



RESEARCH ARTICLE

Orchestrating nutrient synergy in transplanted rice: Yield partitioning and partial budgeting under zinc, iron and silicon enrichment

K Akshaya Dharshini^{1*}, P Sudhakar¹, S Manimaran¹ & D Venkatakrishnan²

¹Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar, Chidambaram 608 002, Tamil Nadu, India

²Department of Soil Science and Agricultural Chemistry, Faculty of Agriculture, Annamalai University, Annamalai Nagar, Chidambaram 608 002, Tamil Nadu, India

*Correspondence email - akshayadharshiniagri@gmail.com

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Abstract

Rice (*Oryza sativa* L.) productivity is highly dependent on balanced nutrient management. Micronutrients such as zinc (Zn) and iron (Fe), along with beneficial elements like silicon (Si), play a crucial role in enhancing growth, yield formation and stress tolerance in rice. The present study aimed to systematically evaluate the combined effect of Zn, Fe and Si on the growth, yield partitioning and economic efficiency of transplanted rice under field conditions. The experiment was laid out in a randomised block design with 3 replications and 10 treatments, combining various forms of Zn, Fe and Si. The study found that the treatment combining recommended dose of fertiliser (RDF) along with the soil application of 25 kg ZnSO₄, 25 kg FeSO₄ and 50 kg diatomaceous earth (T₆) significantly improved the partitioning of assimilates towards grain production. This led to enhanced growth parameters resulting in a higher productive tiller count and more filled grains per panicle. This enhanced yield partitioning was reflected in the highest grain yield (5512 kg ha⁻¹) and straw yield (7726 kg ha⁻¹) during season I and grain yield (5721 kg ha⁻¹) and straw yield (8019 kg ha⁻¹) during season II, indicating effective carbon partitioning and biomass distribution. The partial budget analysis revealed that treatment (T₆) maximised both agronomic efficiency and economic profitability by achieving the highest gross and net returns, outperforming all other treatments, with the highest return per rupee invested of ₹2.18 and ₹2.20 in seasons I and II, respectively. Thus, the combined application of Zn, Fe and Si along with RDF can be recommended as an effective nutrient management strategy for improving the productivity, resource-use efficiency and profitability of transplanted rice under similar agro-ecological conditions.

Keywords: diatomaceous earth; FeSO₄; micronutrients; partial-budget analysis; rice; yield partitioning; ZnSO₄

Introduction

Rice (*Oryza sativa* L.) is a critical staple crop for a large segment of the global population, particularly in Asia, where it is the cornerstone of both dietary and cultural frameworks (1). Yield partitioning in rice is a key focus of agronomic research because it directly impacts grain yield and economic returns. The recommended dose of fertiliser (RDF) is commonly used in rice farming to meet crop nutrient needs. However, RDF alone may not maximise yield due to inefficient nutrient use and insufficient micronutrient supply. Micronutrients are critical for physiological processes and maximising the efficiency of Nitrogen (N), Phosphorus (P) and Potassium (K) (NPK) fertilisers. In Tamil Nadu, intensive farming has led to significant micronutrient depletion, with zinc (Zn) deficiency at 58 % and iron (Fe) at 19 % (2). Zinc, the fourth most essential micronutrient is widely deficient in global soils, leading to reduced crop yields and exacerbating malnutrition, particularly in rice-dependent regions. It plays a crucial role in enzyme activity, biochemical processes, auxin metabolism and promoting root development. Iron is an essential micronutrient needed by plants in larger amounts than most other micronutrients. It is crucial for respiration, photosynthesis and the formation of healthy green leaves. Silicon (Si) is regarded as a nearly essential

element that greatly enhances rice growth, yield and stress tolerance. Silicon deficiency can limit rice yield potential. Therefore, applying Si fertilisers externally can enhance crop resilience and productivity. The integration of RDF with micronutrients like Zn, Fe and Si has been shown to enhance yield partitioning by improving nutrient use efficiency and promoting better biomass distribution.

Furthermore, the partial budgeting technique was employed to assess the economics and profitability of the treatments compared to the RDF. The partial budgeting technique is grounded in the principle that any change in production methods will have economic consequences, which can be categorized into four key areas: increased income, reduced costs, increased costs and reduced income (3). This analysis underscores the economic viability and agronomic benefits of micronutrients, as it captures the true economic impact of adopting innovative practices in rice farming systems.

