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EFFECT OF IRON MANAGEMENT ON LEAF AREA INDEX AND YIELD OF RICE (*Oryza sativa* L.)

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ABSTRACT

A field experiment was conducted during the *kharif* seasons of 2020–21 and 2021–22 at Navsari Agricultural University, Navsari, Gujarat, India, to evaluate the effect of iron management on leaf area index (LAI) and yield of rice (*Oryza sativa* L.). The experiment comprised twelve treatments with three replications involving different iron fertilizers and biofertilizers, laid out in a randomized block design. The results revealed a non-significant effect of iron management treatments on LAI at 30 days after transplanting (DAT). However, significant differences were observed in LAI at 60 DAT and at harvest, as well as in grain and straw yield. Among the treatments, the application of FeSO_4 at 50 kg ha⁻¹ along with arbuscular mycorrhiza (250 g ha⁻¹, 3000 IP g⁻¹) and *Pseudomonas fluorescens* (10x cfu ml⁻¹) recorded the highest LAI (6.237 at 60 DAT and 5.122 at harvest), grain yield (53.64 q ha⁻¹) and straw yield (68.41 q ha⁻¹) in pooled analysis. However, FeSO_4 at 25 kg ha⁻¹ combined with biofertilizers produced statistically comparable results with lower input use, indicating its potential as a more economical and resource-efficient alternative. Therefore, the application of FeSO_4 at 25 kg ha⁻¹ along with biofertilizers can be considered an effective integrated nutrient management approach for improving vegetative growth and rice yield.

Key words : Iron management, Arbuscular mycorrhiza, *Pseudomonas fluorescens*, Leaf area index, Rice yield.

Introduction

Globally, rice (*Oryza sativa* L.) is one of the fundamental staple food crops and the primary source of dietary energy for more than half of the global population (GRiSP, 2013; FAO, 2024). In developing countries like India, rice plays a crucial role in providing food and nutritional security as well as sustaining rural livelihoods. Rapid population growth is steadily increasing demand for food, making it an important target of agricultural research for improving rice productivity through efficient nutrient management practices (Begum *et al.*, 2022).

Iron (Fe) is an essential micronutrient that plays a crucial role in several biochemical and physiological processes of plant growth. Although required in trace amounts, iron is requisite for metabolic activities, enzyme

activation, chlorophyll synthesis and electron transport chain reaction (Balk and Schaedler, 2014; Kobayashi and Nishizawa, 2021). In India, Iron deficiency is widely observed in rice-growing soils, particularly in calcareous and alkaline soils of Gujarat, where DTPA-extractable iron availability is low which limits crop productivity (Shukla *et al.*, 2021; Bashir and Ishimaru, 2022). Iron deficiency induces chlorosis, declined photosynthetic efficiency, poor plant growth and ultimately diminished crop productivity (Briat *et al.*, 2015; Rout and Sahoo, 2015).

Ensuring an optimal supply of iron is therefore a prerequisite for sustaining vigorous plant growth and achieving maximum yield in rice cultivation. As per Indian Council of Agricultural Research (2013) recommendations, application of iron fertilizers such as

FeSO₄ is needed in iron-deficient soils to sustain rice productivity. Adequate iron supply stimulates chlorophyll formation and photosynthetic activity, which directly influences vegetative growth parameters such as leaf development and leaf area expansion (Therby-Vale *et al.*, 2022; Ning *et al.*, 2023). Leaf Area Index (LAI) is key indicator of plant growth and canopy development, which represents the leaf surface area accessible for photosynthesis. Higher leaf area index (LAI) generally indicates better canopy development, improved light interception and higher photosynthetic activity, which ultimately results in greater biomass production and grain yield (Raza *et al.*, 2020). Improvement LAI during vegetative and reproductive stages plays a key role in determining the harvest yield of rice cultivation. Appropriate iron supply with sustainable nutrient management can enhance canopy development, maintain vigorous vegetative foliage and enhance assimilation of photosynthates which leads to improved tiller, grain formation and grain filling, all of which in turn to higher yield potential (Begum *et al.*, 2022; Ullah *et al.*, 2023). Even though iron is important for plant growth, the response of rice to different iron management practices may vary depending on soil conditions, crop growth stage and application method. Therefore, the present investigation was undertaken to evaluate the effect of different iron management practices on leaf area index and yield of rice.

