AATCC Review

13 November 2024: Received
31 January 2025: Revised
25 February 2025: Accepted
02 March 2025: Available Online

https://aatcc.peerjournals.net/

Original Research Article

Open Access

Evaluating the Impact of Genetic Diversity and Iron Fertilization Methods on Iron Bioavailability in Aerobic Rice Cultivation System

B. Soumya[1], K. P. Vani[2], K. Surekha[3] and Kada Siddappa M. M[4]

[1] *Livestock Farm Complex, College of Veterinary Science, Korutla, Telangana, India*
[2] *Department of Agronomy, College of Agriculture, Rajendranagar, Hyderabad, India*
[3] *Department of (Soil Science), Indian Institute of Rice Research, Hyderabad, Telangana, India*
[4] *Department of Agronomy, Professor Jayashankar Telangana State Agricultural University, India*

ABSTRACT

Iron deficiency is a significant constraint to rice production, particularly in aerobic systems. A two-year field experiment was conducted at Professor Jayashankar Telangana State Agricultural University, Hyderabad, India to evaluate the iron uptake of three aerobic rice cultivars (M1, M2, and M3) under twelve different iron fertilization strategies in sandy clay loam soil. The experiment laid out in a split-plot design, examined the efficacy of iron sulphate and iron chelate applied through foliar and soil applications, as well as their combinations. Iron content and uptake were measured at various growth stages (seedling, maximum tillering, panicle initiation and harvest). Results revealed significant differences in iron uptake among cultivars and fertilization treatments. Cultivar M3 (KRH 2) consistently demonstrated the highest iron uptake in both grain and straw. The most effective fertilization strategy involved the basal application of iron chelate @ 25 kg ha^{-1} followed by three foliar sprays of iron sulphate starting from 21 days after sowing at 7-day intervals. These findings suggest that the judicious selection of rice cultivars and application of a combined soil and foliar iron fertilization strategy can significantly enhance iron uptake and potentially improve yields in aerobic rice cultivation.

Keywords: *Aerobic rice, KRH 2, MTU 1010, Tellahamsa, Iron uptake, Iron fertilization, Soil application, Foliar sprays, Iron sulphate, Iron chelate, Iron harvest index.*

1. INTRODUCTION

Rice holds a prominent position among the world's food crops, serving as a primary source of carbohydrates for over half of the global population [16]. However, they often lack essential micronutrients, such as iron, zinc, and vitamin A [15, 24] making rice-based diets a leading cause of micronutrient deficiencies, particularly in developing countries [2, 3, 4]. These micronutrients, although needed in small quantities, are crucial for vital plant processes, such as photosynthesis, respiration, protein synthesis, and reproduction, impacting both grain and straw yield [13]. Traditional rice cultivation methods, such as puddled transplanted rice, create anaerobic conditions by submerging fields [19], which has drawbacks such as soil degradation, methane emissions, and inefficient water use [5, 29].

Aerobic rice systems offer an alternative, growing rice in non-flooded, non-saturated soil, similar to other upland crops [18, 25]. This method reduces water usage and labour requirements but faces challenges such as the lack of suitable varieties, weed and nematode infestations, and iron deficiency [9, 12, 23]. This shift in cultivation has brought about an increase in Fe deficiency in rice, especially at the vegetative and reproductive stages of growth, depressing iron availability and reducing Fe supplies to humans. Iron deficiency is one of the most prevalent micronutrient deficiencies in humans, causing 0.8 million deaths annually and affecting approximately 2 billion people [27]. Iron, despite being abundant in the Earth's crust, is a limiting nutrient because of the low solubility of its oxidized form ($Fe3+$) in aerobic environments [8, 30, 26].

Iron fertilization can be achieved through soil application, foliar application, or a combination of both. Soil application provides a sustained release of iron, while foliar application offers a rapid correction of deficiency symptoms. Chelated iron fertilizers are often preferred for soil application due to their higher solubility and availability compared to inorganic iron sources like iron sulphate. However, the effectiveness of iron fertilization depends on factors like the type of iron fertilizer, application rate, timing, and method of application [21].