However, limited studies have evaluated the combined effect of Zn, Fe and Si on yield partitioning and economic returns in transplanted rice under field conditions. Moreover, the economic assessment of such integrated nutrient management practices using partial budgeting remains limited. The novelty of the present

study lies in the integrated assessment of Zn, Fe and Si application on both yield partitioning and economic efficiency of transplanted rice under field conditions using partial budgeting analysis. Therefore, the present study was undertaken to evaluate the combined effect of Zn, Fe and Si along with RDF on growth, yield partitioning and economic efficiency of transplanted rice.

Materials and Methods

Experimental site

A field experiment was conducted during the Kuruvai (June–September 2023) and Navarai (January–May 2024) seasons in the “A” block of the experimental farm, Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar, Chidambaram, Cuddalore district, Tamil Nadu, India. The experimental site is located at 11°24'N latitude and 79°44'E longitude, at an altitude of approximately 5.79 m above mean sea level (MSL) and 16 km from the coast of the Bay of Bengal.

The experimental field was representative of the tail-end area of the Cauvery delta. The soil of the experimental field is classified as *Udicchromustert* (clay) according to FAO/ UNESCO (4). The initial analysis of the experimental soil revealed that clay with neutral reaction (pH = 7.4), with a low level of soluble salts (EC 0.33 dSm⁻¹). Analysis of initial soil fertility status indicated low available nitrogen (228 kg ha⁻¹), medium available phosphorus (21 kg ha⁻¹), high available potassium content (280 kg ha⁻¹), low available Zn (0.58 ppm), medium available Fe (5.25 ppm) and low available Si (68.4 mg ha⁻¹).

Experimental treatment and design

The experiment was designed using a randomised block design (RBD) comprised 10 treatments viz, T₁- control, T₂- DF, T₃- RDF + soil application of 25 kg ZnSO₄, T₄- RDF + soil application of 25 kg FeSO₄, T₅- RDF + soil application of 50 kg diatomaceous earth, T₆- RDF + soil application of 25 kg ZnSO₄ + 25 kg FeSO₄ + 50 kg diatomaceous earth, T₇- RDF + foliar application of Zn EDTA at 1 % and T₈- RDF + foliar application of Fe EDTA at 0.5 %, T₉- RDF + foliar application of nano Si at 400 g ha⁻¹, T₁₀- RDF + foliar application of Zn EDTA at 1 % + Fe EDTA at 0.5 % + nano Si at 400 g ha⁻¹.

The chosen rice variety for the experiment was ADT43, a widely cultivated and high yielding variety suitable for the region. The experiment was conducted with a gross plot size of 5 m × 4 m and net plot size of 4.7 m × 3.8 m. Twenty-one-day-old seedlings were transplanted at a spacing of 15 cm × 10 cm with two seedlings per hill under puddled conditions. Standard agronomic practices including land preparation, irrigation scheduling, weed control, pest and disease management and post-harvest handling were meticulously followed to ensure the validity of the experimental results. The experiment was conducted following regionally recommended fertiliser management protocols, where all plots, except the control (T₁), received an optimal application of N, P, K at the recommended dose of 120 : 40 : 40 kg ha⁻¹, as per standard agronomic practices for rice cultivation. Soil application of ZnSO₄, FeSO₄ and diatomaceous earth was carried out as basal application before transplanting by mixing with sand and incorporated into the soil. Foliar applications were carried out at 30 and 45 days after transplanting (DAT) using a hand-operated knapsack sprayer with a spray volume of 500 L ha⁻¹. The nano Si used in the study was procured from Silica Nano Solutions, Uttar Pradesh, India.

Data collection and observations

Growth parameters were measured at critical stages of crop development, whereas yield attributes and final yield were recorded at harvest. All observations were taken from the net plot area of 4.7 m × 3.8 m.

Statistical analysis

The recorded data were statistically analysed using Analysis of Variance (ANOVA) in AGRES software, with a critical difference set at the 0.05 probability level. The ANOVA results provided insights into the statistical significance of nutrient management practices on growth, yield and soil nutrient dynamics.