Materials and Methods

Experimental site

A field experiment was conducted during the *khari* seasons of 2020–21 and 2021–22 at the College Farm, Navsari Agricultural University, Navsari, Gujarat, India. The experimental site is located at 20°57' N latitude and 72°54' E longitude, with an altitude of approximately 10 m above mean sea level. The region experiences a humid tropical climate with warm temperatures and moderate to high rainfall, most of which is received during the southwest monsoon season, providing favorable conditions for rice cultivation.

Soil properties

The experimental field was uniform and well levelled with clayey soil, locally known as deep black cotton soil. The soil was slightly alkaline in reaction and had a medium fertility status. Composite soil samples (0–15 cm depth) were collected before initiation of the experiment and analyzed for physico-chemical properties using standard laboratory procedures. The initial soil properties are presented in Table 1.

Treatments

The experiment consisted of twelve iron management treatments involving FeSO₄, Fe-EDTA, arbuscular mycorrhiza (AM) and *Pseudomonas fluorescens* applied individually or in combination (Table 2).

Seedling treatment (S) : Rice seedlings were dipped in a slurry containing arbuscular mycorrhiza (250 g ha⁻¹; 3000 IP g⁻¹) and *Pseudomonas fluorescens* (10⁸ cfu ml⁻¹) prepared in 40 L of water for 15–30 min before transplanting.

Field application (F) : Arbuscular mycorrhiza (250 g ha⁻¹) and *P. fluorescens* (1 L ha⁻¹) were mixed with well-decomposed farmyard manure (FYM) and applied uniformly in the field.

Table 1 : Initial physico-chemical properties of experimental soil (2020–21 and 2021–22).

S. no.	Soil property	2020-21	2021-22
1	Soil texture	Clayey	Clayey
2	Organic carbon (%)	0.36	0.42
3	Available nitrogen (kg ha ⁻¹)	204.4	214.1
4	Available phosphorus (kg ha ⁻¹)	36.2	34.7
5	Available potassium (kg ha ⁻¹)	300.3	312.4
6	Available Iron (mg kg ⁻¹)	9.63	10.36
7	Soil pH (1:2.5)	8.01	7.98

Table 2 : Different treatments of experiment.

Treatment	Description
M ₀	Control (RDF only)
M ₁	Fe-EDTA at 1.5 kg ha ⁻¹
M ₂	FeSO ₄ at 50 kg ha ⁻¹
M ₃	Arbuscular mycorrhiza (AM) S + F
M ₄	<i>Pseudomonas fluorescens</i> (P) S + F
M ₅	Arbuscular mycorrhiza + <i>Pseudomonas fluorescens</i> (S + F)
M ₆	FeSO ₄ at 25 kg ha ⁻¹ + Arbuscular mycorrhiza (S + F)
M ₇	FeSO ₄ at 25 kg ha ⁻¹ + <i>P. fluorescens</i> (S + F)
M ₈	FeSO ₄ at 25 kg ha ⁻¹ + Arbuscular mycorrhiza + <i>P. fluorescens</i> (S + F)
M ₉	FeSO ₄ at 50 kg ha ⁻¹ + Arbuscular mycorrhiza (S + F)
M ₁₀	FeSO ₄ at 50 kg ha ⁻¹ + <i>P. fluorescens</i> (S + F)
M ₁₁	FeSO ₄ at 50 kg ha ⁻¹ + Arbuscular mycorrhiza + <i>P. fluorescens</i> (S + F)

The doses of FeSO_4 (25 and 50 kg ha^{-1}) were selected based on standard agronomic recommendations for correction of iron deficiency in alkaline soils and previous findings under similar conditions (Fageria *et al.*, 2002; Indian Council of Agricultural Research, 2013). Fe-EDTA was included as a chelated source of iron to compare its efficiency with inorganic sources under alkaline soil conditions, where iron availability is often limited.