However, the majority of research on alleviating Fe deficiency in rice has been limited to transplanted rice in lowland environments, with a notable lack of information on aerobic rice systems [14]. To address this knowledge gap, the current study aimed to investigate the impact of various iron fertilization approaches on the iron content and uptake in aerobic rice cultivars across different growth stages.

2. MATERIALS AND METHODS

2.1. Experimental Site and Design

The field experiment was conducted over two consecutive years at the experimental farm of Professor Jayashankar Telangana State Agricultural University, Hyderabad, India. The site is located at a latitude of 17°19' N and longitude of 78°28' E, with an altitude of 542.3 meters above sea level. The soil at the experimental site is sandy clay loam in texture, with a slightly alkaline pH of 7.2. The site has low organic carbon content (0.45%), low available nitrogen (210 kg ha^{-1}), medium levels of available phosphorus (22.6 kg ha^{-1}), and available potassium

*Corresponding Author: ***B. Soumya***

DOI: https://doi.org/10.21276/AATCCReview.2025.13.01.517

(250 kg ha^{-1}). Iron content is adequate, measured at 4.18 mg kg^{-1}.

2.2. Treatments

The experiment comprised twelve treatment combinations of iron fertilization (S1 to S12) and three rice cultivars (M1, M2, and M3) and was laid out in a split-plot design with three replications. The detailed description of the treatments is given below:

Cultivars (M):
M1: Tellahamsa (Local variety)
M2: KRH 2 (Hybrid variety)
M3: MTU 1010 (Improved variety)
Iron Fertilization Treatments (S):
S1: Control (No iron fertilization)
S2: Soil application of iron sulphate @ 25 kg ha^{-1} (Basal)
S3: Soil application of iron chelate @ 25 kg ha^{-1} (Basal)
S4: Foliar application of iron sulphate @ 2% at 21, 28, and 35 days after sowing (DAS)
S5: Foliar application of iron sulphate @ 2% at 21, 31, and 41 DAS up to maximum tillering
S6: Foliar application of iron sulphate @ 2% at 21, 36, and 51 DAS up to the panicle initiation stage
S7: Soil application of iron sulphate @ 25 kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 28, and 35 DAS
S8: Soil application of iron sulphate @ 25 kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 31, and 41 DAS up to maximum tillering
S9: Soil application of iron sulphate @ 25 kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 36, and 51 DAS up to the panicle initiation stage
S10: Soil application of iron chelate @ 25 kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 28, and 35 DAS
S11: Soil application of iron chelate @ 25 kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 31, and 41 DAS up to maximum tillering
S12: Soil application of iron chelate @ 25kg ha^{-1} (Basal) + Foliar application of iron sulphate @ 2% at 21, 36, and 51 DAS up to the panicle initiation stage

2.3. Crop Management

Recommended nitrogen @ 120 kg ha^{-1} was applied in three equal splits *i.e.,* at sowing, maximum tillering and panicle initiation stage of the crop, in the form of urea. Phosphorus and potassium were applied basally as per the recommended dose of 60 kg each of P_2O_5 and K_2O ha^{-1} in the form of SSP and MOP respectively. Iron sulphate and chelate @ 25 kg FeSO4 ha^{-1} were applied at the time of sowing as per the treatments. These fertilizers were applied as bands in the seed furrow. Three foliar sprays of iron sulphate @ 2% + citric acid 2.0 g l^{-1} of water were sprayed starting from 21 DAS at weekly, 10-day intervals and 15 day intervals as per the treatments.

2.4. Data Collection

Plant samples were collected at seedling, maximum tillering, panicle initiation, and harvest stages. Iron content in plant samples (grain and straw at harvest) was determined using atomic absorption spectrophotometry with results expressed in milligrams per kilogram (mg kg^{-1}) [17].

