Improving Nutrient Uptake and Protein Yield of Rice through Integrated Nitrogen Management and Foliar Fe and Zn Application in Calcareous Soils

Karthika M[1]; Choudhary S.K[2]; Banavath Mahesh Naik[3*]; Soundharya N[4]

[1,2]Amrita Vishwa Vidyapeetham, Coimbatore, Tamil Nadu, India-642120
[2]Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India - 848125.
[*3]Assistant professor, Department of Agronomy, Malla Reddy University, Hyderabad
[4]JKKM College of Agricultural Science, Tamil Nadu, India - 638506.
*Corresponding Author

Received:- 16 September 2025/ Revised:- 23 September 2025/ Accepted:- 29 September 2025/ Published: 05-10-2025

Abstract— *Rice productivity and grain nutritional quality are strongly influenced by nutrient management, particularly under calcareous soils where nitrogen (N) use efficiency is low and micronutrient deficiencies of iron (Fe) and zinc (Zn) are widespread. A field experiment was conducted during the Kharif seasons of 2018 and 2019 at Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, to evaluate the effects of integrated nitrogen management (INM) and foliar micronutrient application on nutrient uptake and protein yield of aerobic rice (*Oryza sativa *L.). The trial was laid out in a factorial randomized block design comprising six INM practices (75-125% recommended dose of nitrogen, partly substituted with vermicompost, poultry manure or farmyard manure) and three foliar regimes ($FeSO_4$ 1%, $ZnSO_4$ 0.5% and combined $FeSO_4$ + $ZnSO_4$). Results indicated that 100% RDN through chemical fertilizers with 25% RDN through vermicompost (N4) significantly enhanced total N, P and K uptake, recording 115.33, 20.13 and 91.87 kg ha^{-1}, respectively, corresponding to increases of 34%, 44% and 38% over sole chemical fertilization (N5). Foliar application of Fe + Zn (F3) further improved nutrient uptake, with total N and P uptake 9% and 12% higher, respectively, than Fe spray alone. Protein content was not significantly affected, but protein yield reached a maximum under N4 (531.37 kg ha^{-1}), 34% greater than N5, while F3 increased protein yield by 10% compared with Fe alone. The combination of N4 and F3 proved most effective, offering a viable strategy for enhancing both productivity and biofortification potential of rice under calcareous soil conditions.*

Keywords— Integrated nutrient management, Vermicompost, Poultry manure, Nutrient uptake, Protein yield, Calcareous soils.

I. INTRODUCTION

Rice (Oryza sativa L.) is one of the most important cereal crops worldwide, serving as the primary source of calories and nutrition for more than half of the global population. In Asia, where nearly 90% of rice is produced and consumed, it forms the dietary backbone for millions of smallholder farmers and consumers alike (Paramesha et al., 2025). However, sustaining high rice productivity while ensuring grain nutritional quality remains a major challenge under current production systems. Intensive cultivation practices with high dependency on chemical fertilizers have resulted in soil nutrient depletion, reduced factor productivity, and deterioration of soil health (Walia et al., 2024). Among macronutrients, nitrogen (N) is the most yield-limiting element, but imbalanced application and low recovery efficiency often less than 40% lead to nutrient losses and environmental risks (Shrestha et al., 2020).

Integrated nutrient management (INM), which combines chemical fertilizers with organic sources such as farmyard manure (FYM), poultry manure, and vermicompost, has emerged as a sustainable approach for improving soil fertility, enhancing microbial activity, and increasing nutrient use efficiency (Paramesha et al., 2025). The addition of organic sources not only supplements plant nutrients but also improves soil physical properties and supports long-term productivity. Recent studies highlight that substitution of a portion of N fertilizers with organic manures can enhance nitrogen-use efficiency, reduce dependency on chemicals, and maintain yield stability in rice-based systems (Shrestha et al., 2020).