Experimental design

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Seedlings were transplanted at a spacing of 20×15 cm. Recommended dose of fertilizers (RDF) for rice was applied uniformly across all treatments. Observations were recorded from ten randomly selected plants in each net plot and averaged for statistical analysis.

Crop management practices

The field was prepared by ploughing, levelling and puddling before transplanting. Twenty-five to thirty-day-old rice seedlings were transplanted at a spacing of 20×15 cm with 2–3 seedlings per hill. Iron fertilizers and biofertilizers were applied according to the treatment schedule. A water depth of 5 ± 2 cm was maintained throughout the crop growth period except before harvest. Recommended agronomic and plant protection practices were followed uniformly in all treatments. The crop was harvested at physiological maturity and grain and straw yields were recorded.

Measurement of Leaf Area index

Leaf length (L) and maximum breadth (B) of representative fully expanded leaves were measured, and the leaf area of a single leaf was estimated using a correction factor of 0.75 (Palaniswamy and Gomez, 1974).

$$\text{Leaf area (single leaf)} = L \times B \times 0.75$$

The total leaf area per plant was calculated by multiplying the single leaf area by the number of functional leaves (n):

$$\text{Total leaf area per plant} = L \times B \times 0.75 \times n$$

LAI was then computed as the ratio of total leaf area per plant to ground area per plant (G):

$$LAI = \frac{L \times B \times 0.75 \times n}{G}$$

Measurements were recorded at 30 and 60 days after transplanting (DAT) and at harvest from ten tagged plants per plot (Yoshida *et al.*, 1976).

Yield measurement

At physiological maturity, grain and straw yields were

recorded from the net plot area and expressed as q ha^{-1} . Harvest index (HI) was calculated using the following formula (Donald, 1962):

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

Statistical analysis

The experimental data were analysed by analysis of variance (ANOVA) appropriate for a Randomized Block Design (RBD) following the procedure described by Panse and Sukhatme (1967). Treatment means were compared using the Critical Difference (CD) test at the 5% probability level. The results are presented as Standard Error of Mean [S.E.m. ($\pm$)] and Critical Difference (CD).

Results and Discussion

Leaf area index (LAI)

LAI is an important indicator of crop canopy development and photosynthetic capacity, as it regulates light interception, carbon assimilation, and biomass production (Gong *et al.*, 2021). As per the data in Table 3-6, the LAI values at 30 DAT (Day After Transplanting) were relatively low and statistically non-significant across all treatments (0.861–0.985 pooled), indicating that early-stage rice plants had not yet fully expanded their leaf area. During the early vegetative stage, assimilates are preferentially utilized for root establishment and tiller initiation rather than extensive leaf expansion, resulting in comparatively lower LAI values (Yoshida, 1981). This is typical during the initial vegetative stage, as plants are primarily investing in root establishment and initial tillering rather than producing a fully developed leaf canopy.

At 60 DAT, the LAI increased markedly across treatments, ranging from 4.892 to 6.237 (pooled), with significant differences observed between treatments. The highest LAI was recorded under M_{11} (FeSO_4 at 50 kg ha^{-1} + AM + *P. fluorescens*), followed by M_9 , M_{10} and M_8 , which were statistically at par with M_{11} . The enhanced LAI under integrated iron management may be attributed to the vital role of iron in chlorophyll biosynthesis, electron transport, respiration and activation of several metabolic enzymes, which collectively improve photosynthetic efficiency, cell division and leaf expansion (Bandyopadhyay and Prasad, 2021; Kobayashi and Nishizawa, 2021). Similarly, biofertilizers such as AM and *P. fluorescens* enhance nutrient uptake and water absorption, supporting vigorous canopy development (Begum *et al.*, 2022). Treatments M_9 (6.190), M_{10} (6.155) and M_8 (6.082) were statistically similar with M_{11} (6.237),

Table 3 : Leaf length, leaf breadth, leaf area and leaf area index of *kharif* rice at 30 DAT (2020-21, 2021-22 and pooled data).

