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Iron Toxicity and its Management in Rice: A Comprehensive Review

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ABSTRACT

Iron toxicity in rice is a significant challenge, especially under prolonged flooding conditions. Symptoms include appearance of small brown spots on leaf lamina, bronzing of leaf tips and root decay. Affected roots often exhibit a dark brown to black coating, stunted growth and reduced tillering. Direct toxicity occurs when excessive Fe absorption causes cellular damage, while indirect toxicity disrupts the uptake and metabolism of essential nutrients, leading to nutrient imbalances and reduced productivity. Factors contributing to Fe toxicity include the release of Fe from parent materials into the soil solution, decreased oxidation-reduction potential, increased ionic strength, low soil fertility, low soil pH, organic matter content, microbial activity, nutrient interactions and plant genetic variability. Rice plants have developed three adaptation strategies to cope with high Fe conditions: exclusion, inclusion and tolerance. Effective management of Fe toxicity in rice includes using tolerant varieties, avoiding continuous flooding, applying lime to acid soils, application of silicon, adjusting planting times, practicing dry tillage and ensuring balanced nutrition. An integrated approach combining varietal selection, balanced nutrient management, soil amendments and biotechnological tools is crucial for managing Fe toxicity.

Key words: Adaptation strategies, Biotechnological tools, Integrated approach, Root decay, Soil amendments.

Iron is crucial for all living organisms as it is essential for metabolic functions like respiration, photosynthesis and DNA synthesis. It is also involved in enzymes and chlorophyll synthesis. Lowland rice production is primarily affected by iron toxicity, which occurs in wet soils and is associated with elevated levels of reduced iron (Fe^{2+}). This leads to the “bronzing” of rice leaves, resulting in production losses. Iron toxicity has been found in South America, Asia and Africa. Other soil types where iron toxicity can occur include acid sulphate, acid clay, peat, valley-bottom soils, ultisols, oxisols, sandy soils and low to moderately high organic matter content.

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Symptoms of iron toxicity in rice

Fe toxicity symptoms may initially manifest within 1 to 2 weeks after transplantation, although they can also take longer than 2 months to appear. Initially, small brown spots form on the tips of older leaves and gradually spread toward the base. In severe cases, the entire leaf is affected. Leaf bronzing is observed in potassium-deficient rice plants that cannot sustain adequate root oxidation capacity. Limited growth, significantly decreased tillering, a thick, sparse and compromised root system exhibiting a dark brown to black coating on the root surface, along with numerous dead roots (Dobermann and Fairhurst, 2000). As the symptoms progress, the leaf tips in some rice varieties turn orange-yellow and dry out. These effects are especially noticeable in older leaves with higher rates of transpiration (Yamanouchi and Yoshida, 1981). The entire leaf turns orange, reddish brown, or even purple-brown under extreme toxicity situations (Fairhurst and Witt, 2002). According to Abu *et al*. (1989), toxicity during the vegetative stages reduces plant height and dry matter production; the biomass of the shoots is more negatively affected than that of the roots (Fageria, 1988). A decrease in the number of panicles per hill (Singh *et al*., 1992), increased spikelet sterility (Virmani, 1977) and delays in blooming and maturity of up to 20-25 days are all associated with iron toxicity during the late vegetative or early reproductive stages. Plant height, panicle length, the number of productive tillers and total yield are all reduced by iron toxicity (Abraham, 1989).

Effects of iron toxicity

There are two main ways that metal poisoning in agricultural plants presents itself. The first type, known as direct toxicity, is when metals are taken in excess and have fatal effects on the cells of the plant. Indirect toxicity is the second type, which is related to interfering with plant’s ability to absorb and utilize vital nutrients. The plants experience nutritional imbalances as a result of this indirect poisoning.

Interestingly, this form of iron toxicity (indirect toxicity) is more common in lowland rice than direct toxicity (Fageria

et al., 2006). Zinc (Zn), potassium (K) and phosphorus (P) are the three main nutritional deficiencies seen in Brazilian rice that is flooded or irrigated (Barbosa *et al.*, 1983). Furthermore, the effect of iron (Fe) toxicity on rice cultivar production differs according to the cultivar's tolerance or sensitivity to this toxicity.