Alongside macronutrient management, micronutrient deficiencies have gained increasing attention due to their dual role in crop productivity and human nutrition. Iron (Fe) and zinc (Zn) deficiencies are among the most widespread constraints in paddy soils, particularly under flooded anaerobic conditions that reduce micronutrient availability (Singh et al., 2018). These deficiencies not only lower rice yields but also contribute to "hidden hunger" in human populations dependent on rice as a staple food. Zinc is vital for enzyme activation, auxin metabolism, and grain filling, while iron plays a central role in chlorophyll synthesis, respiration, and electron transport. Global estimates suggest that more than two billion people suffer from Zn and Fe deficiencies and biofortification of rice grains with these nutrients is considered a promising solution to combat malnutrition (Ram et al., 2024; Liu et al., 2023).

Foliar application of micronutrients has been widely recommended as an efficient strategy to overcome soil-related limitations and improve nutrient uptake at critical growth stages. In rice, foliar sprays of $FeSO_4$ and $ZnSO_4$ during tillering and panicle initiation have been reported to improve nutrient accumulation, enhance photosynthetic efficiency, and increase grain micronutrient content (Ram et al., 2024). Moreover, the interaction between nitrogen management and micronutrient uptake is particularly important: higher nitrogen supply stimulates root activity and transporter expression, thereby enhancing Fe and Zn assimilation in rice plants (Singh et al., 2018). However, the combined impact of integrated N sources with foliar Fe and Zn application on rice yield and nutritional enrichment has not been adequately studied.

Given these gaps, the present study was undertaken to investigate the interactive effects of integrated nitrogen management and foliar application of Fe and Zn on rice. The aim was to assess how different combinations of organic and inorganic nitrogen sources, along with targeted foliar micronutrient supplementation, influence crop productivity, nutrient uptake, and grain nutritional quality under irrigated conditions.

II. MATERIALS AND METHODS

2.1 Experimental site:

The field investigation was conducted during the *Kharif* seasons of 2018 and 2019 at the experimental farm of Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India. The site is located at 25.59°N latitude, 84.40°E longitude, at an altitude of 52.14 m above mean sea level and falls under a sub-humid, subtropical climate.

2.1.1 Experimental design and treatment details:

The experiment was laid out in a randomized block design (RBD) with a factorial arrangement to evaluate the combined effects of integrated nitrogen management (INM) practices and foliar application of micronutrients on aerobic rice in calcareous soil. Six INM treatments were imposed, consisting of 75% of the recommended dose of nitrogen (RDN) through chemical fertilizers and 25% through vermicompost (N1), 75% RDN through chemical fertilizers and 25% through poultry manure (N2), 75% RDN through chemical fertilizers and 25% through farmyard manure (N3), 100% RDN through chemical fertilizers along with 25% through vermicompost (N4), 100% RDN through chemical fertilizers alone (N5), and 125% RDN through chemical fertilizers (N6). These were combined with three micronutrient foliar spray treatments: $FeSO_4$ @ 1% applied at tillering and panicle emergence (F1), $ZnSO_4$ @ 0.5% applied at tillering and panicle emergence (F2), and $FeSO_4$ @ 1% + $ZnSO_4$ @ 0.5% applied at the same stages (F3). The recommended dose of fertilizers was 120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1}, supplied through prilled urea, diammonium phosphate (DAP), and muriate of potash (MOP), while organic manures were incorporated according to the treatment combinations and analyzed for nutrient content (Table 1).

2.2 Crop management:

The experimental field was prepared by two primary ploughings followed by secondary tillage and planking. Seeds of the rice variety *Abhishek* were directly sown using a seed rate of 30 kg ha^{-1} with an inter row spacing of 20 cm. A full basal dose of phosphorus and potassium was applied at sowing. Nitrogen was applied in three splits: 50% as basal (partially substituted with organic manures as per treatment), 25% at tillering, and 25% at panicle initiation.