LAI at 30 DAT												
Treatments	2020-21				2021-22				Pooled			
	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI
M ₀	30.5	1.30	29.8	0.866	30.3	1.29	29.4	0.857	30.4	1.30	29.6	0.861
M ₁	31.0	1.32	30.7	0.891	30.5	1.31	30.0	0.859	30.7	1.32	30.3	0.875
M ₂	31.5	1.34	31.7	0.913	31.0	1.33	30.9	0.902	31.2	1.34	31.3	0.908
M ₃	30.8	1.31	30.4	0.870	30.4	1.30	29.7	0.857	30.6	1.31	30.0	0.864
M ₄	31.0	1.31	30.5	0.888	30.5	1.30	29.8	0.859	30.7	1.31	30.1	0.874
M ₅	31.2	1.33	31.1	0.890	31.0	1.32	30.5	0.870	31.1	1.33	30.8	0.880
M ₆	31.3	1.33	31.2	0.901	31.1	1.32	30.6	0.878	31.2	1.33	30.9	0.890
M ₇	31.4	1.34	31.6	0.902	31.2	1.33	31.0	0.891	31.3	1.34	31.3	0.896
M ₈	32.0	1.35	32.4	0.924	31.8	1.34	32.0	0.923	31.9	1.35	32.2	0.924
M ₉	32.2	1.35	32.6	0.955	32.0	1.34	32.2	0.944	32.1	1.35	32.4	0.950
M ₁₀	32.1	1.35	32.5	0.945	31.9	1.34	32.1	0.927	32.0	1.35	32.3	0.936
M ₁₁	32.5	1.36	33.0	0.986	32.3	1.35	32.8	0.984	32.4	1.36	32.9	0.985

Table 4 : Leaf length, leaf breadth, leaf area and leaf area index of *kharif* rice at 60 DAT (2020-21, 2021-22 and pooled data).

LAI at 60 DAT												
Treatments	2020-21				2021-22				Pooled			
	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI
M ₀	52.0	1.95	76.1	4.875	52.5	1.92	75.6	4.909	52.2	1.93	75.6	4.892
M ₁	54.5	2.00	81.8	5.413	54.0	1.97	79.8	5.350	53.8	1.98	79.9	5.382
M ₂	56.0	2.05	86.1	5.740	55.8	2.02	84.6	5.733	55.9	2.02	84.7	5.737
M ₃	53.5	1.98	79.4	5.267	53.0	1.94	77.1	5.039	53.2	1.95	77.8	5.153
M ₄	54.0	1.98	80.2	5.322	53.2	1.94	77.4	5.065	53.5	1.95	78.2	5.194
M ₅	54.8	2.00	82.2	5.433	54.8	1.99	81.8	5.500	54.8	1.99	81.8	5.467
M ₆	55.0	2.00	82.5	5.450	54.5	1.98	80.9	5.413	54.7	1.98	81.2	5.432
M ₇	55.2	2.00	82.8	5.460	54.7	1.99	81.6	5.497	54.9	1.99	81.9	5.478
M ₈	58.0	2.10	91.4	6.130	57.5	2.03	87.5	6.034	57.7	2.03	87.9	6.082
M ₉	58.5	2.12	93.0	6.213	58.0	2.04	88.7	6.167	58.2	2.04	89.1	6.190
M ₁₀	58.3	2.10	91.8	6.197	57.8	2.03	88.0	6.114	58.0	2.03	88.3	6.155
M ₁₁	58.7	2.12	93.3	6.221	58.2	2.05	89.5	6.253	58.4	2.05	89.7	6.237

suggesting that the combined application of FeSO₄ with biofertilizers effectively enhanced canopy development irrespective of the iron dose.