Fe uptake mechanism

Iron is primarily found in oxidized soils in the ferric state (Fe^{3+}), which is linked to oxides and hydroxyoxides and causes low solubility. To effectively absorb iron, plants need to transform it into the Fe^{2+} form. To combat iron deficiency, plants have developed two primary defense mechanisms, as shown in the Fig 1. In the first method of iron uptake, roots release of protons (H^+), which lowers the rhizosphere's pH, allowing reduced iron to be absorbed through a transport pathway for Fe^{2+} across the plasma membrane. Primarily, dicots and nongraminaceous monocots employ this strategy. Phytosiderophores, substances that bind to Fe^{3+} without changing it into Fe^{2+}, are secreted by crop plants as a second method for iron uptake. These chelating chemicals, such as avenic and mugineic acids, are nonprotein amino acids. The greening of chlorotic tomato mutants may be supported by iron transfer within cells due to structural similarities to nicotianamine, a substance found in green plants that helps mobilize iron (Epstein and Bloom, 2005).

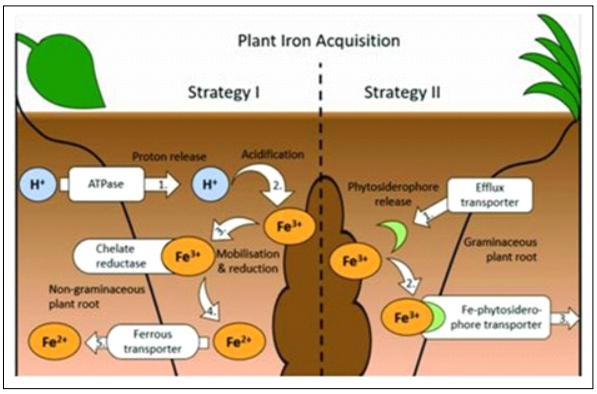


Fig 1: Fe uptake by plants.

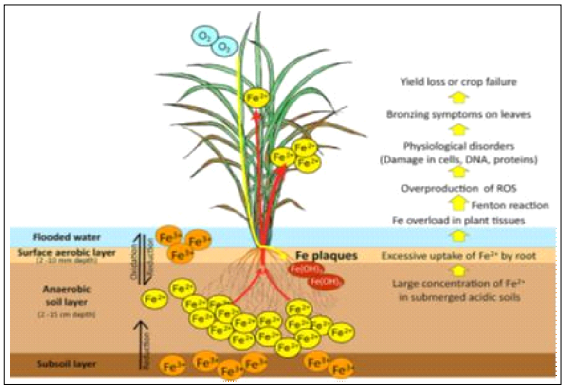


Fig 2: Fe acquisition by rice plant.

Fe uptake mechanism by rice

As shown in Fig 2, waterlogging reduces ferric iron (Fe^{3+}) to the more soluble ferrous iron (Fe^{2+}) in the soil by creating an anaerobic environment (Aung and Masuda, 2020). There is a notable buildup of Fe^{2+} as a result of this reduction, which mostly takes place in the anaerobic soil layer (2-15 cm depth). This excess Fe^{2+} is absorbed by plant roots, where it may result in iron plaques, $Fe(OH)_3$ on the root surfaces. Iron overload occurs in the plant's tissues when excessive Fe^{2+} uptake overwhelms the plant, even if these plaques can occasionally serve as a barrier. Fenton reactions are set off inside the plant by Fe^{2+}, generating reactive oxygen species (ROS) that cause oxidative stress and harm cellular components like membranes, proteins and DNA. This manifests as bronzing symptoms on leaves and, in severe cases, leads to reduced growth, poor yield, or crop failure.

Factors inducing iron toxicity

Iron poisoning in rice rhizosphere occurs when solubility and concentration of iron exceed plant needs. Soil conditions affecting these factors are not fully understood (Fageria *et al.*, 1990), but include iron release, oxidation-reduction potential, low pH, ionic strength, fertility, organic matter, microbial activity and plant genetic variability.

