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Iron Dynamics in Pakistani Agroecosystems: A Review

***Muhammad Hanzala Mansha*[1], *Hafiz Tanvir Ahmad*[1]*, *Syed Kazim Ali*[1], *Arisha*[1], *Rana Asad Jabbar*[1], *Hafsa Rameen*[1], *Ijaz Mehboob*[2], *Ayesha Irum*[3]**

[1]Department of Soil Science, Institute of Soil and Water Resources, the Islamia University, Bahawalpur-63100, Pakistan
[2]Provincial Reference Fertilizer Testing Laboratory Raiwind, Lahore-54000, Pakistan
[3]Senior Scientist, Agricultural Biotechnology Research Institute, AARI Faisalabad

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Abstract

Iron (Fe) is an important micronutrient in agroecosystem performing key roles in plants like photosynthesis, respiration, and enzymatic activity but its bio availability in calcareous and alkaline soils of Pakistan remains a significant challenge. Although iron is present in abundance in earth's crust but most often it is present in insoluble ferric oxides and hydroxides, this restricts iron uptake by major crops such as wheat, rice, maize, and pulses. In this review we will discuss current understanding of iron dynamics in Pakistani soils, and how soil chemistry, pH, redox potential, organic matter, irrigation regimes, and microbial interactions influence iron solubility and plant uptake. We highlight plant adaptive mechanisms like rhizosphere acidification, reduction of ferric to ferrous forms, and Phyto-siderophore release this enables survival under iron limited conditions, while also discuss the physiological impact of deficiency such as chlorosis, impaired photosynthesis, and reduced yield quality. Agronomic practices, ranging from iron enriched fertilizers and foliar sprays to organic amendments, biochar applications, and microbial siderophore inoculation, are discussed as sustainable approaches to increase iron availability. It is important to note that soil may be rich in iron, many people mainly women and children suffer from iron deficiency. This highlights close connection between soil health, plant nutrition and human. Bio fortification techniques, integrated soil reclamation, and nutrition focused research are therefore important to fill this gap, ensuring both agricultural productivity and improved public health. By consolidating findings from soil science, crop physiology, and nutrition, this review provides practical insight for researchers, agronomist and policymakers which are looking to improve food security and reduce iron deficiency through sustainable iron management in Pakistan's agroecosystems.

1. Introduction

Iron is an important micronutrient for healthy plant growth and development by playing crucial role in photosynthesis, respiration and enzymes activity. Although iron is present in abundance in the earth's crust, yet its bio availability in plants, mainly in the calcareous and alkaline soils of Pakistan remains a significant challenge for sustainable agriculture practices (Dudwal et al., 2022). In these soils iron is mainly present as ferric oxide and hydroxide that are poorly soluble and their availability is limited to crops. This limited availability of iron effect important physiological functions which ultimately lower crop yield and quality (Porkodi et al., 2023). Therefore, understanding complex dynamics of iron in soil and plant systems of Pakistan is important for improving farming techniques and crop yield.

Corresponding Author: Hafiz Tanvir Ahmad Email: hafiz.tanvir@yahoo.com

Soils in Pakistan mainly belong to arid and semi-arid regions with high pH, rich in calcium carbonate and low in organic matter all these limit the iron availability (Arain et al., 2017). These conditions limit iron availability by converting it into less available forms like Fe^{+3} which plants cannot uptake easily. Additionally, soil factors like soil texture, nutrients and microbial activity affect how iron moves through the soil and how plants uptake is. To uptake iron from the rhizosphere crops have developed complex strategies like converting ferric ion to more usable ferrous form and releasing compound (root exudates) like chelates that bind iron and help bringing it to roots (Grotz and Guerinot, 2006). In Pakistan, important crops like wheat, maize, rice, and pulses often struggle with iron deficiency, highlighting the importance of careful iron management.

Different agronomic and soil improvement techniques have been tested to mitigate the iron deficiency and improve its availability to crops. These methods include addition of iron containing amendments and applying foliar spray and bio fortification programs aimed at increasing iron contents in the grains and helping people fight against iron deficiency disease like anemia (Majeed et al., 2020; Akhtar, 2013). In addition, biological techniques like using microorganisms that produce siderophores which boost iron availability in the rhizosphere and enhance iron uptake efficiency of plants (Dudwal et al., 2022). Efforts to reclaim salt affected and calcareous soils by using organic amendments and better irrigation practices improve soil health, which indirectly improve iron uptake by promoting healthier soil structure and more effective cycling of nutrients.