2.3 Plant sampling and analysis:

At harvest, composite plant samples were collected from each treatment plot, washed with dilute HCl followed by deionized water, oven-dried at 65 ± 5 °C for 48 hours, and ground using a Willey grinder. The powdered samples were digested and analyzed for nutrient content following standard procedures: nitrogen by the modified Kjeldahl method (Bremner and Mulvaney, 1982), and phosphorus and potassium by the tri-acid digestion method (Jackson, 1967). Protein content was estimated using the factor proposed by Merill and Watt (1973), calculated as:

Protein content (%) = N % x 6.25

Protein yield was computed using the formula:

Protein yield (kg ha-1) = Protein content (%) x Grain yield (kg ha-1)/100

2.4 Statistical analysis:

The data obtained from the experiment were subjected to analysis of variance (ANOVA) for randomized block design with factorial concept as described by Gomez and Gomez (1984). Statistical significance was tested at the 5% probability level using the F-test, and the critical difference (CD) was computed for mean separation wherever treatment effects were significant.

III. RESULTS AND DISCUSSION

Nitrogen uptake varied significantly among integrated nutrient management (INM) treatments, with N4 (100% RDN through chemical fertilizers + 25% RDN through vermicompost) recorded the highest total N uptake (115.33 kg ha^{-1}), about 34% greater than sole chemical fertilization (N5, 85.83 kg ha^{-1}) (Table 1). Substitution with poultry manure (N2) and vermicompost (N1) also improved uptake by 31% and 26% over N5, respectively. Similar positive effects of organic substitution on nitrogen uptake and efficiency have been reported in rice and maize systems, where organic amendments enhanced microbial biomass and reduced nitrogen losses (Bhattacharyya et al., 2015; Xu et al., 2018; Li et al., 2019). Foliar supplementation further influenced N uptake, with the combined Fe + Zn spray (F3) improving total uptake by 9% compared with sole Fe spray. The advantage of combined sprays aligns with findings that Fe and Zn interact synergistically with nitrogen to improve transporter activity and assimilation (Cakmak and Kutman, 2018; Wang et al., 2021).

TABLE 1
N UPTAKE (kg ha^{-1}) OF RICE AS AFFECTED BY INM AND MICRONUTRIENT APPLICATION PRACTICES (2018, 2019 AND MEAN)

Treatments	N Uptake (kg ha^{-1})								
	2018			2019			Mean		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
Integrated Nutrient Management									
N_1	75.17	26.28	101.45	85.20	30.07	115.28	80.19	28.17	108.36
N_2	78.49	26.56	105.05	88.43	31.75	120.19	83.46	29.16	112.62
N_3	66.92	22.70	89.62	71.37	25.16	96.53	69.15	23.93	93.08
N_4	81.43	28.85	110.28	88.61	31.48	120.39	85.02	30.31	115.33
N_5	62.53	22.52	85.05	64.05	22.56	86.61	63.29	22.54	85.83
N_6	71.37	26.14	97.51	78.69	28.95	107.64	75.03	27.54	102.57
SEm(±)	2.91	1.43	3.09	2.15	1.08	2.44	2.21	1.06	2.35
CD $_{(P=0.05)}$	8.35	4.11	8.87	6.17	3.11	7.02	6.36	3.05	6.74
Micronutrients									
F_1	69.54	24.85	94.49	76.69	27.81	104.51	73.17	26.33	99.50
F_2	71.51	25.10	96.61	77.88	27.93	105.81	74.70	26.52	101.21
F_3	76.80	26.57	103.37	83.60	29.40	112.99	80.20	27.98	108.18
SEm(±)	2.05	1.01	2.18	1.52	0.76	1.73	1.57	0.75	1.66
CD $_{(P=0.05)}$	NS	NS	6.27	4.36	2.20	4.96	4.49	NS	4.77
Interaction (NxF)	NS	NS	NS	NS	NS	NS	NS	NS	NS

Phosphorus uptake also increased under INM, with N4 achieving 20.13 kg ha⁻¹, which was 44% higher than N5 (13.99 kg ha⁻¹) (Table 2). Substitution with poultry manure (N2) raised uptake by 38% over N5, highlighting the role of organics in enhancing P mobilization. Foliar Fe + Zn sprays further increased P uptake by 12% compared with Fe alone. This response may be due to increased enzymatic activity and organic acid exudation that improve solubilization and root uptake (Zhou et al., 2017; Adhikari et al., 2019). Integrated nutrient sources have also been shown to stimulate phosphatase activity and enhance P availability in calcareous soils (Zhang et al., 2020).