Release of iron into the soil solution from the parent material

Goethite, hematite, pyrite, siderite, and magnetite are among the iron minerals found in soils (Fageria, 2013). Iron released into the soil solution by parent materials can be harmful to plants, particularly rice plants. Kosaki and Juo (1986) found a strong correlation between Fe^{2+} iron levels in Nigerian soil and bronzing, a condition in West African rice plants living in lowlands, inland valley swamps, and hydromorphic settings, indicating iron poisoning as the main cause.

Oxidation-reduction potential

The chemical process of oxidation-reduction involves the exchange of electrons between substances. The oxidation number of the electron acceptor decreases and becomes decreased when the electron donor loses electrons, increasing its oxidation number. Organic materials provide electrons for biological reduction processes (Ponnamperuma, 1972). The conversion of Fe^{3+} to Fe^{2+} increases absorption, but as Fe^{2+} is converted to Fe^{3+}, its concentration decreases, causing plants to absorb less. Submerged soils undergo various reduction processes, including H^+ to H_2, CO_2 to CH_4, nitrate to dinitrogen, sulphate to H_2S and Fe^{3+} to Fe^{2+}. Redox potential, measured in millivolts, influences these processes.

Soil pH

Because of the dynamic interactions between plants, microbes and soil processes, the pH of soil varies greatly (Adams, 1984). Iron changes into less soluble forms when

pH increases, mostly as the oxide FeO_3. Acidic soils are more harmful to iron than alkaline ones. While the pH of sodic and calcareous soils lowers when submerged, the amount that the pH of acidic soils changes depends on crop rotation, fertility, organic matter, rice cultivar and soil type. Soils rich in organic matter and reducible iron typically achieve a pH of approximately 6.5 after a few weeks of immersion (Ponnamperuma, 1972).

Ionic strength

The electrical environment that surrounds ions in a solution is measured by a property called ionic strength. As macro- and micronutrients are released into the soil solution, ionic strength increases in submerged soils, improving rice plant absorption of Fe^{2+} and raising iron toxicity. This rise is associated with the solubilization of phosphorus and the decrease of Fe^{2+} and Mn^{2+} in acidic soils. It happens in alkaline soils when Fe^{2+} iron from reduction processes displaces cations (Patrick and Mikkelsen, 1971).

Low soil fertility

Iron toxicity in rice can be caused by essential nutrient deficits in wet or depleted soils. Nutrients like potassium, phosphorus, calcium and magnesium can hinder iron absorption, increasing the risk. According to Yamauchi, 1989 increasing potassium levels in shoots can improve rice dry matter output and reduce iron toxicity. According to Trolldenier (1977), Low potassium and phosphorus levels can exacerbate toxicity. Increased nitrogen levels may promote excess iron absorption. High salinity can also increase iron intake due to chemicals like magnesium or sodium chloride (Breemen and Moormann, 1978).

Interaction with other nutrients

Iron can interact with other nutrients in a neutral, antagonistic, or synergistic manner, depending on how the plants respond to their growing environment. In rice plants, manganese is an example of an antagonistic connection with iron (Olsen and Watanabe, 1979). The amount of iron that rice absorbs is significantly reduced when manganese is supplied to the soil. Fageria *et al.* (1981) found that as the iron concentration in the nutritional solution increased from 0 to 160 mg Fe L^{-1}, the absorption of phosphorus, potassium, calcium and magnesium decreased. Calcium and magnesium absorption decreased linearly as the amount of iron in the nutritional solution increased.

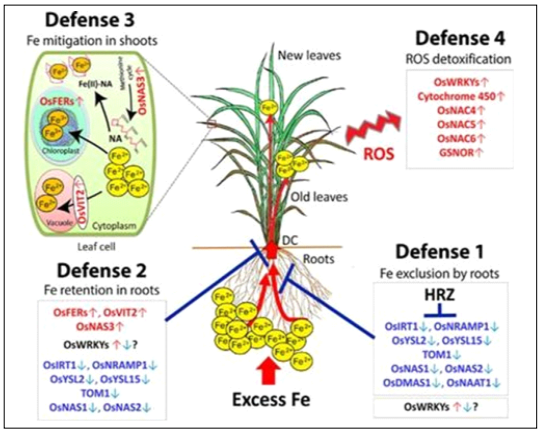


Fig 3: Defense mechanism of rice to Fe toxicity.