The iron uptake was calculated by multiplying the iron concentration with the dry weight of the respective plant part and was expressed as mg plant^{-1}. Other traits, such as the Iron Harvest Index (FeHI) were computed using the following formulae and expressed in terms of percentage [22, 31].

Iron uptake (g ha^{-1}) = Iron content (mg kg^{-1}) x Weight of the dry matter (kg ha^{-1}) 1000

Total uptake (kg ha^{-1} or g ha^{-1}) = Uptake in grain + Uptake in straw

$$\text{Fe harvest index (FeHI)} = \frac{\text{Total Fe uptake by grain}}{\text{Total above ground Fe uptake at harvest}} * 100$$

2.5. Statistical Analysis

The data were statistically analysed using the *F*-test as per the procedure cited [6]. The significance of differences between treatments was determined using the least significant difference (LSD) test at a 5% probability level ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1. Effect of Cultivar on Iron content and uptake

The study revealed significant differences in iron content among the three rice cultivars (KRH 2, MTU 1010 and Tellahamsa) throughout their growth stages (Table 1). Iron content in seedlings of all the cultivars under study was low and among them, KRH 2 exhibited a slight advantage over MTU 1010 and Tellahamsa. Iron content increased significantly at the maximum tillering stage, with KRH 2 demonstrating the highest values, on par with MTU 1010, and significantly higher than Tellahamsa. The peak iron content occurred at panicle initiation, with KRH 2 again leading, followed closely by MTU 1010, and then Tellahamsa. As the plants matured to harvest, iron levels decreased across all cultivars, though KRH 2 maintained the highest iron concentration in both grain and straw, significantly exceeding MTU 1010 and Tellahamsa. Overall, iron content tended to decrease as the crop progressed through its growth stages, likely due to a dilution effect from increasing dry matter production. This difference in iron content among cultivars can be attributed to their genetic makeup, root morphology, and physiological mechanisms for iron acquisition [7]. KRH 2, being a hybrid variety, potentially possesses superior root growth and nutrient uptake efficiency compared to the other two varieties. These findings are consistent with previous studies that have reported significant genotypic variation in iron uptake among rice cultivars [1, 10]. Initially, iron uptake was low at the seedling stage due to limited dry matter production in the stem, sheath, and leaf blade, which was compounded by low iron content. However, as the crop matured, dry matter production increased, particularly leading up to the harvest 0tage, resulting in higher iron content. Consequently, the levels of iron uptake in the rice crop peaked during the maximum tillering and panicle initiation stages, followed by a gradual decline at harvest due to reduced iron content. KRH 2 cultivar exhibited superior iron uptake, followed by MTU 1010 and Tellahamsa. This pattern reflects the inherent characteristics of the varieties, as KRH 2 produced significantly greater dry matter and possessed higher iron content in its shoots compared to the other cultivars, leading to its markedly higher iron uptake. Several scientisits also reported similar difference in cultivars [21, 10].

Table 1. Iron content (mg kg^{-1}) of aerobic rice as influenced by cultivars and iron fertilization at Sedling, Maximum tillering and Panicle initiation stages