Iron deficiency remains a significant public health concern in Pakistan, particularly among women and children, despite the relatively high iron content in soils. This paradox highlights the gaps in iron bio availability and transfer through the soil-plant-human continuum (Akhtar, 2013). Fortification of wheat flour and other food-based interventions have been proposed as feasible solutions, but agronomic bio fortification through iron management in agroecosystems is equally critical to ensure long term nutritional security (Majeed et al., 2020). Therefore, integrated strategies combining soil fertility improvements, crop bio fortification, and nutrition focused research are urgently required.

This review synthesizes current knowledge on iron dynamics in Pakistani agroecosystems, focusing on soil properties influencing iron availability, plant physiological mechanisms of iron uptake, reclamation and management strategies to improve iron nutrition in crops, and the broader implications for human health. By consolidating research from well-established studies, this article aims to inform researchers, agronomists, and policy makers involved in enhancing crop productivity and nutritional outcomes in Pakistan. In this review we collect data from most recent articles which help other researchers for sustainable strategies to improve Fe uptake and support food security and its status in humans.

1.1. Importance of iron in agroecosystems and human health

Iron is involved in fundamental plant processes, including chlorophyll synthesis and photosynthesis. Iron is a vital component for chlorophyll, essential for light absorption and energy conversion in photosynthesis. Iron sulfur proteins in chloroplasts facilitate electron transport (Alam, 2025; Rout and Sahoo., 2015). It also acts as a cofactor in enzymes responsible for nitrogen fixation, respiration, and amino acid biosynthesis, which are critical for growth and development (Li, 2023). Although abundant, iron's poor solubility in aerobic and alkaline soils limits plant availability. Soil organic matter and chelation improve iron solubility and uptake (Algethami et al., 2023).

In humans, iron performs its functions in oxygen transport and energy metabolism. Iron in hemoglobin transports oxygen, which is vital for cellular respiration and energy production. Iron containing mitochondrial enzymes drives ATP synthesis. Iron is crucial for immune cell differentiation and production of reactive oxygen species to combat pathogens (Obeagu, 2025). Iron deficiency affects 30% of the global population, causing anemia, cognitive impairments, and increased susceptibility to infection. Iron overload risks include liver and heart damage (NIH, 2025; Obeagu, 2025). Bio fortification of crops with iron and balanced dietary intake are essential to address global iron deficiency (Majeed et al., 2020).

2. Iron in Pakistani Soils: Properties and Availability

Iron in Pakistani soils exhibits specific properties and availability challenges that significantly impact agricultural productivity. Most soils in Pakistan, particularly in major agroecological zones, are alkaline and calcareous with high pH and calcium carbonate content. This alkaline nature restricts iron solubility and availability to plants by promoting the formation of insoluble iron compounds, making iron deficiency a common micronutrient limitation in Pakistani soils (Babar et al., 2025; Saleem et al., 2023).

Concentration of Iron varies widely across different soils of Pakistan but most of them exist in the non-available form due to soil chemistry. Studies have reported iron concentrations ranging from about 17.75 to 29.50 mg/kg in different districts, with its availability mostly affected by soil pH, organic matter, and texture (Noorka et al., 2022; Wahid et al., 2021). The availability of iron typically in the calcareous soils of Pakistanis restricted due to high pH, as iron availability decrease as the pH increase leading to the deficiency symptoms in the major crops of the region like wheat and rice which show stunted growth and chlorosis of leaves (Saleem et al., 2023; Babar et al., 2025).

Recent studies have shown that addition of iron to crops, mainly through the application of coated urea fertilizer or seed treatment with iron sulfate before plantation, can significantly improve crop growth, enhance yield and increase iron content in the grains. Bio fortification techniques not only improve iron availability to plants but also combat iron deficiency in the people by improving iron available in their diets (Babar et al., 2025). In addition, addition of soil organic matter and iron rich amendments can increase the iron availability to crops.