Adaptation strategies

The three main types of adaptation strategies include "avoidance" and "tolerance" based procedures, as well as "includer" and "excluder" tactics.

Strategy Ia-iron oxidation occurring at the root surface

Rice roots need to pass through an oxidation barrier in the rhizosphere before absorbing Fe^{2+} from the soil. This barrier is created by transporting molecular oxygen from the air to the roots *via* the aerenchyma, a gas-conducting tissue that increases ethylene synthesis (Kawase, 1981). In flooded rice, aerenchyma can occupy up to 50% of root volume (Armstrong, 1980), with effectiveness varying by growth stage. Early and sustained aerenchyma formation is crucial for iron tolerance, especially under iron-toxic soil conditions (Jayawardena *et al.,* 1977).

Strategy Ib-selectivity of root membranes

Iron, which enters the root apoplast after passing through the rhizosphere's oxidative barrier, can be rejected by root cell membranes (Tadano, 1976; Green and Etherington, 1977). In healthy plants, up to 87% of iron can be blocked by the endodermal barrier. This process, which depends on energy, can be hindered by high Fe^{2+} concentrations (Tadano, 1975) and dietary deficiencies in Ca, K and P (Yamanouchi and Yoshida, 1981). It is sensitive to environmental conditions and plant growth stages, making it less effective under severe iron toxicity or during seedling-stage toxicity.

Strategy IIa-retention within root and stem tissues

Iron in plants can be immobilized at storage sites, but it rises with transpiration once it enters the xylem. Root tissues contain "metabolically inactive" iron (Tanaka *et al.,* 1966) and as plants age, their roots store less iron (Tadano, 1976). Fe^{2+} may become immobile in stem or leaf sheath tissues during transit. Iron-tolerant West African rice varieties typically retain more iron in leaf sheaths than blades (Audebert and Sahrawat, 2000). Phytoferritin production may be part of this iron withdrawal (Seckbach, 1982; Smith, 1984), but its efficacy varies with Fe^{2+} transport rates and may decrease in heavy transpiration or growth cycle.

Strategy IIb-retention within the leaf apoplast

Kosegarten *et al.* (1999) suggest that iron mobility in leaves is influenced by apoplastic pH, with higher pH causing Fe^{2+} oxidation and acidic pH promoting absorption (Mengel and Kosegarten, 2000; Nicolic and Römheld, 2001). Non-diffusible polymers inhibit certain polysaccharides and

ferric-chelate reductase activity (Schmidt, 1999; Lucena, 2000). In plants without pH regulation, excess Fe^{2+} can accumulate uncontrollably in leaf cells (Welch *et al*., 1993).

Strategy III-tolerance in symplastic tissues

Fe^{2+} in plant symplasts can cause oxidative damage, necessitating neutralization for tissue tolerance. Binding Fe^{2+} to phytoferritin helps control oxidation processes. Ascorbate and glutathione reduce oxidative stress. Zinc increases superoxide dismutase (SOD) enzyme activity, enhancing iron tolerance. Hydrogen peroxide requires detoxification by peroxidases or catalases. SOD and peroxidases must work together to manage stress, especially during seedling toxicity and transplanting stress. Genetic variations in these responses are poorly understood and not used for screening in rice breeding.

Defense mechanism

As shown in the Fig 3, plants have developed 4 defense mechanisms to control and mitigate iron levels.

Defense 1: Fe exclusion by roots

The first line of defense is to keep excessive amounts of iron out of the plant's root system. Genes like OsIRT1, OsNRAMP1, OsYSL2, OsYSL15, TOM1, OsNAS1, OsNAS2, OsDMAS1 and OsNAAT1 mediate iron transfer into the root cells. HRZ functions as a regulatory protein that prevents the activation of the aforementioned Fe uptake genes, hence reducing Fe absorption.