Treatments		Seedling		Maximum tillering		Panicle initiation	
		2012	2013	2012	2013	2012	2013
Main plots (M)							
M_1- Tellahamsa		28	31	50	52	60	63
M_2 - MTU 1010		31	35	56	58	66	70
M_3- KRH 2		35	38	60	61	71	73
SE m (±)		0.9	0.8	1.6	1.6	1.9	2.0
CD (P=0.05 %)		2.7	2.5	6.3	6.4	7.5	7.8
Sub plots (S)							
S_1- Control (No Iron)		27	30	47	48	56	59
S_2-BA of IS @ 25 kg ha^{-1}		32	36	49	50	57	61
S_3- BA of IC @ 25 kg ha^{-1}		35	38	50	51	59	62
S_4-3 FS of IS from 21 DAS @ 7 DI		28	31	55	56	64	68
S_5- 3 FS of IS from 21 DAS @ 10 DI		29	32	53	55	63	67
S_6- 3 FS of IS from 21 DAS @ 15 DI		29	32	52	54	62	65
S_7- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 7 DI		33	35	58	61	71	73
S_8- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 10 DI		32	35	57	58	68	71
S_9- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 15 DI		32	34	56	57	67	69
S_{10}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 7 DI		34	38	66	66	75	79
S_{11}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 10 DI		33	36	64	64	74	77
S_{12}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 15 DI		35	37	62	63	72	75
SE m (±)		1.2	1.1	1.3	1.4	1.6	1.6
CD (P=0.05 %)		3.3	3.2	3.7	3.8	4.4	4.7
Interaction							
Main at sub	SE m (±)	2.0	2.1	2.3	2.4	2.7	2.9
	CD (P=0.05 %)	NS	NS	NS	NS	NS	NS
Sub at main	SE m (±)	2.1	2.2	2.7	2.8	3.2	3.4
	CD (P=0.05 %)	NS	NS	NS	NS	NS	NS

BA-Basal application, IS- Iron Sulphate, IC- Iron Chelate, FS-Foliar spray, DI-Days interval.

Table 2. Iron content (mg kg^{-1}) of aerobic rice as influenced by cultivars and iron fertilization at harvesting stage

Treatments		Harvest stage			
		Grain		Straw	
		2012	2013	2012	2013
Main plots (M)					
M_1- Tellahamsa		24	26	43	44
M_2 - MTU 1010		27	28	45	48
M_3- KRH 2		31	32	49	51
SE m (±)		0.5	0.8	0.8	0.7
CD (P=0.05 %)		1.6	3.1	3.1	3.2
Sub plots (S)					
S_1- Control (No Iron)		19	20	38	39
S_2-BA of IS @ 25 kg ha^{-1}		21	22	40	40
S_3- BA of IC @ 25 kg ha^{-1}		22	23	40	41
S_4-3 FS of IS from 21 DAS @ 7 DI		27	28	44	46
S_5- 3 FS of IS from 21 DAS @ 10 DI		26	26	42	44
S_6- 3 FS of IS from 21 DAS @ 15 DI		24	25	42	44
S_7- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 7 DI		32	32	49	51
S_8- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 10 DI		29	30	47	49
S_9- BA of IS @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 15 DI		29	29	45	48
S_{10}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 7 DI		35	36	56	58
S_{11}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 10 DI		33	34	53	55
S_{12}- BA of IC @ 25 kg ha^{-1}+3 FS of IS from 21 DAS @ 15 DI		32	33	51	53
SE m (±)		0.6	0.8	0.9	0.8
CD (P=0.05 %)		1.6	2.3	2.5	2.3
Interaction					
Main at sub	SE m (±)	0.7	1.4	1.4	1.0
	CD (P=0.05 %)	NS	NS	NS	NS
Sub at main	SE m (±)	0.8	1.6	1.6	1.2
	CD (P=0.05 %)	NS	NS	NS	NS

BA-Basal application, IS- Iron Sulphate, IC- Iron Chelate, FS-Foliar spray, DI-Days interval