At harvest, LAI declined slightly (3.898–5.122 pooled), which is a normal physiological phenomenon in rice. The reduction in LAI at maturity is mainly associated

with natural leaf senescence and remobilization of photosynthates and nutrients from leaves to developing grains during the grain-filling stage (Yoshida, 1981; Ullah *et al.*, 2023). Consequently, photosynthetic activity gradually decreases as the crop approaches maturity. Despite this decline, treatments receiving integrated iron

Table 5 : Leaf length, leaf breadth, leaf area and leaf area index of *kharif* rice at harvest (2020-21, 2021-22 and pooled data).

Treatments	LAI at harvest											
	2020-21				2021-22				Pooled			
	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI	Leaf length (cm)	Leaf breadth (cm)	Leaf area (cm ²)	LAI
M ₀	50.2	1.90	71.5	3.870	50.5	1.91	72.3	3.927	50.3	1.90	71.7	3.898
M ₁	51.8	1.93	75.0	4.327	51.5	1.92	74.2	4.253	51.6	1.93	74.7	4.290
M ₂	53.8	1.97	79.5	4.850	53.2	1.96	78.2	4.643	53.5	1.97	79.0	4.747
M ₃	50.8	1.91	72.8	3.990	50.8	1.91	72.8	4.003	50.8	1.91	72.8	3.997
M ₄	51.0	1.91	73.1	4.013	51.0	1.91	73.1	4.010	51.0	1.91	73.1	4.012
M ₅	52.5	1.95	76.8	4.380	52.8	1.95	77.2	4.393	52.6	1.95	76.9	4.387
M ₆	52.7	1.95	77.1	4.433	52.9	1.95	77.4	4.400	52.8	1.95	77.2	4.417
M ₇	53.0	1.96	77.9	4.507	53.0	1.95	77.6	4.413	53.2	1.96	78.2	4.460
M ₈	55.8	2.00	83.7	5.033	55.8	2.00	83.7	5.033	55.8	2.00	83.7	5.033
M ₉	56.2	2.01	84.7	5.093	56.0	2.01	84.4	5.077	56.1	2.01	84.6	5.085
M ₁₀	56.0	2.00	84.0	5.087	55.9	2.00	83.9	5.067	56.0	2.00	84.0	5.077
M ₁₁	56.5	2.02	85.6	5.143	56.2	2.02	85.1	5.100	56.4	2.02	85.4	5.122

Table 6 : Leaf area index (LAI) of *kharif* rice as affected by different treatments.

Treatments	Leaf area index								
	30 DAT			60 DAT			At harvest		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
M ₀	0.866	0.857	0.861	4.875	4.909	4.892	3.870	3.927	3.898
M ₁	0.891	0.859	0.875	5.413	5.350	5.382	4.327	4.253	4.290
M ₂	0.913	0.902	0.908	5.740	5.733	5.737	4.850	4.643	4.747
M ₃	0.870	0.857	0.864	5.267	5.039	5.153	3.990	4.003	3.997
M ₄	0.888	0.859	0.874	5.322	5.065	5.194	4.013	4.010	4.012
M ₅	0.890	0.870	0.880	5.433	5.500	5.467	4.380	4.393	4.387
M ₆	0.901	0.878	0.890	5.450	5.413	5.432	4.433	4.400	4.417
M ₇	0.902	0.891	0.896	5.460	5.497	5.478	4.507	4.413	4.460
M ₈	0.924	0.923	0.924	6.130	6.034	6.082	5.033	5.033	5.033
M ₉	0.955	0.944	0.950	6.213	6.167	6.190	5.093	5.077	5.085
M ₁₀	0.945	0.927	0.936	6.197	6.114	6.155	5.087	5.067	5.077
M ₁₁	0.986	0.984	0.985	6.221	6.253	6.237	5.143	5.100	5.122
S.Em. ±	0.037	0.040	0.027	0.252	0.246	0.176	0.216	0.232	0.158
C.D. at 5%	NS	NS	NS	0.74	0.72	0.50	0.63	0.68	0.45
Y x T									
SEm ±			0.038			0.249			0.224
CD (P=0.05)			NS			NS			NS
CV%	6.94	7.72	7.34	7.74	7.63	7.68	8.21	8.87	8.54