Partial budgeting evaluates the economic impact of modifications in production practices by considering changes that could affect one or more of the following: an increase in income, reduction in costs, an increase in costs and reduction in income. The net economic effect was calculated by subtracting the total negative effects (increased costs and reduced income) from the total positive effects (increased income and cost savings) (3).

Net change/Net gain = (Additional revenue + Reduced costs) – (Additional costs + Reduced revenue)

A positive net result indicates that the treatment improves farm profitability, while a negative net result suggests that the treatment is economically unsustainable. A comparative cost-benefit analysis of the treatments provided a clear understanding of which nutrient management strategy offered the best return on investment under the given agro-climatic conditions.

In addition, leaf damage assessment was carried out to evaluate the influence of nutrient management practices on pest incidence and plant health. The effect of Zn, Fe and Si nutrition on leaf folder incidence during season I and season II is presented in Fig. 1 and Fig. 2 respectively. The damaged leaves and total leaves from 10 randomly selected hills were observed in each plot at tillering and flowering stages. The per cent incidence was calculated as given below. The individual leaf damage was calculated by using a mobile application called Bio leaf (5).

$$\text{Per cent incidence} = \frac{\text{Number of damaged leaves}}{\text{Total number of leaves}} \times 100$$

Results and Discussion

Yield partitioning

The effect of Zn, Fe and Si nutrition on yield partitioning in rice is presented in Table 1. Yield partitioning was optimally enhanced through the soil application of 25 kg ZnSO₄, 25 kg FeSO₄ and 50 kg diatomaceous earth, resulting in the highest additional yields of 3940 kg ha⁻¹ and 4179 kg ha⁻¹ during season I and II respectively. This substantial yield increment can be attributed to the synergistic effects of Zn, Fe and Si in conjunction with the RDF. Improved nutrient availability increased nutrient uptake, leading to more grain and straw biomass. The benefits of Zn application are likely attributed to its essential role in activating several enzymes, particularly those involved in chlorophyll synthesis and carbohydrate metabolism. Additionally, application of Zn led to higher harvest index values, which suggests more efficient translocation of photosynthates from the source to the sink, resulting in improved partitioning towards reproductive growth (6), although the present study recorded a comparatively higher response due to the combined application of Zn, Fe and Si.