3.2. Effect of Iron Fertilization on Iron Content and Uptake

The study investigated the impact of different iron fertilization strategies on iron content in rice plants across various growth stages. At the seedling stage, a combination of basal iron fertilization with foliar sprays of iron sulphate resulted in the highest iron content, with no significant differences observed among these treatments. Notably, treatments involving basal applications of iron chelate (S3, S10, S11, S12) exhibited comparatively higher iron content than those with basal iron sulphate (S2) or basal iron sulphate combined with foliar iron sulphate sprays (S7, S8, S9). Treatments relying solely on foliar iron sulphate application (S4-S6) and the control group (S1), lacking any iron supplementation, displayed the lowest iron content. At maximum tillering and panicle initiation, the highest iron content was consistently found in treatments combining basal iron chelate with foliar sprays of iron sulphate (S10, S11, S12), followed by those combining basal and foliar applications of iron sulphate (S7, S8, S9). Treatments with only foliar iron sprays (S4, S5, S6) showed lower iron content, while plots with only basal application of iron chelate (S3) followed by (S2) and (S1) exhibited significantly the lowest iron content. Furthermore, Treatments involving a combined soil and foliar application of iron (S10, S11, S12) resulted in higher iron content in both grain and straw. The observed lower effectiveness of basal iron application alone, particularly under alkaline conditions with high bicarbonate levels, likely stems from reduced Fe^{3+}solubility and subsequent limited uptake by plant roots, as supported by previous research [11]. These findings highlight the advantage of combining soil and foliar application methods for optimizing iron nutrition in rice [32].

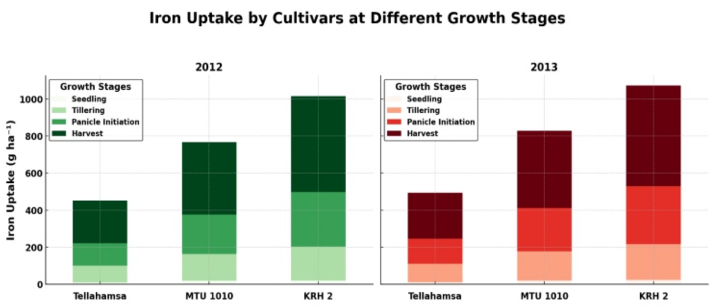

Figure 1. Iron uptake (g ha^{-1}) of aerobic rice as influenced by cultivars during 2012 and 2013

The study revealed significant variations in iron uptake among different iron fertilization treatments at the seedling stage. Notably, treatments combining basal iron fertilization with foliar sprays of iron sulphate showed the highest iron uptake. Specifically, basal application of iron chelate at 25 kg ha^{-1}, coupled with three foliar sprays of 2.0% $FeSO_4$ at 15-day intervals (S12), resulted in iron uptake comparable to the basal application of iron chelate along with foliar sprays of iron sulphate at 10 days interval (S10) and 7 days interval (S11). Foliar sprays of iron sulphate, 7 days interval sprays *i.e.,* (S4), 10 days interval *(*S5), 15 days interval sprays (S6) and control *i.e.,* (S1) recorded the lowest iron uptake and significant difference among them was not found. While iron uptake generally increased with crop growth, peaking at harvest, the application method significantly influenced final grain iron uptake. The highest grain iron uptake was observed with basal iron chelate combined with foliar iron sulphate sprays at 7, 10, and 15-day intervals (S10, S11, S12), respectively, with no significant difference between the 10 and 15-day interval treatments. Despite these variations, the interaction effect between cultivars and iron nutrition on iron uptake was non-significant.

Ultimately, the highest iron uptake at harvest, encompassing both grain and straw, resulted from combining basal and foliar iron application strategies, likely due to their positive impact on grain and straw yields, which subsequently influenced overall iron content [28].

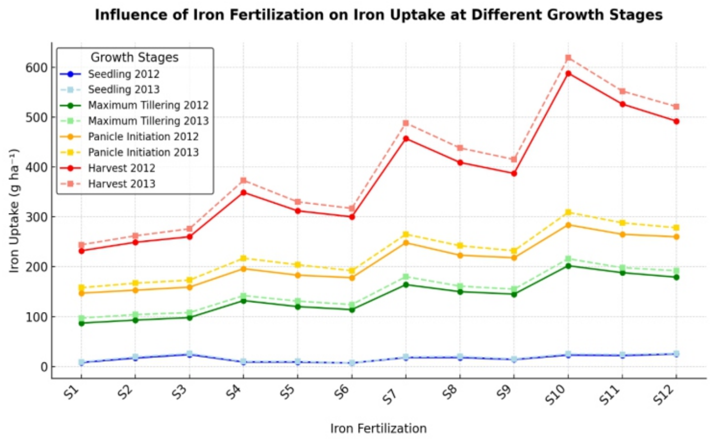

Figure 2. Iron uptake (g ha-1) of aerobic rice as influenced by iron fertilization during 2012 and 2013