management maintained higher LAI than the control, indicating prolonged maintenance of green leaf area during grain filling, which likely contributed to greater biomass accumulation and improved grain yield. Overall, the pattern of low LAI at 30 DAT, maximum LAI at 60 DAT and a gradual decline at harvest reflects the normal growth behaviour of rice. The significant improvement in LAI under integrated application of FeSO_4 , arbuscular mycorrhiza and *Pseudomonas fluorescens* demonstrates the beneficial role of balanced iron nutrition and microbial inoculation in improving canopy development, photosynthetic efficiency and ultimately rice productivity.

Yield of *kharif* rice

The data on grain yield, straw yield and harvest index of *kharif* rice are presented in Table 7. The results revealed that iron management practices significantly influenced both grain and straw yield during both the years as well as in pooled analysis. Among the treatments, application of FeSO_4 at 50 kg ha⁻¹ in combination with arbuscular mycorrhiza (AM) and *Pseudomonas fluorescens* as seedling treatment and field application at 1 L ha⁻¹ (M_{11}) recorded the highest grain yield (55.22, 53.07 and 53.64 q ha⁻¹) and straw yield (67.81, 69.00

and 68.41 q ha⁻¹). However, this treatment remained statistically at par with M_2 (FeSO_4 at 50 kg ha⁻¹), M_8 (FeSO_4 at 25 kg ha⁻¹ + AM + *P. fluorescens*), M_9 (FeSO_4 at 50 kg ha⁻¹ + AM) and M_{10} (FeSO_4 at 50 kg ha⁻¹ + *P. fluorescens*). Based on pooled results, the treatments showed the following order for grain yield: $M_{11} > M_9 > M_{10} > M_8 > M_2 > M_6 > M_7 > M_5 > M_1 > M_4 > M_3 > M_0$, while for straw yield the order was $M_{11} > M_{10} > M_9 > M_8 > M_2 > M_7 > M_6 > M_5 > M_1 > M_3 > M_4 > M_0$. The highest increase in grain yield (73.95%) and straw yield (80.97%) over the control (M_0 : RDF) was recorded under treatment M_{11} . The lowest grain and straw yields were recorded under the control treatment during both the years and in pooled analysis. Iron management treatments did not exert a significant effect on harvest index during either year or in the pooled analysis. However, numerically the highest harvest index was observed under M_0 (RDF only) during 2020–21, whereas M_9 (FeSO_4 @ 50 kg ha⁻¹ + AM) recorded the highest harvest index during 2021–22 and in the pooled analysis. The lowest harvest index was recorded under M_2 (FeSO_4 @ 50 kg ha⁻¹) during both years, while in the pooled analysis it was observed under M_4 (*P. fluorescens* applied as seedling treatment and field application).

Table 7 : Yield and harvest index of *kharif* rice as affected by different treatments.