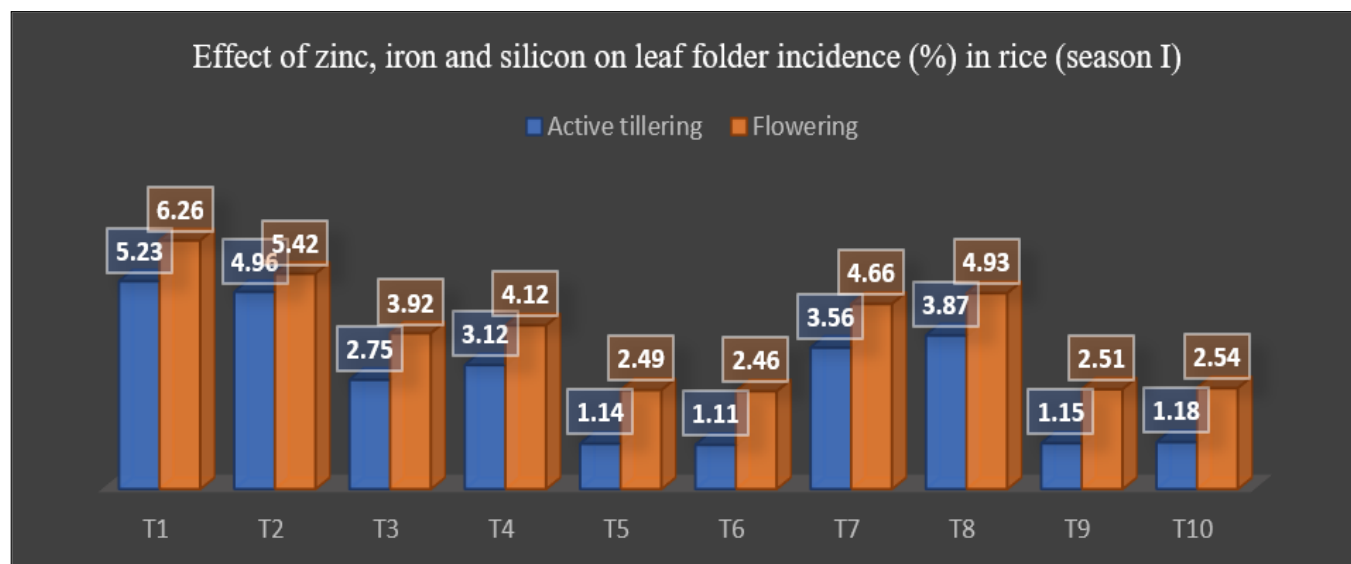


Fig 1. Effect of zinc, iron and silicon nutrition on leaf folder (%) in rice (season I).

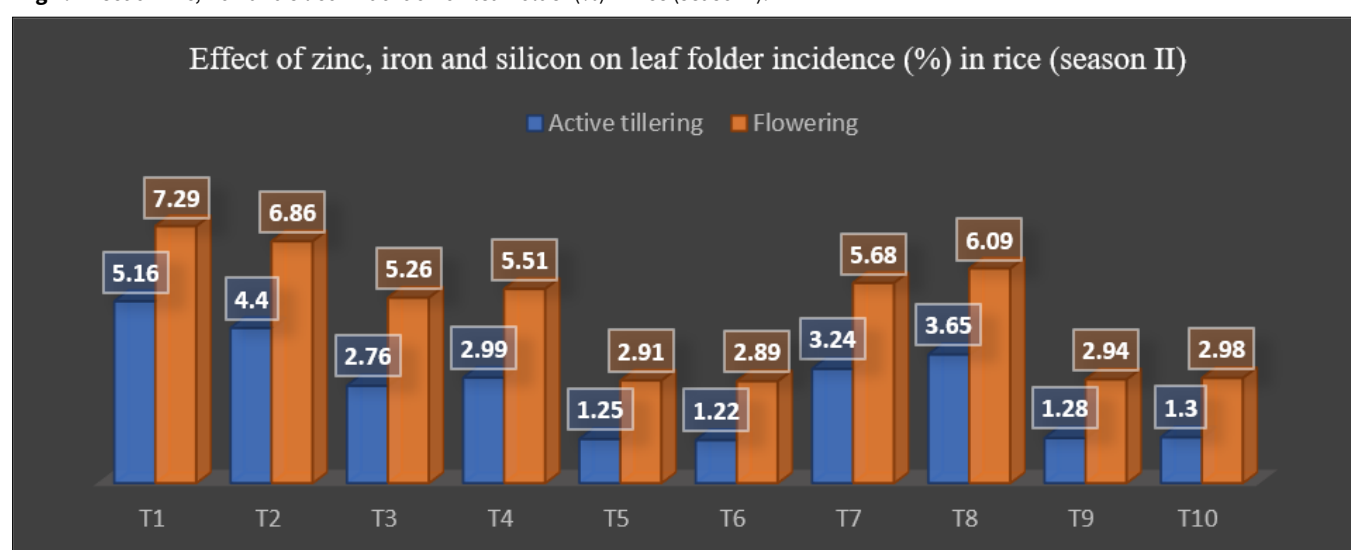


Fig 2. Effect of zinc, iron and silicon nutrition on leaf folder (%) in rice (season II).

Table 1. Effect of zinc, iron and silicon on partitioning of yield in rice

Treatments	Grain yield (kg ha ⁻¹)		Straw yield (kg ha ⁻¹)		Additional yield (kg ha ⁻¹)	
	Season I	Season II	Season I	Season II	Season I	Season II
T ₁ - Control	2025	1987	3200	2984	-	-
T ₂ - Recommended dose of fertiliser (RDF)	3950	4052	5348	6056	0	0
T ₃ - RDF + soil application of 25 kg ZnSO ₄	4740	4964	6680	7434	2122	2388
T ₄ - RDF + soil application of 25 kg FeSO ₄	4539	4736	6355	6979	1596	1638
T ₅ - RDF + soil application of 50 kg diatomaceous earth	4489	4627	6174	6892	1365	1497
T ₆ - RDF + soil application of 25 kg ZnSO ₄ + 25 kg FeSO ₄ + 50 kg diatomaceous earth	5512	5720	7726	8019	3940	4178
T ₇ - RDF + foliar application of Zn EDTA at 1 %	4346	4553	6065	6685	1113	1176
T ₈ - RDF + foliar application of Fe EDTA at 0.5 %	4130	4344	5782	6419	614	647
T ₉ - RDF + foliar application of nano silicon at 400 g ha ⁻¹	4092	4238	5601	6395	395	470
T ₁₀ - RDF + foliar application of Zn EDTA at 1 % + Fe EDTA at 0.5 % + nano silicon at 400 g ha ⁻¹	4865	5080	6908	7643	2475	2715