Defense 2: Fe retention in roots

The second defense activates if Fe enters the roots, aiming to contain and immobilize it within root cells. The genes such as OsFERs, OsVIT2 are help to store iron within root cells, particularly by sequestering it in specific compartments where it is less likely to cause harm, OsNAS3 aids in binding Fe to specific molecules, which helps in storing and immobilizing it, OsWRKYs may regulate the retention process and activate other Fe-related defense mechanisms.

Defense 3: Fe mitigation in shoots

The third defense aims to handle Fe that reaches the shoots, specifically in the leaf cells, by storing it safely and preventing damage. The protein OsFERs helps store Fe in leaf cell compartments like chloroplasts and vacuoles, which are specialized for storage and can contain Fe safely, the OsVIT2 transporter moves Fe into the vacuoles within leaf cells, reducing free Fe that could be toxic and OsNAS3 binds Fe with compounds like nicotianamine (NA), forming stable complexes that reduce Fe reactivity and toxicity.

Defense 4: ROS detoxification

Reactive oxygen species (ROS), which are harmful byproducts of iron buildup, can be produced by an excess of iron. In order to save plant cells from oxidative damage, this last line of defense neutralizes ROS. Transcription factors known as OsWRKYs regulate and activate genes related to ROS detoxification. The cytochrome 450 enzyme may aid in controlling ROS levels and is engaged in a number of detoxifying procedures. Transcription factors OsNAC4, OsNAC5 and OsNAC6 may activate genes that aid in ROS detoxification and are involved in stress responses. The GSNOR enzyme aids in preserving cellular equilibrium and detoxifying dangerous ROS.

By using these techniques, the plant efficiently controls excess iron, avoiding toxicity and preserving the health of its cells throughout all of its tissues.

Management practices

Using tolerant cultivars like IR8192-200, IR9764-45 and Mahsuri is the most effective and cost-effective way to address this problem (Dobermann and Fairhurst, 2000). Chuvannamodan, an indigenous landrace of Kerala and Varsha, a mid-early, high-yielding redkernelled rice variety, shown tolerance to high iron concentrations (> 600 ppm) (Suma *et al.,* 2022). Although they have a somewhat lower potential yield, African cultivars are often more resistant to this stress than Asian ones. Regarding water management, the effects of drain time and length for 6 and 9 days within 30 days post-transplanting, soil improvement and fertilizer application, the Indragiri variety demonstrated the highest tolerance to iron toxicity. The most efficient way to achieve grain output under Fe toxicity was to combine a 75% seed treatment, 90 kg/ha of P_2O_5 and 100 kg/ha of K_2O. This significantly boosted rice production in the acid sulphate soils of tidal swamplands (Khairullah *et al.,* 2021). By lowering the amount of iron available in the soil solution, efficient irrigation water management successfully decreased the amount of iron toxicity in rice plants cultivated in field circumstances. de Campos *et al.* (2021), in acid sulphate soils, leaching every two weeks and adding 2.5 tons of organic matter per hectare are recommended as ways to lower iron toxicity and increase rice output (Nugroho *et al.,* 2022). Iron toxicity and soil acidity in paddy soils derived from laterite can be effectively managed by applying a combined total of 300 kg/ha of limestone powder and 300 kg/ha of phosphogypsum. This joint application enhances nutrient availability, improves nutrient uptake by plants and promotes rice growth and yield (Joseph *et al*., 2020). Mini and Lekshmi (2021) were discovered that the best treatment for increasing yield by 23% was a combination of soil test-based RDF + rice husk ash @ lime (based on pH) + foliar spray of 0.5% solution of customized formulation @ 5 kg ha^{-1} as foliar application of 0.5% solution in two splits at maximum tillering and panicle initiation stage. The B:C ratio also increased from 1.53 to 1.91. Grain and straw yields increased significantly when 5 tons of organic matter, 90:45:120 kg of N:P:K 150 kg of lime and 100 kg of silica were applied per hectare. Additionally, silica application helps reduce the prevalence of pests (Yadav *et al.,* 2017). In temperate regions where seeds are sown directly, coating seeds with oxidants, such as calcium peroxide (at 50100% of the seed's weight), can enhance germination and seedling growth by boosting oxygen availability. Postpone planting until the peak levels