Treatments	Grain yield (q ha ⁻¹)			Straw yield (q ha ⁻¹)			Harvest index (%)		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
M_0	31.10	30.57	30.84	37.74	37.85	37.80	45.29	44.51	44.90
M_1	35.23	35.62	35.43	44.22	44.61	44.42	44.35	44.38	44.36
M_2	49.29	46.04	47.67	63.68	60.19	61.93	43.63	43.34	43.49
M_3	33.84	34.57	34.20	43.63	44.48	44.06	43.42	43.52	43.47
M_4	34.70	34.66	34.68	44.07	44.03	44.05	43.97	43.96	43.96
M_5	37.83	40.38	39.11	47.47	49.78	48.63	44.36	44.80	44.58
M_6	43.22	42.46	42.84	53.74	51.45	52.59	44.59	45.22	44.90
M_7	42.91	43.14	43.03	53.22	54.13	53.67	44.61	44.33	44.47
M_8	52.33	51.47	51.90	65.57	61.07	63.32	44.37	45.79	45.08
M_9	53.87	52.04	52.95	66.88	65.13	66.01	44.61	44.42	44.52
M_{10}	53.54	51.74	52.64	66.68	66.51	66.59	44.54	43.79	44.17
M_{11}	54.22	53.07	53.64	67.81	69.00	68.41	44.42	43.47	43.95
S.Em. $\pm$	3.275	3.047	2.237	3.736	3.490	2.556	0.571	0.870	0.520
C.D. at 5%	9.61	8.94	6.38	10.96	10.24	7.29	NS	NS	NS
Y x T									
SEm $\pm$			3.163			3.615			0.736
CD (P=0.05)			NS			NS			NS
CV%	13.04	12.28	12.67	11.86	11.19	11.53	2.23	3.40	2.88

Iron plays a vital role in plant growth and development as it is a component of important electron transport proteins such as cytochromes and ferredoxins, which are actively involved in photosynthesis and mitochondrial respiration (Liang, 2022). It also serves as a cofactor for several enzymes, including catalase and peroxidase, which detoxify reactive oxygen species generated during respiration, thereby protecting plant cells from oxidative damage (Riaz and Guerinot, 2021). Furthermore, iron is involved in several biochemical and physiological processes, including chlorophyll biosynthesis, nitrogen and sulphur metabolism, maintenance of chloroplast structure and iron homeostasis, all of which collectively enhance photosynthetic efficiency, plant growth and ultimately crop productivity (Gao and Dubos, 2021).

Inoculation with arbuscular mycorrhiza (AM) enhances root development, water uptake and nutrient absorption, resulting in increased dry matter accumulation and improved crop productivity (Bano *et al.*, 2022; Fasusi *et al.*, 2023). Mycorrhizal association also promotes the synthesis of important phytochemicals such as chlorophyll, carotenoids and phenolic compounds, which contribute to better plant growth and physiological activity. Similarly, *Pseudomonas fluorescens* acts as a plant growth-promoting rhizobacterium that produces siderophores and phytohormones such as indole acetic acid, cytokinin and gibberellin. These compounds enhance nutrient availability in the rhizosphere and stimulate plant growth while also providing protection against certain soil-borne pathogens (Aloo *et al.*, 2022). The combined application of iron fertilizer with arbuscular mycorrhiza and *Pseudomonas fluorescens* might have improved nutrient uptake, translocation and assimilation within the plant. Enhanced photosynthate production and efficient partitioning between source and sink could have increased dry matter accumulation in reproductive parts, leading to improved yield attributes, grain yield and straw yield of rice (Fasusi *et al.*, 2023; Kumawat *et al.*, 2023). The non-significant variation in harvest index suggests that iron nutrition primarily enhanced source strength (photosynthetic capacity) without significantly affecting sink partitioning.

Conclusion

The present study demonstrated that integrated iron management significantly improved leaf area index (LAI), yield attributes, grain yield and straw yield of rice. Among the treatments, the application of FeSO_4 at 50 kg ha^{-1} along with arbuscular mycorrhiza (250 g ha^{-1} , 3000 IP g^{-1}) and *Pseudomonas fluorescens* (10^8 cfu mL^{-1}) recorded the highest performance. However, FeSO_4 at

25 kg ha^{-1} in combination with the same biofertilizers produced statistically comparable results with lower iron input, indicating its potential as a more economical and resource-efficient alternative. The integrated application of iron and biofertilizers enhanced canopy development and photosynthetic efficiency, leading to improved crop productivity. Therefore, the combined application of FeSO_4 at 25 kg ha^{-1} with arbuscular mycorrhiza (250 g ha^{-1} , 3000 IP g^{-1}) and *Pseudomonas fluorescens* (10^8 cfu mL^{-1}) can be recommended as a cost-effective and sustainable nutrient management strategy for rice cultivation.

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