Iron application improved yield by ensuring optimal availability of essential nutrients in the soil, which in turn positively influenced physiological processes and facilitated the accumulation of photosynthates (7), with a similar trend observed in the present study, but with greater yield enhancement under integrated nutrient application. Iron plays a crucial role in photosynthesis and respiration through its involvement in electron transport systems and it supports antioxidant activity that reduces oxidative stress in plants, thereby contributing to enhanced yield (8).

Silicon, applied through diatomaceous earth, played a key role in mitigating biotic and abiotic stresses, thereby enhancing physiological resilience and photosynthetic efficiency in rice. The gradual release of bioavailable Si improved structural integrity, stomatal regulation and water-use efficiency, resulting in better vegetative and reproductive growth. These findings agree with earlier reports (9, 10, 11), which indicated that Si application enhances stress tolerance and nutrient uptake, ultimately improving resource-use efficiency and yield. However, the magnitude of yield

improvement observed in the present study was higher due to the combined application of Zn, Fe and Si. The cumulative effect of stress reduction improved physiological processes and enhanced photosynthate partitioning underscores the critical role of Si in elevating rice productivity through diatomaceous earth (Si) application.

The simultaneous application of Zn, Fe and Si facilitated enhanced nutrient uptake and optimised physiological functions, contributing to higher yields in both growing seasons. The interaction of these micronutrients, along with RDF, resulted in increased nutrient availability in the soil, better root development and more efficient partitioning of assimilates to reproductive organs. This optimised yield partitioning contributed to the substantial yield increases in both seasons, reinforcing the importance of balanced micronutrient management in rice cultivation.

Partial budgeting

The partial budgeting analysis for rice cultivation under Zn, Fe and Si nutrition is presented in Table 2. The analysis reveals critical insights into the economic implications and benefits of micronutrient applications. The financial impacts of different treatments on additional costs, net returns and net gains in two growing seasons, with a particular focus on comparing each treatment against the RDF which serves as the baseline, with zero additional costs or returns associated with its application. The cost of cultivation for the control treatment, which does not include any additional nutrient applications was recorded at ₹47050. The partial budgeting details for RDF during season I and season II are presented in Table 3 and Table 4 respectively.

Additional costs: From the components of partial budgeting, treatments utilising various combinations of micronutrients significantly influence both costs and yield. Specifically, treatment T₆ incurred the highest additional costs of ₹ 5690 in season I and season II, due to the expenses related to Zn sulphate, ferrous sulphate, diatomaceous earth and their application charges. Despite this substantial investment, the analysis indicates that these costs are justified by the remarkable yield gains and economic returns

associated with this treatment. Detailed partial budgeting of soil application of Zn, Fe and Si nutrition over RDF during season I and season II is presented in Table 5 and Table 6 respectively.

Reduced costs: Treatments involving Si application, either through diatomaceous earth or nano-Si, reduced the need for chemical pest control, thereby lowering input costs. This reduction was associated with improved plant resistance to biotic (12) and abiotic stresses (13), which enhanced plant resilience and reduced pest incidence. Silicon uptake strengthened plant structural integrity and increased resistance to pest damage, as evidenced by the lower percentage of damaged leaves recorded using the Bio Leaf application (5). These observations are consistent with earlier findings (13–21), which reported improved plant defence mechanisms and reduced pest and disease incidence with Si application. Consequently, reduced pest damage contributed to lower production costs and improved economic efficiency. The reduced cost details for season I and season II are presented in Table 5 and Table 6 respectively.