of Fe have subsided. Opt for intermittent irrigation instead of continuous flooding on poorly drained soils with high levels of iron and organic matter. Perform dry tillage after harvesting rice to enhance iron oxidation during the fallow period, helping to minimize iron accumulation during the next flooding phase (Dobermann and Fairhurst, 2000). One effective strategy to lessen the negative effects of Fe toxicity on rice output and photosynthesis is the use of Si (Dos Santos *et al.,* 2020).

CONCLUSION

A major problem impacting rice production is iron toxicity, especially in regions where soil iron concentrations are high. This is because the ferrous ion (Fe^{2+}) is more soluble in anaerobic settings, like rice fields that are submerged. This causes oxidative stress, which hinders the growth and development of plants. Reduced output and symptoms like leaf bronzing emphasize how urgently this agricultural issue needs to be resolved. Many techniques are used to reduce iron toxicity and improve rice tolerance, including as providing organic matter, managing water levels, applying particular potassium fertilizers and creating rice cultivars that are resistant to iron toxicity. The identification of brassinosteroids and quantitative trait loci (QTLs) can also improve resistance to iron toxicity. To create sustainable management strategies that incorporate chemical and biological interventions, more study is required and biotechnology advancements can produce cultivars with improved tolerance features. A comprehensive understanding of iron toxicity and its management is crucial for sustainable farming methods.

Conflict of interest

The authors say that there is no conflict of interest.

REFERENCES

Abraham, M.J., Pandey, D.K. (1989). Performance of selected varieties and advanced generation genotypes in rainfed lowland iron toxic soil. *International Rice Research Newsl*. **14:** 21-21.

Abu, M.B., Tucker, E.S., Harding, S.S. and Sesay, J.S. (1989). Cultural practices to reduce iron toxicity in rice. *International Rice Research Newsl*. **14:** 19-19.

Adams, F. (1984). Crop response to lime in the southern United States. *Soil Acidity and Liming*. **12:** 211-265.

Armstrong, W. (1980). Aeration in higher plants. *Advances in Botanical Research*. **7:** 225-332.

Audebert, A. and Sahrawat, K.L. (2000). Mechanisms for iron toxicity tolerance in lowland rice. *Journal of Plant Nutrition.* **23 (11-12):** 1877-1885.

Aung, M.S., Masuda, H. (2020). How does rice defend against excess iron: Physiological and molecular mechanisms. *Frontiers Plant Science*. **7:** 11:1102.

Barbosa, F.M.P., Fageria, N.K. and Stone, L.F. (1983). Water management and liming in relation to grain yield and iron toxicity. *Pesquisa Agropecuaria Brasileira*. **18:** 903-910.

Bienfait, H.F. (1985). Regulated redox processes at the plasmalemma of plant root cells and their function in iron uptake. *Journal of Bioenergetics and Biomembranes*. **17:** 73-83.

Breemen, N.V. and Moormann, F.R. (1978). Iron-Toxic Soils. In: Soils and Rice, ed. International Rice Research Institute, Los Ba˜nos, Philippines.

de Campos Carmona, F., Adamski, J.M., Wairich, A., de Carvalho, J.B., Lima, G.G., Anghinoni, I., Jaeger, I.R., da Silva, P.R.F., de Freitas Terra, T., Fett, J.P. and Carlos, F.S. (2021). Tolerance mechanisms and irrigation management to reduce iron stress in irrigated rice. *Plant and Soil.* **469:** 173-191.

Dobermann, A. and Fairhurst, T. (2000). Rice: Nutrient Disorders and Nutrient Management. International Rice Research Institute, Philippines. 193p.

Dobermann, A. and Fairhurst, T.H. (2000). Nutrient Disorders and Nutrient Management. Potash and Phosphate Institute, Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore. 191p.

