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Iron fertilization strategies for improving yield and economic returns of aerobic direct-seeded rice under indo-Gangetic alluvial soils

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Abstract

Iron (Fe) deficiency is a major constraint to aerobic direct-seeded rice (DSR) production in calcareous soils of the Indo-Gangetic plains due to high soil pH and low Fe availability. A two-year on-farm trial was conducted during the kharif seasons of 2019–20 and 2021–22 at five farmer fields in Muzaffarpur district, Bihar, to evaluate the effectiveness of soil and foliar iron fertilization strategies on the productivity and profitability of direct-seeded rice. The experiment was laid out in a randomized block design with four treatments: farmers' practice (T_0), recommended dose of fertilizers (RDF: 120–60–40 kg N–P₂O₅–K₂O ha⁻¹) (T_1), RDF + soil application of FeSO₄ @ 16 kg ha⁻¹ (T_2), and RDF + foliar spray of FeSO₄ @ 2.5 g L⁻¹ at 45 and 60 days after sowing (T_3). Stage-wise foliar application of FeSO₄ significantly enhanced yield attributes, including productive tillers, panicle length, and grains per panicle, compared to soil application and control treatments. The highest pooled grain yield (3516 kg ha⁻¹) and straw yield (7151 kg ha⁻¹) were recorded under T_3 , representing a substantial improvement over farmers' practice. Biological yield (10,394 kg ha⁻¹) and harvest index (35.67%) were also maximized with foliar Fe application. Economic analysis revealed that T_3 produced the highest gross return (₹67,668 ha⁻¹), net return (₹32,168 ha⁻¹), and benefit–cost ratio (1.92), indicating superior profitability. The study demonstrates that stage-wise foliar application of FeSO₄ is more effective than soil application in correcting Fe deficiency and improving yield and economic returns of aerobic direct-seeded rice under calcareous soils of North Bihar. This strategy offers a practical and economically viable nutrient management option for enhancing DSR productivity in the Indo-Gangetic plains.

Keywords: Direct-seeded rice (DSR), iron deficiency, foliar FeSO₄ application, calcareous soils, grain yield, B:C ratio, on-farm trial, nutrient management

Introduction

Rice (*Oryza sativa* L.) is the staple food for more than half of the global population, with nearly 90% of production concentrated in Asia [1]. India is one of the leading rice-producing countries, and eastern Indo-Gangetic plains play a significant role in national food security [2, 3]. However, conventional puddled transplanted rice is highly water-intensive and contributes substantially to methane emissions [4]. In this context, direct-seeded rice (DSR) has emerged as a resource-efficient alternative due to reduced water requirement, lower labour costs, and decreased greenhouse gas emissions [5]. Despite its advantages, aerobic DSR systems often suffer from micronutrient deficiencies [6], particularly iron (Fe), which limit crop productivity. Iron is an essential micronutrient [7, 8] involved in chlorophyll synthesis, electron transport, respiration, and enzymatic activity [9]. Its deficiency leads to interveinal chlorosis, impaired photosynthesis, and reduced biomass accumulation [10], ultimately affecting grain yield. Iron deficiency is especially prevalent in calcareous and alkaline soils due to high pH, excessive calcium carbonate, and reduced Fe solubility [11]. The Indo-Gangetic alluvial soils of North Bihar are predominantly calcareous with alkaline reaction [12, 13], where DTPA-extractable Fe is often below critical limits [13]. Under aerobic soil conditions typical of DSR, Fe availability further declines due to oxidation of ferrous (Fe²⁺) to ferric (Fe³⁺) forms [12], which are poorly soluble and unavailable to plants. Moreover, farmers rarely apply iron fertilizers, leading to progressive nutrient mining and yield stagnation.

Although both soil and foliar application of Fe fertilizers have been recommended for correcting iron deficiency [14], their comparative effectiveness under aerobic DSR systems in calcareous soils remains inadequately documented under farmers' field conditions [15, 18]. Soil application of FeSO_4 often suffers from rapid oxidation and fixation, whereas foliar application may provide a more direct and efficient route of nutrient correction at critical growth stages [16]. However, systematic evaluation of stage-wise foliar Fe application in DSR systems of the eastern Indo-Gangetic plains is limited [17, 19]. Therefore, the present study was undertaken to evaluate the response of direct-seeded rice to different iron fertilization strategies under calcareous soils of North Bihar. The specific objectives were: (i) to compare soil and foliar application of FeSO_4 on growth and yield attributes of aerobic DSR; (ii) to assess their impact on grain yield and harvest index; and (iii) to determine the economic viability of iron fertilization under farmers' field conditions.