Additional returns: The additional returns were primarily driven by the significant increase in grain and straw yield under combined application of Zn, Fe and Si. This enhanced yield was attributed to the complementary roles of these nutrients in improving growth, nutrient uptake and assimilate partitioning. Zinc contributed to photosynthetic activity and assimilate formation (22), while Fe enhanced growth and metabolic functions through improved nutrient utilization (23–25). Silicon improved structural integrity, stress tolerance and resource-use efficiency, resulting in better growth and yield (26, 27). The combined effect of these nutrients led to higher productivity, which translated into increased economic returns.

Reduced returns: In the context of partial budgeting across two seasons, it is important to note that while there is a significant increase in added returns due to the combined application of Zn, Fe and Si and there is no observable reduction in returns. This can be attributed to the efficacy of the treatments in enhancing crop productivity without negatively impacting yield potential.

Table 2. Effect of zinc, iron and silicon nutrition on partial budgeting in rice

Treatments	Biological yield		Additional cost of cultivation over treatment T ₂ (in Rs) season I and II	Additional net return (in Rs)		Additional net gain (in Rs)	
	Season I	Season II		Season I	Season II	Season I	Season II
T ₁ - Control	5225	4971	-	-	-	-	-
T ₂ - Recommended dose of fertiliser (RDF)	9298	10208	0	0	0	0	0
T ₃ - RDF + soil application of 25 kg ZnSO ₄	11420	12496	2440	18938	23562	16498	18365
T ₄ - RDF + soil application of 25 kg FeSO ₄	10894	11698	1190	14147	16534	12957	15344
T ₅ - RDF + soil application of 50 kg Diatomaceous Earth	10663	11605	2940	12755	15289	9815	12339
T ₆ - RDF + soil application of 25 kg ZnSO ₄ + 25 kg FeSO ₄ + 50 kg Diatomaceous Earth	13238	14287	5690	36933	40741	31243	35051
T ₇ - RDF + foliar application of Zn EDTA at 1 %	10411	11284	1980	9591	12526	7611	10986
T ₈ - RDF + foliar application of Fe EDTA at 0.5 %	9912	10755	1890	4576	6576	2746	5186
T ₉ - RDF + foliar application of nano silicon at 400 g ha ⁻¹	9693	10578	1540	3431	5437	1891	4337
T ₁₀ - RDF + foliar application of Zn EDTA at 1 % + Fe EDTA at 0.5 % + nano silicon at 400 g ha ⁻¹	11773	12823	3590	21969	26411	18379	25311

Table 3. Effect of RDF on partial budgeting of rice (season I)

S.No	Credit	Amount (Rs. ha ⁻¹)	S.No	Debit	Amount (Rs. ha ⁻¹)
	Added returns (ha ⁻¹)			Added cost (ha ⁻¹)	
1	3950 kg of grain yield at Rs.20.60 kg ⁻¹	81370	1	120 kg Nitrogen (urea at Rs. 7 kg ⁻¹)	1822
2	5348 kg of straw yield at Rs. 2 kg ⁻¹	10696	2	40 kg Phosphorous (SSP at Rs. 11 kg ⁻¹)	2750
			3	40 kg Potassium (MOP at Rs.34 kg ⁻¹)	2257
			4	Application cost	1760
	Sub total	92066		Sub total	8589
	Reduced cost (ha ⁻¹)			Reduced returns (ha ⁻¹)	
	NIL	-		NIL	-
	Sub total	-		Sub total	-
	TOTAL (A)	92066		TOTAL (B)	8589

Net gain = A - B = 92066 - 8589 = 83477

Table 4. Effect of RDF on partial budgeting of rice (season II)

S.No	Credit	Amount (Rs. ha ⁻¹)	S.No	Debit	Amount (Rs. ha ⁻¹)
	Added returns (ha ⁻¹)			Added cost (ha ⁻¹)	
1	4052 kg of grain yield at Rs.20.60 kg ⁻¹	83471	1	120 kg Nitrogen (urea at Rs. 7 kg ⁻¹)	1822
2	6056 kg of straw yield at Rs. 2 kg ⁻¹	12112	2	40 kg Phosphorous (SSP at Rs. 11 kg ⁻¹)	2750
			3	40 kg Potassium (MOP at Rs.34 kg ⁻¹)	2257
			4	Application cost	1760
	Sub total	95583		Sub total	8589
	Reduced cost (ha ⁻¹)			Reduced returns (ha ⁻¹)	
	NIL	-		NIL	-
	Sub total	-		Sub total	-
	TOTAL (A)	95583		TOTAL (B)	8589