The assessment of soils from various regions in Punjab highlights that while total iron levels might be adequate, the plant-available fraction suffers due to soil chemistry constraints. Widespread iron deficiency in orchard and field soils is also reported, necessitating integrated nutrient management for sustaining crop productivity in Pakistan's agroecosystems (Kakakhel et al., 2024; Noorka et al., 2022). A detailed survey of about 40,000 soil samples across Sargodha district in 2021 revealed DTPA extractable iron averaging 4.9 mg/kg with 43% deficient and 57% adequate (Qazi, 2021). Recent studies by Afzal et al in 2024 in Jhelum district confirmed about 74% iron deficiency across 823 samples (range 1.1-9.23 mg/kg, mean 3.9 mg/kg), and recommend Iron chelated fertilizer to boost bio availability (Afzal et al., 2024)

2.1. Forms of iron in soils and factors controlling its availability

Iron in soils occurs in multiple chemical forms that profoundly influence its availability to plants. The primary forms include ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions, along with iron bound within minerals and associated with organic matter (Table 1). Most of the soil iron is present as insoluble ferric oxides or hydroxides in aerobic and alkaline soils, making it largely unavailable to plants. Ferrous iron is more soluble and available but predominates in anaerobic conditions, such as waterlogged soils (Porkodi et al., 2023; Briat et al., 2015). Iron is embedded in primary silicate minerals like mica and biotite, which release iron slowly through weathering and contribute minimally to immediate plant-available iron (Porkodi et al., 2023). Iron oxides and hydroxides are commonly found as amorphous or crystalline iron oxides and hydroxides such as ferrihydrite, goethite, and hematite. These serve as the main reservoirs of iron in soils but are generally insoluble, especially under high pH and oxygenated conditions (Schulte, 2023). Iron associated with organic matter forms stable complexes or chelates with organic molecules (humic and fulvic acids), enhancing its solubility and mobility. This complexation is critical for iron bioavailability in many soils (Porkodi et al., 2023; Uren, 1984). Plant available iron pool is the small fraction of iron present as soluble Fe^{2+} and Fe^{3+} ions or weakly bound forms in the soil solution that plants can take up.

Soil pH is the most significant factor controlling iron solubility. At acidic pH (less than 6), iron remains soluble and available, mainly as Fe^{2+} and Fe^{3+} ions. However, at neutral to alkaline pH (>7), typical of calcareous soils, iron precipitates as insoluble oxides and hydroxides, sharply reducing its availability to plants (Lindsay & Schwab, 1982; Porkodi et al., 2023). Redox Potential of Soil influence iron oxidation states, oxidizing conditions favor insoluble Fe^{3+} oxides, while reducing or anaerobic conditions (e.g., flooded soils) promote the formation of soluble Fe^{2+}, which enhances availability (Roden et al., 2004). Organic matter increases iron availability by forming soluble chelates that prevent iron precipitation. It also supports microbial activity that can reduce Fe^{3+} to Fe^{2+}, further facilitating iron availability (Porkodi et al., 2023; Uren, 2023).

Irrigation practices significantly influence iron dynamics in soil by altering the soil's moisture regime and redox conditions, directly affecting iron's chemical forms and availability to plants. Flood irrigation commonly leads to waterlogged, anaerobic soil conditions that increase the concentration of soluble ferrous iron (Fe^{2+}), making iron more accessible but also posing risks of toxicity and oxidative damage to plant roots. Irrigation practices like drip and intermittent practices keep maintaining aerobic conditions in the soil, this promotes transformation of ferrous ions into less soluble ferric form, which limits the immediate availability of iron thus reducing the toxicity of iron. Recent studies have shown that in calcareous soils having high pH, too much irrigation limits iron availability and cause iron deficiency chlorosis. This is because iron mostly exists as insoluble oxides form which make it harder for plants to access under alkaline conditions (Porkodi et al., 2023; Watanabe et al., 2021; Singh et al., 2020).

In short, soil's iron availability is affected by the dynamic balance between its chemical forms and environmental factors like pH, redox potential, and the amount of organic matter present. Properly managing these factors using soil amendments and careful irrigation is essential to provide crops with enough iron for healthy growth.