Materials and Methods

Study Site Description

The on-farm experiment was conducted during the kharif seasons of 2019–20 and 2021–22 at five pre-selected farmers' fields in Muzaffarpur district, Bihar, India. The study area lies in the Indo-Gangetic North-West Alluvial Plains at 26.1197° N latitude and 85.3910° E longitude, with an average elevation of 154 feet above mean sea level. The region is characterized by a subtropical humid climate with warm summers and moderate rainfall during the monsoon season. The dominant cropping system of the area is rice–wheat. The experimental fields were representative of calcareous alluvial soils prevalent in North Bihar [20].

Soil Characteristics

Before layout of the experiment, composite surface soil samples (0–15 cm depth) were collected from each selected field and analyzed using standard procedures [21]. Soil samples were analyzed for pH and EC in 1:2.5 soil water suspension ratios. The organic carbon was estimated (Walkley and Black, 1934) [22]. The available N was determined by using alkaline K permanganate method ascribed by Subbiah and Ashija [23], available P was analyzed by method described by Olsen *et al.* [24], and available K was determined by flame photometrically as described Jackson [21]. The available Fe cations were analysed by method describe as DTPA Extractable Fe [25].

Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with four treatments and five replications across farmers' fields. The treatments consisted of: T₀: Farmers' practice; T₁: Recommended dose of fertilizers (RDF: 120–60–40 kg N–P₂O₅–K₂O ha⁻¹); T₂: RDF + soil application of FeSO_4 @ 16 kg ha⁻¹; T₃: RDF + foliar spray of FeSO_4 @ 2.5 g L⁻¹ at 45 and 60 days after sowing (DAS). Nitrogen, phosphorus, and potassium were applied through urea and diammonium phosphate. Nitrogen was applied in split doses as per standard agronomic recommendations [26, 27].

Crop Management Practices

Direct-seeded rice cultivar 'Rajendra Bhagwati' was sown on 21 June 2019 and 21 June 2021 under aerobic conditions. The crop was harvested on 20 October 2019 and 22 October 2021, respectively. Standard agronomic practices for weed,

pest, and water management were followed uniformly across treatments [28]. The experimental fields were maintained under non-puddled aerobic conditions throughout the crop growth period.

Data Collection

Observations were recorded from three randomly selected hills per plot for non-destructive measurements. The parameters were recorded for Productive tillers (m⁻¹), Panicle length (cm), Grains per panicle, Test weight (1000-grain weight). At harvest, grain and straw yields were recorded from the net plot area and converted to kg ha⁻¹. Biological yield was calculated as the sum of grain and straw yield. Harvest index (%) was computed using the formula [19]:

$$\text{Harvest Index (\%)} = \frac{(\text{Grain yield})}{(\text{Biological yield})} \times 100$$

Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a randomized block design. The significance of treatment effects was tested at the 5% probability level. Standard error of mean (SEM±) and critical difference (CD) values were calculated to compare treatment means. Statistical procedures were followed as described by Gomez and Gomez [29].

Economic Analysis

Economic evaluation was carried out by calculating gross return, net return, and benefit–cost (B:C) ratio. Gross return (₹ ha⁻¹) was calculated based on prevailing market price of grain and straw. Net return (₹ ha⁻¹) = Gross return – Cost of cultivation. Benefit–cost ratio = Gross return / Cost of cultivation. Cost of cultivation included input costs for fertilizers, iron application, labour, and other agronomic operations

Results and Discussion

Initial soil test value of experimental plot (0–15 cm)

The soils were alkaline in reaction (pH 8.29) with low electrical conductivity (0.30 dSm⁻¹). Organic carbon content was 0.62%. The available nitrogen, phosphorus (P₂O₅), and potassium (K₂O) were 298.20, 29.91, and 182.97 kg ha⁻¹, respectively. DTPA-extractable iron content was 0.90 ppm, indicating Fe deficiency under aerobic conditions. The result was in conformity with the work of many scientists [30]