TABLE 2
P UPTAKE (kg ha^{-1}) OF RICE AS AFFECTED BY INM AND MICRONUTRIENT APPLICATION PRACTICES (2018, 2019 AND MEAN)

Treatments	P uptake (kg ha^{-1})								
	2018			2019			Mean		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
Integrated Nutrient Management									
N_1	9.12	6.03	15.15	11.81	7.79	19.59	10.46	6.91	17.37
N_2	10.05	7.13	17.18	12.68	8.83	21.51	11.36	7.98	19.35
N_3	7.84	5.24	13.08	9.79	6.56	16.35	8.82	5.90	14.71
N_4	11.00	7.44	18.44	13.26	8.57	21.82	12.13	8.00	20.13
N_5	7.96	4.92	12.88	9.38	5.71	15.09	8.67	5.32	13.99
N_6	9.25	6.47	15.72	11.55	7.79	19.34	10.40	7.13	17.53
SEm(±)	0.43	0.41	0.61	0.45	0.42	0.57	0.37	0.41	0.54
CD $_{(P=0.05)}$	1.24	1.19	1.75	1.29	1.21	1.65	1.07	1.17	1.56
Micronutrients									
F_1	8.71	5.70	14.41	10.92	7.22	18.14	9.81	6.46	16.27
F_2	9.08	6.17	15.24	11.22	7.49	18.71	10.15	6.83	16.98
F_3	9.83	6.75	16.58	12.10	7.92	20.02	10.96	7.33	18.30
SEm(±)	0.30	0.29	0.43	0.32	0.30	0.41	0.26	0.29	0.38
CD $_{(P=0.05)}$	0.88	NS	1.23	0.91	0.85	1.17	0.76	NS	1.10
Interaction (NxF)	NS	NS	NS	NS	NS	NS	NS	NS	NS

Potassium uptake followed a similar trend, with N4 and N2 producing mean total uptake of 91.87 and 90.35 kg ha⁻¹, representing 38% and 36% increases over N5, respectively (Table 3). Although foliar micronutrient sprays produced small numerical gains, the differences were non-significant. The improvement in K uptake under organic–inorganic integration can be attributed to increased cation exchange capacity and improved root proliferation due to organic matter addition (Badole et al., 2019; Jat et al., 2021). Earlier studies also confirm that INM systems improve soil aggregation, thereby facilitating better potassium availability and uptake (Choudhary et al., 2018).

TABLE 3
K UPTAKE (kg ha^{-1}) OF RICE AS AFFECTED BY INM AND MICRONUTRIENT APPLICATION PRACTICES (2018, 2019, MEAN)

Treatments	K uptake (kg ha^{-1})								
	2018			2019			Mean		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
Integrated Nutrient Management									
N_1	8.89	68.79	77.67	13.13	77.66	90.78	11.01	73.22	84.23
N_2	9.78	72.49	82.28	13.96	84.6	98.42	11.87	78.47	90.35
N_3	7.91	59.34	67.26	11.01	64.14	75.15	9.46	61.74	71.20
N_4	9.98	77.54	87.52	13.85	82.36	96.21	11.92	79.95	91.87
N_5	7.44	57.85	65.28	9.76	58.16	67.92	8.60	58.00	66.60
N_6	8.41	63.89	72.30	11.88	72.96	84.84	10.15	68.42	78.57
SEm(±)	0.31	2.61	2.63	0.68	2.65	2.62	0.44	2.57	2.56
CD $_{(P=0.05)}$	0.89	7.49	7.55	1.96	7.60	7.53	1.27	7.39	7.35
Micronutrients									
F_1	8.50	65.71	74.21	12.14	72.42	84.57	10.32	69.07	79.39
F_2	8.58	65.33	73.91	12.00	72.31	84.31	10.29	68.82	79.11
F_3	9.12	68.91	78.03	12.66	75.13	87.79	10.89	72.02	82.91
SEm(±)	0.21	1.84	1.85	0.48	1.87	1.85	0.32	1.82	1.81
CD $_{(P=0.05)}$	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction (NxF)	NS	NS	NS	NS	NS	NS	NS	NS	NS