3.3. Iron harvest index

In aerobic rice iron harvest index was significantly influenced by cultivars and iron fertilization strategies during the two years of study. Among the cultivars, maximum values registered by KRH 2 were on par with MTU 1010 and significantly superior to Tellahamsa. In the case of iron fertilization maximum iron harvest index was recorded with basal application of iron chelate and iron sulphate in combination with foliar sprays of iron sulphate @ 7 DI, 10 DI and 15 DI *i.e,* S_{10}, $S_{11,}$ S_{12} $S_{7,}$ S_8 and S_9significant difference among these treatments was not found. The next descent order was with foliar sprays of IS @ 7 DI, 10 DI and 15 DI *i.e.,* S_4 $S_5$and S_6. A significantly lower iron harvest index was noticed in treatments without foliar sprays of iron sulphate *i.e.,* $S_{3,}$ $S_2$and S_1.

3.4. Correlation between grain yield, straw yield and Fe uptake

Fe uptake was positively correlated with grain and straw yield during both years (Figures 1 to 4). Grain yield showed a linear relation with Fe uptake (R2 = 0.9849, 0.9825) and similarly straw yield also showed a linear relation with Fe uptake (R2 = 0.9402, 0.9446).

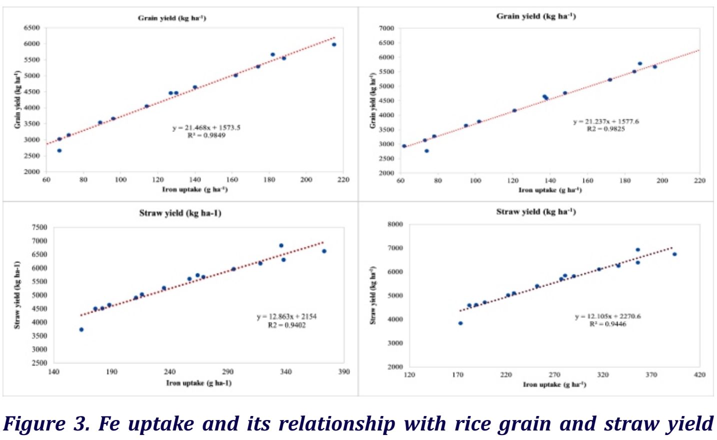

Figure 3. Fe uptake and its relationship with rice grain and straw yield during 2012&2013.

4. CONCLUSION

The investigation strongly suggests that rice cultivar KRH 2 exhibits a greater capacity for iron uptake compared to the other two cultivars tested.

Furthermore, the study highlights the effectiveness of the combined application of iron through basal and foliar methods. Notably, the basal application of iron chelate at a rate of 25 kg ha^{-1} combined with three foliar sprays of iron sulphate beginning from 21 days after sowing (DAS) and applied at 7-day intervals (S10) consistently resulted in the highest iron uptake. Treatments S11 and S12 also demonstrated substantial improvements in iron uptake, positioning them as viable alternatives to enhance iron nutrition in aerobic rice cultivation. These findings were consistent across both years of the study, strengthening the reliability of the conclusions.

5. Acknowledgement
We are very thankful to Professor JayashankarTelangana State Agricultural University (PJTSAU), Hyderabad, Telangana, India for providing the necessary facilities and inputs for carrying out the experiment.