Yield Attributes

Iron fertilization significantly influenced the yield attributes of aerobic direct-seeded rice (DSR) (Table 2). Pooled data over two years indicated that treatment T₃ (RDF + foliar FeSO_4 @ 2.5 g L⁻¹) produced the highest number of productive tillers (303.43 m⁻¹), which was significantly greater than the farmers' practice (273.68 m⁻¹). Panicle length was also markedly improved under foliar iron application, with a maximum value of 22.95 cm in T₃ compared to 21.37 cm in T₀. Similarly, the number of grains per panicle was highest in T₃ (120.78), followed by T₂ (117.88) and T₁ (114.97). Test weight showed a numerical increase with iron fertilization, reaching a maximum of 17.35 g in T₃; however, the differences were not statistically significant. Overall, the results demonstrate that direct-seeded rice is highly responsive to iron application,

particularly through foliar feeding. The enhanced yield attributes under T_3 may be attributed to improved metabolic activity and physiological efficiency resulting from iron supplementation, which promotes the formation of productive tillers and their conversion into reproductive structures. Since nitrogen was uniformly applied across all treatments, the observed improvements can be primarily ascribed to iron nutrition. These findings are consistent with earlier reports indicating that micronutrient application enhances vegetative growth and facilitates the conversion of tillers into productive panicles [31, 32].

Grain and Straw Yield

Grain yield was significantly affected by iron fertilization strategies (Table 3). The highest pooled grain yield (3516 kg ha^{-1}) was recorded in T_3 , which was 20.9% higher than farmers' practice (2908 kg ha^{-1}). Soil application of FeSO_4 (T_2) also improved grain yield (3378 kg ha^{-1}) but remained inferior to foliar application. Straw yield followed a similar trend. The maximum pooled straw yield (7151 kg ha^{-1}) was obtained in T_3 , followed by T_2 (6913 kg ha^{-1}), while the lowest straw yield was observed under farmers practice in T_0 (6423 kg ha^{-1}). The higher improvement in grain and straw yield due to foliar and soil application of iron with RDF led to the higher vegetative growth and photosynthesis production resulted in higher dry weight production [33]. Moreover, external fertilization of iron in DSR has shown better response due to availability of nutrient at most critical stages for nutrient requirements. So, application of Fe could only avert the possible deficiencies of Fe element and can result in prevention of yield reduction due to insufficient uptake by aerobic rice [34].

Biological Yield and Harvest Index

Biological yield and harvest index were significantly influenced by iron fertilization treatments (Table 3). Pooled analysis revealed that treatment T_3 (RDF + foliar $\text{FeSO}_4 @ 2.5 \text{ g L}^{-1}$) recorded the highest biological yield ($10,394 \text{ kg}$

ha^{-1}) and harvest index (35.67%), followed by T_2 (soil application of Fe) and T_1 (RDF alone). In contrast, the lowest biological yield ($9,413 \text{ kg ha}^{-1}$) and harvest index (32.99%) were observed under the farmers' practice (T_0). The improvement in biological yield under iron application can be attributed to enhanced vegetative growth and greater dry matter accumulation, resulting from improved nutrient availability and metabolic activity. Furthermore, external application of micronutrients in aerobic direct-seeded rice ensures adequate nutrient supply during critical growth stages, thereby preventing hidden deficiencies and enhancing overall productivity. The higher harvest index under T_3 indicates more efficient partitioning of assimilates towards grain yield. These findings are in agreement with earlier reports [34, 35], who highlighted the role of micronutrient fertilization in improving growth and yield in rice under aerobic conditions [36].

Economics

Economic analysis revealed that iron fertilization significantly enhanced profitability (Table 4). Pooled data over two years indicated that treatment T_3 (RDF + foliar $\text{FeSO}_4 @ 2.5 \text{ g L}^{-1}$) recorded the highest gross return ($\text{₹}67,668 \text{ ha}^{-1}$), net return ($\text{₹}32,168 \text{ ha}^{-1}$), and benefit-cost ratio (1.92). This was followed by T_2 (soil application of $\text{FeSO}_4 @ 16 \text{ kg ha}^{-1}$ with RDF) and T_1 (RDF alone). In contrast, the farmers' practice (T_0) resulted in the lowest net return ($\text{₹}23,374 \text{ ha}^{-1}$) and B:C ratio (1.73). The superior economic performance of T_3 can be attributed to higher yield and improved resource-use efficiency under foliar iron application. Although soil application of FeSO_4 also enhanced returns, it was comparatively less profitable than foliar application. These findings are consistent with earlier studies [37], as reported higher net returns with foliar application compared to soil application and control, [38] while Yadav *et al.* [39], also observed that FeSO_4 application significantly influenced cost of cultivation, net returns, and benefit-cost ratio in aerobic rice.