Protein content of rice grains did not show significant variation among treatments, although numerically higher values were noted in N4 (9.64%) and F3 (9.70%) compared with N5 (9.26%) (Table 4). Protein yield, however, differed markedly: N4 produced 531.37 kg ha^{-1}, 34% greater than N5 (395.55 kg ha^{-1}). N2 and N1 improved protein yield by 32% and 27% over N5, respectively. Foliar Fe + Zn sprays further enhanced protein yield by 10% compared with Fe alone. These results confirm that greater nitrogen uptake under INM directly translated into higher protein synthesis and yield. Similar enhancements in rice protein quality and nutritional value under integrated nutrient supply and micronutrient supplementation have been observed in multiple studies (Saha et al., 2015; Suryapani et al., 2019; Li et al., 2021). Additionally, foliar Zn application has been shown to increase protein content by improving enzymatic activities involved in amino acid synthesis (Zou et al., 2012; Hafeez et al., 2013).

TABLE 4
PROTEIN CONTENT (%) AND PROTEIN YIELD (kg ha^{-1}) AS INFLUENCED BY INM AND MICRONUTRIENT APPLICATION PRACTICES (2018, 2019 AND MEAN)

Treatments	Protein content (%)			Protein yield (kg ha^{-1})		
	2018	2019	Mean	2018	2019	Mean
Integrated Nutrient Management						
N_1	9.45	9.52	9.48	469.79	532.53	501.16
N_2	9.51	9.72	9.62	490.55	552.70	521.62
N_3	9.34	9.48	9.41	418.23	446.09	432.16
N_4	9.54	9.74	9.64	508.94	553.80	531.37
N_5	9.16	9.37	9.26	390.82	400.28	395.55
N_6	9.28	9.44	9.36	446.05	491.82	468.94
SEm(±)	0.28	0.27	0.24	18.17	13.42	13.83
CD $_{(P=0.05)}$	NS	NS	NS	52.22	38.56	39.76
Micronutrients						
F_1	9.11	9.25	9.18	435.27	479.34	457.30
F_2	9.40	9.60	9.50	446.95	486.78	466.86
F_3	9.63	9.78	9.70	479.97	522.49	501.23
SEm(±)	0.20	0.19	0.17	12.85	9.49	9.78
CD $_{(P=0.05)}$	NS	NS	NS	NS	27.26	28.11
Interaction (NxF)	NS	NS	NS	NS	NS	NS

Overall, the integration of organic amendments with mineral fertilizers significantly improved nutrient uptake and protein yield compared with sole chemical fertilization, with vermicompost and poultry manure proving particularly effective. Foliar supplementation with Fe and Zn further enhanced N and P uptake and protein yield, with combined application consistently outperforming individual sprays. These findings corroborate evidence that INM improves nutrient cycling, soil fertility, and crop productivity (Pathak et al., 2019; Somanath and Sharma, 2020; Li et al., 2022). In addition, foliar micronutrient supplementation has been shown to overcome soil fixation constraints and improve nutrient bioavailability in rice, leading to both yield gains and nutritional enrichment (Phattarakul et al., 2012; Prom-u-Thai et al., 2020; Zhao et al., 2020). Therefore, adopting INM along with targeted Fe and Zn sprays is a promising approach to improve both productivity and nutritional quality of rice grown in calcareous soils.