6. Competing Interests
The authors have declared that no competing interests exist.

7. Future scope of the study
To identify and study the varieties suitable under aerobic system which adopt to change in the oxidation and reduction state of iron in soil. Futthur to study and develop an alternate sources for iron chelate to minimize the cost of iron fertilizer and enhance growth and yield of aerobic rice.

REFERENCES

1. Becker, M. and Asch, F. 2005. Iron Toxicity in Rice—Conditions and Management Concepts. *Journal of Plant Nutrition and Soil Science,* 168:558-573.

2. Bouis, H.E., Hotz, C., McClafferty, B., Meenakshi, J. V. and Pfeiffer, W. H. 2011. Biofortification: A new tool to reduce micronutrient malnutrition. *Food Nutrition Bulletin,* 32: 31–40.

3. Cakmak, I. 2010. Biofortification of cereals with zinc and iron through fertilization strategy 19th World Congress Soil Science Soil Solutions Changing World. 5:1–6.

4. Dipti, S.S., Bergman, C., Indrasari, SD., Herath, T., Hall, R., Lee, H., Habibi, F., Bassinello, PZ., Graterol, E., Ferraz, JP. and Fitzgerald, M. 2012. The potential of rice to offer solutions for malnutrition and chronic diseases. *Rice,* 5 (16): 1–18.

5. Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Kumar, V. and Sharma, P.K. 2011. Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. *Soil Science Society of America Journal,* 75:1851–1862.

6. Gomez, K.A. and Gomez, A.A. 1984. *Statistical procedure for agriculture research,* 2nd edn. John Wiley and Sons Publishers, New York, USA. 357–423.

7. Ishimaru, Y., Suzuki, M., Tsukamoto, T., Suzuki, K., Nakazono, M., Kobayashi, T., Wada, Y., Watanabe, S., Takahashi, M. and Nakanishi, H. 2006. Rice plants take up iron as an Fe^{3+}-phytosiderophore and as Fe^{2+}. *Plant Journal,* 45:335-346.

8. Kappler, A. and Straub, K.L. 2005. Geomicrobiological cycling of iron. *Reviews in Mineralogy and Geochemistry,* 59 (1): 85–108.

9. Kumar, V., Kumar, D. and Singh, Y.V. 2017. Water productivity, nutrients uptake and quality of aerobic rice as influenced by varieties and iron nutrition. *Paddy and Water Environment,* 15: 821–830.

10. Kumar, V., Kumar, D., Singh, Y.V. and Raj, R. 2015. Effect of iron fertilization on dry-matter production, yield and economics of aerobic rice (Oryza sativa). *Indian Journal of Agronomy,* 60 (4): 547–553.

11. Lucena, C., Romera, F.J., Rojas, C.L., Garcia, M.J., Alcantara, E. and Perez, V.R. 2007. Bicarbonate blocks the expression of several genes involved in the physiological response to Fe deficiency of strategy I plants. *Functional Plant Biology,* 34: 1002–1009.

12. Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., Eazhilkrishna, N., Choudhary, A.K., Deiveegan, M. and Subramanian, E. 2023. Maximizing Water Use Efficiency in Rice Farming: A Comprehensive Review of Innovative Irrigation Management Technologies. *Water,* 15 (10):1802.

13. Marschner, H. and Marschner P. 2011. *Marschner's Mineral Nutrition of Higher Plants* 3rd edition. Elsevier/Academic Press, London; Waltham, MA 672 pp.

14. Meena, B.L., Rattan, R.K., Datta, S.P. and Meena, M.C. 2016. Effect of iron application on iron nutrition of aerobic rice grown in different soils. *Journal of Environmental Biology,* 37: 1377-1383.

15. Olson, R., Gavin-Smith, B., Ferraboschi, C. and Kraemer, K. 2021. Food Fortification: The Advantages, Disadvantages and Lessons from Sight and Life Programs. *Nutrients,* 13 (4):1118.