Net gain = A - B = 95583 - 8589 = 86994

Table 5. Effect of soil application of zinc, iron and silicon nutrition on partial budgeting of rice over RDF (Season I)

S.No	Credit	Amount (Rs. ha ⁻¹)	S.No	Debit	Amount (Rs. ha ⁻¹)
	Added returns (ha ⁻¹)			Added cost (ha ⁻¹)	
1	1562 kg of grain yield at Rs.20.60 kg ⁻¹	32177	1	25 kg Zinc sulphate at Rs. 80 kg ⁻¹	2000
2	2378 kg of straw yield at Rs. 2 kg ⁻¹	4756	2	25 kg Ferrous sulphate at Rs. 30 kg ⁻¹	750
			3	50 kg diatomaceous earth at Rs.50 kg ⁻¹	2500
			4	Application cost	440
	Sub total	36933		Sub total	5690
	Reduced cost (ha ⁻¹)			Reduced returns (ha ⁻¹)	
1	Pesticide cost	1825		NIL	-
2	Application charges	440			
	Sub total	2265		Sub total	-
	TOTAL (A)	39,198		TOTAL (B)	5690

Note: Credit and debit values were arrived from treatment T₆ in comparison with treatment T₂ - RDF

Additional Net gain = A - B = 39198 - 5690 = 33508

Table 6. Effect of soil application of zinc, iron and silicon nutrition only on partial budgeting of rice over RDF (Season II)

S.No	Credit	Amount (Rs. ha ⁻¹)	S.No	Debit	Amount (Rs. ha ⁻¹)
	Added returns (ha ⁻¹)			Added cost (ha ⁻¹)	
1	1741 kg of grain yield at Rs.20.60 kg ⁻¹	35864	1	25 kg Zinc sulphate at Rs. 80 kg ⁻¹	2000
2	2438 kg of straw yield at Rs. 2 kg ⁻¹	4876	2	25 kg Ferrous sulphate at Rs. 30 kg ⁻¹	750
			3	50 kg diatomaceous earth at Rs.50 kg ⁻¹	2500
			4	Application cost	440
	Sub total	40740		Sub total	5690
	Reduced cost (ha ⁻¹)			Reduced returns (ha ⁻¹)	
1	Pesticide cost	1825		NIL	-
2	Application charges	440			
	Sub total	2265		Sub total	-
	TOTAL (A)	43,005		TOTAL (B)	5690

Note: Credit and debit values were arrived from treatment T₆ in comparison with treatment T₂ - RDF

Additional net gain = A - B = 43005 - 5690 = 37315

Conclusion

Based on the yield partitioning and partial budget analysis of the present investigation, it can be concluded that application of RDF along with soil application of 25 kg ZnSO₄ and FeSO₄ with 50 kg diatomaceous earth demonstrates exceptional efficacy for transplanted rice cultivation.

Economic implication: This treatment also resulted in the highest economic returns, with return per rupee invested of ₹2.18 and ₹2.20, indicating superior profitability and efficient resource utilization.

Practical relevance: The results demonstrate that integrated application of Zn, Fe and Si along with RDF is an effective nutrient management strategy for enhancing rice productivity and farm income under similar agro-ecological conditions.

Future perspective: Further studies may be conducted to validate this nutrient management strategy across different soil types and climatic conditions.

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Authors' contributions

KAD conceptualised the research, designed and conducted the field experiments, analysed the data, and prepared the initial draft of the manuscript. PS provided overall supervision and key intellectual contributions to experimental design and results interpretation. SM assisted in experiment planning, data analysis and manuscript review. DV offered technical guidance, performed critical revisions, and finalised the editing. All authors read and approved of the final manuscript.

Compliance with ethical standards

Conflict of interest: All authors declare that they have no conflicts of interest.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process : During the preparation of this article, the authors used Grammarly to improve the language and readability of the text. After using this tool, the authors carefully reviewed and edited the content as required and take full responsibility for the final content of the publication.

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