IV. CONCLUSION

The present investigation demonstrated that integration of organic manures with chemical fertilizers substantially improved nutrient uptake and protein yield of rice compared with sole chemical fertilization. Among the INM practices, the application of 100% RDN through chemical fertilizers supplemented with 25% RDN through vermicompost (N4) consistently achieved the highest nitrogen, phosphorus, and potassium uptake as well as protein yield, followed closely by 75% RDN with poultry manure (N2). Foliar supplementation with Fe and Zn further enhanced nutrient assimilation, with the combined spray (F3) proving superior to individual applications. The synergistic effects of organic substitution and micronutrient foliar feeding highlight the importance of adopting integrated strategies for sustaining yield and improving grain nutritional quality in calcareous soils. These findings support the use of INM, particularly vermicompost-based substitution coupled with Fe + Zn foliar sprays, as a viable approach for enhancing productivity, nutrient use efficiency, and biofortification potential of rice under resource-intensive production systems.

ACKNOWLEDGEMENT

The authors are thankful to Dr. Rajendra Prasad Central Agricultural University for providing necessary financial support during the research study.

REFERENCES

[1] Adhikari, T., Kundu, S., Rao, A. S. and Subba Rao, A. 2019. Mobilization of phosphorus and micronutrients through organic amendments in calcareous soils. *Journal of Plant Nutrition, 42*(12), 1425–1437.

[2] Badole, S., Patel, M., and Tiwari, K. N. 2019. Potassium management under integrated nutrient systems in rice–wheat cropping. *Indian Journal of Agronomy, 64*(3), 301–308.

[3] Bhattacharyya, R., Das, T. K., Sudhishri, S., Sharma, A. R. and Jat, M. L. 2015. Effects of conservation agriculture on soil quality and productivity in intensive cereal systems of South Asia. *Soil and Tillage Research, 150,* 204–214.

[4] Bremner, J. M. and Mulvaney, C. S. 1982. Nitrogen-Total. pp. 595-624, In: Page, A. L. et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agronomy Monograph 9.

[5] Cakmak, I., and Kutman, U. B. (2018). Agronomic biofortification of cereals with zinc: A review. *European Journal of Soil Science, 69*(1), 172–180.

[6] Choudhary, M., Datta, A., Jat, H. S., Yadav, A. K., Sapkota, T. B., Mondal, S. and Sharma, P. C. 2018. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. *Geoderma, 313,* 193–204.

[7] Gomez, K. A. and Gomez, A. A. 1984. *Statistical procedures for agricultural research* (2nd ed.). John Wiley and Sons.

[8] Hafeez, B., Khanif, Y. M. and Saleem, M. 2013. Role of zinc in plant nutrition—A review. *American Journal of Experimental Agriculture, 3*(2), 374–391.

[9] Islam, S., Hossain, A. and Begum, K. 2024. Integrated nutrient management enhances rice productivity and nitrogen use efficiency in South Asia. *Nutrient Cycling in Agroecosystems, 118*(1), 55–69.

[10] Jackson, M. L. 1967. Soil chemical analysis, *Prentice Hall of India Pvt. Ltd*. New Delhi, India.

[11] Jat, H. S., Choudhary, M., Datta, A., Yadav, A. K., Sharma, P. C. and Jat, M. L. 2021. Organic amendments and nutrient dynamics in rice-based systems. *Agriculture, Ecosystems and Environment, 310,* 107295.

[12] Ji, X., Wang, S., Xu, H. and Li, C. 2022. Zinc fertilization regulates nitrogen uptake and assimilation in rice by modulating transporter activity. *Plant Physiology and Biochemistry, 185,* 173–182.

[13] Li, H., Huang, G., Meng, Q., Ma, L., Yuan, L., Wang, F. and Zhang, F. 2019. Integrated soil and nutrient management for sustainable rice production. *Field Crops Research, 234,* 47–54.

[14] Li, X., Chen, Y., Wang, Z. and Zhang, Y. 2021. Zinc biofortification and grain protein improvement through foliar application in rice. *Journal of Cereal Science, 100,* 103260.