Dos Santos, M.S., Sanglard, L.M., Barbosa, M.L., Namorato, F.A., de Melo, D.C., Franco, W.C., Pérez-Molina, J.P., Martins, S.C. and DaMatta, F.M. (2020). Silicon nutrition mitigates the negative impacts of iron toxicity on rice photosynthesis and grain yield. *Ecotoxicology and Environmental Safety.* **189:** 110008.

Epstein, E. and Bloom, A.J. (2005). Mineral Nutrition of Plants: Principles and Perspectives. Sinauer Associates. 380p.

Fageria, N.K. (2013). Mineral Nutrition of Rice. CRC Press.

Fageria, N.K. (1981). *International Rice Research Newsletter*. **13(1):** 20-2.

Fageria, N.K. (2006). Liming and copper fertilization in dry bean production on an oxisol in no-tillage system. *Journal of Plant Nutrition*. **29(7):** 1219-1228.

Fageria, N.K., Baligar, V.C and Wright, R.J. (1990). Iron nutrition of plants: An overview on the chemistry and physiology of its deficiency and toxicity. *Pesquisa Agropecuaria Brasileira*. **25:** 553-570.

Fairhurst, T.H. and Witt, C. (2002). Rice: A Practical Guide to Nutrient Management. The International Rice Research Institute, Manila, Philippines.

Green, M.S. and Etherington, J.R. (1977). Oxidation of ferrous iron by rice roots: A mechanism for waterlogging tolerance. *Journal of Experimental Botany.* **28(3):** 678-690.

Gupta, A.S., Webb, R.P., Holaday, A.S. and Allen, R.D. (1993). Overexpression of superoxide dismutase protects plants from oxidative stress. *Plant Physiol.* **103:** 1067-1073.

Jayawardena, S.D.G., Watabe, T. and Tanaka, K. (1977). Relation between root oxidizing power and resistance to iron toxicity in rice. *The Report of the Soc. of Crop Sci. and Breeding in Kinki (Japan)*. **22:** 38-47.

Joseph, B., Gladis, R., Aparna, B. and Bindhu, J.S. (2020). Assessment of iron toxicity in lateritic wetland soils of Kerala and management using non conventional sources of lime. *International Journal of Current Microbiology and Applied Science*. **9(5):** 21392148.

Kawase, M. (1981). Anatomical and morphological adaptation of plants to waterlogging. *Hort Science*. **16(1):** 30-34.

Khairullah, I., Saleh, M. and Alwi, M. (2021). Increasing Productivity of Rice Through Iron Toxicity Control in Acid Sulfate Soils of Tidal Swampland. In: IOP Conference Series: *Earth and Environmental Science*. **648(1):** 012151.

Kosaki, T. and Juo, A.S.R. (1986). Iron Toxicity in Inland Valleys: A Case Study from Nigeria. In: Wetlands and Rice in Sub-Saharan Africa Ibadan, [Juo, A.S.R. and Lowe, J.A. (Eds.)], IITA, Ibadan. pp 167-174.

Kosegarten, H., Hofmann, B. and Mengel, K. (1999): Apoplastic pH and Fe^{3+}-reduction in intact sunflower leaves. *Plant Physiology.* **121(4):** 1069-1079.

Larson, R.A. (1988). The antioxidants of higher plants. *Phytochemistry.* **27(4):** 969-978.

Lucena, J.J. (2000): Effects of bicarbonate, nitrate and other environmental factors on iron deficiency chlorosis: A review. *Journal of Plant Nutrition*. **23(11-12):** 1591-1606.

Mengel, K. and Kosegarten, H. (2000). Iron transport through plant membranes. Jahrestagung der Deutschen Gesellschaft für Pflanzenernährung. pp 3-5.

Mini, V. and Lekshmi, S. (2021). Rice husk ash as a low-cost soil ameliorant for abating iron toxicity in lowland rice. *Agricultural Science Digest.* **41(1):** 96-98. doi: 10.18805/ag.D-5194.