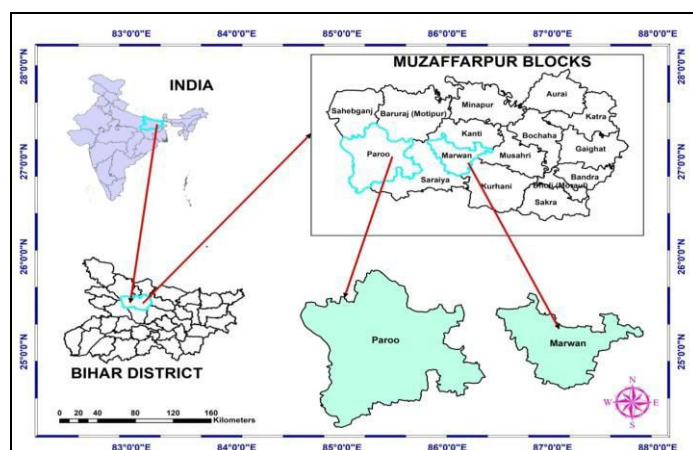


Fig. 1: Location map of study area (Marwan and Paroo Blocks in Muzaffarpur, Bihar)

Table 1: Initial soil test value of experimental plot (0-15 cm)

Particulars	Value	Method	References
pH (1:2.5; Soil:water)	8.29	Potentiometric method	Jackson, 1973 [21]
Electrical Conductivity (dSm^{-1})	0.30	Conductivity method	Jackson, 1973 [21]
Organic carbon (%)	0.62	Rapid Titration method	Walkley and Black, 1934 [22]
Available N (Kg ha^{-1})	298.20	Alkaline KMnO_4 method	Subbiah and Asija, 1956 [23]
Available P_2O_5 (Kg ha^{-1})	29.91	0.5M NaHCO_3 extractable colorimetric method	Olsen <i>et al.</i> , 1954 [24]
Available K_2O (Kg ha^{-1})	182.97	1 N NH_4OAc (pH 7.0) solution (1:5 soil: water solution ratio) method	Jackson, 1973 [21]
DTPA Extractable Fe (ppm)	0.90	0.05 M DTPA method (pH 7.3)	Lindsay and Norvell, 1978 [25]

Table 2: Effect of iron application on yield attributes of aerobic rice

Treatments	Yield attributes											
	Productive tillers (m ⁻¹)		Pooled	Panicle length (cm)		Pooled	Grains panicle ⁻¹		Pooled	Test weight (g)		Pooled
	2019-20	2021-22		2019-20	2021-22		2019-20	2021-22		2019-20	2021-22	
T ₀ : Farmers Practice	277.23	270.12	273.68	21.43	21.30	21.37	103.60	103.19	103.40	16.20	16.25	16.23
T ₁ : RDF (N ₁₂₀ -P ₆₀ -K ₄₀)	289.84	280.51	285.18	22.47	22.36	22.42	118.73	111.21	114.97	16.31	16.42	16.37
T ₂ : RDF + SA of FeSO ₄ @ 16kg ha ⁻¹	298.13	291.16	294.65	22.63	22.63	22.63	120.87	114.89	117.88	17.05	17.08	17.07
T ₃ : RDF + FS of FeSO ₄ @ 2.5gm/lit	305.21	301.65	303.43	22.86	23.03	22.95	121.33	120.22	120.78	17.50	17.20	17.35
SEm±	1.78	2.1	1.94	0.15	0.08	0.12	0.88	0.99	0.94	1.20	0.90	1.05
C. D. (P=0.05)	6.62	6.25	6.44	0.56	0.25	0.41	3.25	2.95	3.10	NS	NS	NS