16. Palanog, A.D., Calayugan, M.I.C., Descalsota-Empleo, G.I., Amparado, A., Inabangan-Asilo, M.A., Arocena, E.C., Sta Cruz, P.C., Borromeo, T.H., Lalusin, A., Hernandez, J.E., Acuin, C., Reinke, R. and Swamy, B.P.M. 2019. Zinc and Iron Nutrition Status in the Philippines Population and Local Soils. *Frontiers in Nutrition,* 6 (81): 1-17.

17. Prasad, R., Shivay, Y.S., Kumar, D. and Sharma, S.N. 2006. *Learning by Doing Exercises in Soil Fertility (A Practical manual for soil fertility),* Division of Agronomy, Indian Agricultural Research Institute, New Delhi, India 68.

18. Prasad, R. 2011. Aerobic rice systems *Advances in Agronomy,* 111: 207-247.

19. Rao, A.N., Wani, S.P., Ramesha, M.S. and Ladha, J.K. 2017. *Rice production systems in Rice production worldwide.* Springer International Publishing.

20. Reddy, C.K. and Siva Prasad, G.V.S. 1986. Varietal response to iron chlorosis in upland rice. *Plant and soil,* 94: 289-292.

21. Romheld, V. and Marschner, H. 1986. Evidence for a specific uptake system for iron phytosiderophores in roots of grasses. *Plant Physiology,* 80 (1):175-80.

22. Shivay, Y.S., Prasad, R. and Rahal A. 2010. Genotypic variation for productivity, zinc utilization efficiencies, and kernel quality in aromatic rices under low available zinc conditions. *Journal Plant Nutrition,* 33:1835–1848.

23. Soumya, B., Vani, K.P., Surendra Babu P., Praveen Rao, V. and Surekha, K. 2017. Impact of iron nutrition on yield and economics of aerobic rice cultivars. *Journal of Pharmacognosy and Phytochemistry,* 6(5): 1096-1100.

24. Stalin, P., Das, T., Muthumanickam, D., Chitdeshwari, T. and Velu, V. 2011 Foliar nutrition of rice to enhance micronutrient concentration in grains. *International Rice Research Notes,* 117 (4185): 1-6.

25. Vijaya kumar, S., Jinger, D., Parthiban, P. and Lokesh, S. 2018. Aerobic rice cultivation for enhanced water use efficiency. *Indian Farming,* 68: 3–6.

26. Weber, K.A., Achenbach, L.A. and Coates, J.D. 2006. Microorganisms pumping iron: anaerobic microbial iron oxidation and reduction. *Nature,* 4: 752–764.

27. WHO. 2007. *Micronutrient deficiency: Iron deficiency anaemia* Geneva: WHO Available from http://wwwwhoint / nutrition/topics/ida.

28. Yadav, G.S., Shivay, Y.S. and Kumar D. 2011. Effect of mulching and iron nutrition on productivity, nutrient uptake and economics of aerobic rice *(Oryza sativa*). *Indian Journal of Agronomy,* 56 (4): 365-372.

29. Yadav, S., Gurjeet, G., Humphreys, E., Kukal, S.S. and Walia, U.S. 2011. Effect of water management on dry seeded and puddled transplanted rice Part 1: Crop performance. *Field Crops Research,* 120 (1): 112-122.

30. Yi, Y., Saleeba, J., Guerinot, M.L., Manthey, J., Luster, D. and Crowley, D.E. 1994. *Biochemistry of Metal Micronutrients in the Rhizosphere* CRC Press, Boca Raton, pp 295-307.

31. Zulfiqar, U., Hussain, S., Ishfaq, M., Ali, N., Yasin, M.U. and Ali, M.A. 2021. Foliar manganese supply enhances crop productivity, net benefits, and grain manganese accumulation in direct-seeded and puddled transplanted rice. *Journal of Plant Growth Regulation,* 40: 1539–1556.

32. Zuo, Y. and Zhang, F. 2011. Soil and crop and crop management strategies to prevent iron deficiency in crops. Plant and Soil, 339 (1): 83-95.