Nicolic, M. and Römheld, V. (2001). The Role of the Leaf Apoplast in Iron Nutrition of Plants. In: Plant Nutrition – Food Security and Sustainability of AgroEcosystems. [Horst, W.J. *et al.* (eds)]: Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 274-275.

Nugroho, N., Kurniasih, B., Utami, S.N.H. and Yusuf, W.A. (2022). The potential of organic matter and water management on the alleviation of iron toxicity in rice plants. *Ilmu Pertanian (Agricultural Science*). **7(1):** 47-55.

Olsen, S.R. and Watanabe, F.S. (1979). Interaction of added gypsum in alkaline soils with uptake of iron, molybdenum, manganese and zinc by sorghum. *Soil Science Society of America Journal*. **43(1):** 125-130.

Patrick, W.J. and Mikkelsen, D.S. (1971). Plant Nutrient Behaviour in Flooded Soil. In: Fertilizer Technology and Use, 2nd ed., [(ed.) R.A. Olson, Madison], Wisc.: Soil Science Society of America. pp 187-215.

Ponnamperuma, F.N. (1972). The chemistry of submerged soils. *Advances in Agronomy*. **24:** 996.

Schmidt, W. (1999). Mechanisms and regulation of reduction-based iron uptake in plants. *The New Phytolgist*. **141(1):** 1-26.

Seckbach, J. (1982). Ferreting out the secrets of plant ferritin - A review. *Journal of Plant Nutrition.* **5(4-7):** 369-394.

Singh, B.P., Das, M., Prasad, R.N. and Ram, M. (1992): Characteristics of Fe-toxic soils and affected plants and their correction in acid Haplaquents of Meghalaya. *International Rice Research. Newsletter*. **17:** 18-19.

Smith, B.N. (1984). Iron in higher plants: Storage and metabolic role. *Journal of Plant Nutrition.* **7(1-5):** 759-766.

Suma, A., Francies, R.M., Radhakrishnan, V.V., Sureshkumar, P. and Varghese, E. (2022). Elucidating the response of rice genotypes to iron toxicity through hydroponics. *Indian Journal of Plant Genetic Resources.* **35(1):** 66-72.

Tadano, T. (1975). Devices of rice roots to tolerated high iron concentration in growth media. *Japan Agricultural Research Quarterly.* **9(1):** 34-39.

Tadano, T. (1976). Studies on the methods to prevent iron toxicity in the lowland rice. Mementos of the Faculty of Agriculture Hokkaido University. **10:** 22-68.

Tanaka, A., Loe, R. and Navasero, S.A. (1966): Some mechanisms involved in the development of iron toxicity symptoms in the rice plant. *Soil Science Plant Nutrition.* **12(4):** 32-38.

Trolldenier, G. (1977). Mineral nutrition and reduction processes in the rhizosphere of rice. *Plant and Soil.* **47:** 193-202.

Virmani, S.S. (1977). Varietal tolerance of rice to iron toxicity in Liberia. *International Rice Research Newsletter.* **2:** 4-5.

Welch, R.M., Norvell, W.A., Schaefer, S.C., Shaff, J.E. and Kochian, L.V. (1993). Induction of iron(III) and copper(II) reduction in pea (*Pisum sativum* L.) by Fe and Cu status: Does the root-cell Fe(III) chelate reductase perform a general role in regulating cation uptake? *Planta.* **190:** 555-561.

Yadav, P.I., Manu, C.R. and Abraham, N. (2017). Silicon nutrition for sustainable rice production in iron toxic laterite soils of Kollam District in Kerala. *Journal of Krishi Vigyan*. **5(2):** 150-153.

Yamanouchi, M. and Yoshida, S. (1981). Physiological Mechanisms of Rice's Tolerance for Iron Toxicity. Paper presented at the IRRI Saturday Seminar, June 6, 1981. The International Rice Research Institute, Manila, Philippines.

Yamauchi, M. (1989). Rice bronzing in Nigeria caused by nutrient imbalances and its control by potassium sulfate application. *Plant and Soil*. **117:** 275-286.

Yoshida, S. (1981). Fundamentals of Rice Crop Science. The International Rice Research Institute, Manila, Philippines. p 269.