SA, Soil applied; FS, Foliar Spray

Table 3: Effect of iron application on yield of aerobic rice

Treatments	Yield (kg ha ⁻¹)											
	Grain		Pooled	Straw		Pooled	Biological		Pooled	HI		Pooled
	2019-20	2021-22		2019-20	2021-22		2019-20	2021-22		2019-20	2021-22	
T ₀ : Farmers Practice	2780	3035	2908	6232	6613	6423	9393	9433	9413	33.75	32.22	32.99
T ₁ : RDF (N ₁₂₀ -P ₆₀ -K ₄₀)	2988	3271	3130	6320	6960	6640	9954	9894	9924	35.40	33.07	34.24
T ₂ : RDF + SA of FeSO ₄ @ 16kg ha ⁻¹	3377	3379	3378	6849	6976	6913	10353	9982	10168	36.37	33.85	35.11
T ₃ : RDF + FS of FeSO ₄ @ 2.5gm/lit	3496	3536	3516	7093	7208	7151	10604	10184	10394	36.60	34.73	35.67
SEm±	27	29	28	54	58	56	63	56	60	0.26	0.19	0.23
C.D. (P=0.05)	99	87	93	202	214	208	232	207	220	0.95	0.71	0.83

SA, Soil applied; FS, Foliar Spray

Table 4: Effect of foliar and soil application of iron on economics of aerobic rice (Pooled data of 2 years)

Treatments	Cost of cultivation (Rs. ha ⁻¹)	Gross return (Rs. ha ⁻¹)	Net return (Rs. ha ⁻¹)	B:C ratio
T ₀ : Farmers Practice	32500.00	55874.00	23374.00	1.73
T ₁ : RDF (N ₁₂₀ -P ₆₀ -K ₄₀)	33500.00	60137.00	26637.00	1.81
T ₂ : RDF + SA of FeSO ₄ @ 16kg ha ⁻¹	34660.00	65026.00	30366.00	1.89
T ₃ : RDF + FS of FeSO ₄ @ 2.5gm/lit	35500.00	67668.00	32168.00	1.92

SA, Soil applied; FS, Foliar Spray

Conclusion

The present on-farm investigation clearly demonstrated that iron fertilization significantly influences the growth, yield, and profitability of aerobic direct-seeded rice cultivated in calcareous soils of the Indo-Gangetic plains. Among the evaluated strategies, stage-wise foliar application of FeSO₄ @ 2.5 g L⁻¹ at 45 and 60 days after sowing, in combination with the recommended dose of fertilizers (120–60–40 kg N–P₂O₅–K₂O ha⁻¹), proved superior to soil application and farmers' practice. Foliar iron application markedly enhanced yield attributes, including productive tillers, panicle length, and grains per panicle, resulting in the highest grain yield (3516 kg ha⁻¹) and biological yield (10,394 kg ha⁻¹). The improvement in harvest index and economic returns (net return ₹32,168 ha⁻¹; B:C ratio 1.92) further established the agronomic and financial viability of this strategy. Soil application of FeSO₄ also improved performance over farmers' practice, but its effectiveness was comparatively lower under aerobic conditions, likely due to Fe fixation and reduced availability in alkaline soils. Overall, the study confirms that stage-wise foliar iron fertilization is a practical, efficient, and economically viable approach for correcting iron deficiency and enhancing productivity of aerobic direct-seeded rice in calcareous soils. Adoption of this nutrient management strategy can contribute to sustainable intensification of rice-based systems in the eastern Indo-Gangetic plains.

Future Scope of the Study

Although the present investigation established the superiority of stage-wise foliar iron application in improving

productivity and profitability of aerobic direct-seeded rice (DSR) under calcareous soils, several research avenues remain open for further exploration. Future research should focus on optimizing foliar iron dosage and timing, integrating iron with other micronutrients, and evaluating long-term sustainability across diverse agro-ecological conditions. Investigations into soil–plant–microbial interactions and physiological mechanisms of Fe uptake would further strengthen nutrient management strategies for aerobic direct-seeded rice in calcareous soils.

Conflict of Interest: The authors declare no conflict of interest.

Author Contributions

Kamlesh Kumar Singh: Conceptualization, Methodology, Investigation, Supervision, Writing – original draft.

Ajeet Kumar: Experimental design support, Data curation, Formal analysis, Writing – review & editing.

Sunita Kumari: Field experimentation, Data collection, Agronomic management.

Sanjay Kumar Singh: Soil analysis, Laboratory investigations, Validation of analytical data.

Santosh Kumar Gupta: On-farm coordination, Resource management, Farmer liaison, Data verification. All authors have read and approved the final manuscript.

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