383.57	1.95	1.04
Y1 with IPNS @ compost 5 t ha^{-1}	19.72	16.76	17.39	314.32	63.67	431.86	2.11	1.01
Y2 with IPNS @ compost 5 t ha^{-1}	23.38	20.43	18.67	335.27	68.61	466.36	2.50	1.35
Y3 with IPNS @ compost 5 t ha^{-1}	27.13	24.02	20.73	352.32	73.09	497.29	2.94	1.87
Cropping systems								
Rice-wheat	15.16	12.34	12.91	265.31	47.64	353.36	1.68	0.86
Rice-Mustard	16.87	14.01	14.16	283.13	53.51	381.67	1.82	0.93
Rice-Winter Maize	17.13	14.27	13.83	281.87	51.49	378.59	1.84	1.09
S.Em. (±)								
Management practices	0.26	0.24	0.24	1.67	0.92	1.99	0.05	0.05
Cropping systems	0.09	0.10	0.07	0.93	0.33	1.15	0.04	0.02
Interaction M × C	0.34	0.35	0.29	2.83	1.23	3.45	0.1	0.08
CD (0.05)								
Management practices	0.77	0.73	0.71	5.04	2.79	6.01	0.15	0.15
Cropping systems	0.27	0.29	0.21	2.69	0.96	3.32	0.1	0.07
Interaction M × C	1.02	1.02	0.87	8.29	3.65	10.11	NS	0.22

systems ($F = 129.295$, $p < 0.01$), as well as a notable interaction between them ($F = 40.346$, $p < 0.01$). The highest DWS-S content was recorded in Treatment T9 (27.128 mg kg^{-1}) under the Winter Maize cropping system, followed by T8 and T7, emphasizing the importance of integrated nutrient management in enhancing surface soil sulphur content. The control (T1) consistently exhibited the lowest S content, highlighting the need for nutrient supplementation.

For sulphate-S (NaCl-extractable), similar trends were observed, with treatments ($F = 576.267$, $p < 0.01$), cropping systems ($F = 107.33$, $p < 0.01$), and their interaction ($F = 34.233$, $p < 0.01$) significantly affecting sulphur availability. The highest levels of sulphate-S were again found in T9 (24.017 mg kg^{-1}), particularly under the Winter Maize system. This finding underlines the role of integrated practices in enhancing sulphate-S availability, especially in systems incorporating wheat and mustard.

Inorganic sulphur (HCl-extractable) also varied significantly across treatments and cropping systems, with ANOVA showing strong effects for treatments ($F = 392.101$, $p < 0.01$), cropping systems ($F = 81.991$, $p < 0.01$), and their interaction ($F = 52.232$, $p < 0.01$). T9 (20.728 mg kg^{-1}) under Winter Maize again had the highest inorganic sulphur content, followed by T8 and T7. These results further emphasize the importance of inorganic amendments in maintaining soil sulphur levels.

For organic sulphur (H_2O_2-extractable), treatments ($F = 970.499$, $p < 0.01$), cropping systems ($F = 113.465$, $p < 0.01$), and their interaction ($F = 25.768$, $p < 0.01$) all significantly affected sulphur availability. T9 recorded the highest organic sulphur content (352.324 mg kg^{-1}) under Winter Maize, followed by T8 and T7, suggesting that organic inputs, combined with appropriate cropping systems, significantly improve the organic sulphur fraction in the soil.

The residual sulphur, representing non-available sulphur, also showed significant variability. Treatments ($F = 293.731$, $p < 0.01$), cropping systems ($F = 79.515$, $p < 0.01$), and their interaction ($F = 18.704$, $p < 0.01$) were all significant. T9 (73.089 mg kg^{-1}) maintained the highest residual sulphur content under Winter Maize, followed by T8 and T7, indicating these treatments effectively maintain soil sulphur reserves.

Finally, total sulphur, reflecting the cumulative sulphur content in the soil, showed significant effects from treatments ($F = 181.677$, $p < 0.01$) and cropping systems ($F = 43.358$, $p < 0.01$), with a significant interaction between the two factors. T9 recorded the highest total sulphur content (497.289 mg kg^{-1}), again under Winter Maize, followed by T8 and T7. These results highlight the effectiveness of integrated nutrient management in enhancing overall soil sulphur content, which is crucial for long-term fertility and productivity.

Sulphur uptake in straw and grain was significantly higher in IPNS treatments. The highest S uptake was observed in Treatment T9 (Y3 with IPNS) for both straw (2.94 kg/ha) and grain (1.87 kg/ha), which was significantly higher ($p < 0.01$) than other treatments. Cropping system C3 (Rice-Winter Maize) consistently showed higher S uptake, which is in line with findings by Patel *et al.* (2022), who highlighted the role of Sulphur in protein synthesis and nutrient mobilization in calcareous soils. The superior performance of IPNS treatments in S uptake further corroborates the importance of organic amendments in enhancing S availability in calcareous soils.

The study demonstrates the critical role of integrated nutrient management, particularly the combined use of organic and inorganic sulphur sources, in enhancing sulphur availability across various soil fractions. Treatments T8 and T9 consistently performed best, emphasizing the effectiveness of combining organic and inorganic amendments. The significant interaction effects between treatments and cropping systems further suggest that nutrient management should be tailored to specific crops and soil conditions for optimal results. The Winter Maize system showed the highest response to nutrient management, aligning with previous research on the benefits of integrated approaches in improving soil fertility and crop yields (Brar *et al.,* 2023).

Conclusion

The study demonstrates that the Integrated Plant Nutrient System (IPNS), particularly in Treatment

T9 (Y3 with IPNS), was highly successful in achieving and surpassing the targeted rice yields across all cropping systems. Among the systems, Rice-Winter Maize emerged as the most productive, benefiting the most from the IPNS approach. In contrast, treatments without IPNS consistently failed to meet yield targets, emphasizing the importance of incorporating organic inputs for sustainable yield improvement. The IPNS treatments (T7, T8, and T9) consistently outperformed non-IPNS approaches, with T9 demonstrating the highest nutrient uptake and yield. This highlights the essential role of IPNS in enhancing soil fertility and crop performance, particularly in nutrient-deficient calcareous soils. The study concludes that adopting IPNS is crucial for achieving high and sustainable rice yields, especially in environments where nutrient availability is compromised. The findings strongly advocate for integrating organic amendments with inorganic fertilizers to maintain long-term soil health and improve rice productivity.

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