[15] Li, Z., Zhang, Y., Zhou, J. and Chen, Q. 2022. Integrated nutrient management improves rice yield and nutrient use efficiency in calcareous soils. *Agronomy Journal, 114*(5), 2311–2324.

[16] Liu, X., Li, H., Jiang, D., Yang, X., Zhang, W. and Zhang, F. 2023. Synergistic effect of nitrogen and zinc on yield and zinc biofortification in rice. *Field Crops Research, 295,* 108901.

[17] Merill, L.A. and Watt, B.K. 1973. Energy value of food: Basis and derivation. *United States Department of Agriculture. Hand Book No. 74.* Pp: 4.

[18] Paramesha, V., Shivakumar, B. G. and Singh, R. 2025. Integrated nutrient management improves soil fertility and crop productivity in rice-based systems. *Soil and Tillage Research, 240,* 105913.

[19] Pathak, H., Mohanty, S. and Jat, R. K. 2019. Integrated nutrient management for sustainable rice systems in South Asia. *Current Science, 116*(1), 45–54.

[20] Phattarakul, N., Rerkasem, B., Li, L. J., Wu, L. H., Zou, C. Q., Ram, H. and Cakmak, I. 2012. Biofortification of rice grain with zinc through zinc fertilization in different countries. *Plant and Soil, 361,* 131–141.

[21] Prom-u-Thai, C., Rashid, A., Ram, H., Zou, C., Guilherme, L. R. G., Cakmak, I. and Stangoulis, J. 2020. Biofortification of rice with zinc and iron: Opportunities and challenges. *Plant and Soil, 457,* 1–16.

[22] Ram, H., Singh, B. and Meena, R. S. 2024. Foliar application of zinc and iron improves growth, yield and biofortification of rice under submerged conditions. *Agronomy, 14*(3), 612.

[23] Saha, S., Saha, B. and Mazumdar, D. 2015. Influence of integrated nutrient management on yield, protein and quality of rice. *Journal of Plant Nutrition, 38*(9), 1393–1403.

[24] Shrestha, R. K., Ladha, J. K. and Dobermann, A. 2020. Integrated nutrient management in rice-based systems: Strategies for sustainable productivity. *Nutrient Cycling in*

[25] Singh, U., Praharaj, C. S. and Kumar, R. 2018. Interaction of nitrogen with zinc and iron nutrition in cereals. *Frontiers in Plant Science, 9,* 307.

[26] Somanath, M. and Sharma, R. 2020. Long-term integrated nutrient management effects on soil fertility and productivity of rice. *Archives of Agronomy and Soil Science, 66*(14), 1912–1924.

[27] Suryapani, S., Dutta, S. and Ray, K. 2019. Impact of zinc and nitrogen fertilization on grain protein content in rice. *Oryza, 56*(1), 58–64.

[28] Walia, S. S., Kumar, R. and Gill, M. S. 2024. Nitrogen fertilization and its consequences for rice productivity and environment: A review. *Heliyon, 10*(1), e13144.

[29] Wang, J., Li, Q. and Liu, Y. 2021. Synergistic interaction between nitrogen and zinc fertilization improves rice yield and quality. *Field Crops Research, 267,* 108142.

[30] Zhang, Y., Wang, Y., Liu, D. and Chen, X. 2020. Effects of organic amendments on phosphorus availability and uptake in rice. *Nutrient Cycling in Agroecosystems, 116*(3), 307–319.

[31] Zhao, A., Li, T., Wang, C. and Ma, X. 2020. Foliar application of micronutrients improves nutritional quality of rice in calcareous soils. *Journal of Plant Nutrition and Soil Science, 183*(5), 631–642.

[32] Zhou, J., Li, H. and Wu, C. 2017. Effect of organic amendments on phosphorus availability in paddy soils. *Soil Use and Management, 33*(3), 426–435.

[33] Zou, C., Zhang, Y., Rashid, A., Ram, H., Savasli, E., Arisoy, R. Z. and Cakmak, I. 2012. Biofortification of wheat with zinc through fertilization. *Plant and Soil, 361,* 119–130.