Deficiency of iron causes noticeable structural changes in chloroplast and disrupts the internal cellular organization, which reduce the efficiency of enzymes important for energy production and the making of chlorophyll precursors (Ning et al., 2023; Wang et al., 2019; Sanders et al., 2015). Beyond its importance in photosynthesis, iron play essential role in DNA synthesis, nitrogen fixation, and helping plants in their defense mechanism against diseases, highlighting how important it is for overall plant health (Rout and Sahoo, 2015; Ponte et al., 2025).

Plants have developed specialized methods to take up iron, mediated to how well they cope with low iron levels in the soil. In dicots and non graminaceous monocots, this process is done by acidifying soils by releasing protons in soils around roots, converting less stable Fe^{3+} iron to the more usable Fe^{2+} form through enzymes, and then transporting it into the plant using specific iron transporters like IRT1. Graminaceous plants, on the other hand, release molecules called phytosiderophores that bind Fe^{3+} and help bring it into the roots. These uptake methods are mostly affected by soil pH and bicarbonate concentrations, which influence root activity and the expression of genes responsible for iron transport. Plants also adapt by growing more root hairs and secreting phenolic compounds to improve iron availability and absorption (Ning et al., 2023; Jeong & Connolly, 2009; Zeng et al., 2019). By carefully managing these iron uptake systems, plants can fulfill their metabolic needs without risking iron overload.

Table 1. Forms of Iron, Sources and Impact on plants

Form of Iron	Sources	Impact on Soil and Plants	References
Ferric form (Fe^{+3})	These are present commonly as iron oxides like goethite, hematite in alkaline and calcareous soils	This is mostly insoluble form leading to iron deficiency in crops thus limits nutrient uptake efficiency	Saleem et al., 2023; Ali et al., 2020
Ferrous form (Fe^{+2})	It is mostly available in waterlogged and anaerobic soils such as rice paddies	Major available form but its excess may cause toxicity and root damage	Phuong et al., 2020; Ahmad et al., 2019
Mineral form of iron	It is derived from parent materials, especially magnetite and siderite minerals	It acts as a long-term iron reservoir influencing soil iron content and availability	Qureshi et al., 2022; Bashir et al., 2021
Organic matter bound iron form	It is chelated form available either organic matter or microbial siderophores	It promotes iron mobilization and uptake by plants effectively, boosting their nutrition even in difficult soil conditions.	Singh et al., 2022; Ghazanfar et al., 2024
Oxides and hydroxides form	Weathered soil surfaces and oxide coatings in arid and semi-arid regions	Influence soil texture and color and can immobilize iron making it less available to plants	Rahman et al., 2023; Khan et al., 2021

3. Plant Physiology and Iron Uptake Mechanisms

Iron plays a fundamental role in plant physiology, primarily by contributing to essential processes such as chlorophyll synthesis, respiration, and enzyme function. About 80% of a plant's iron is in chloroplasts, where it is critical for photosynthesis. Iron deficiency hampers chlorophyll production, leading to leaf chlorosis, impaired photosynthetic efficiency, and overall reduced growth.

4. Soil Reclamation and Management Strategies for Iron Optimization

Soil reclamation and management practices aim at boosting iron availability to plants and focus on improving the physical and chemical characteristics of soils to enhance its bio availability while reducing the risk of toxicity. Iron modified biochar as a soil amendment can help in improving soil fertility, immobilize heavy metals such as cadmium and lead, and improve plants' iron nutrition. Biochar has large surface area which combines with irons reactive properties that help adsorption and precipitation of metals and improve soil health (Algethami et al., 2023; Beesley et al., 2011). Addition of organic amendments and adjusting soil pH either by liming substance or applying acidifying substances mainly in alkaline soils can improve iron solubility and uptake (Lehmann & Joseph, 2015; Saleem et al., 2023).

Managing water effectively through methods such as controlled irrigation schedules and using sub irrigation techniques enhances soil reclamation process by keeping optimum moisture level which improves soil conditions by supporting nutrients cycling and leaching of harmful salts. Crop rotation with leguminous species like alfalfa can improve soil structure and organic matter, indirectly promoting iron availability by modifying rhizosphere conditions favorable for iron solubilization (Rau et al., 2023). Complementary approaches include the integration of synthetic humic like substances combined with iron compounds to form soil amendments that enhance metal adsorption capacities and nutrient retention (Fang et al., 2024). Overall, sustainable reclamation integrates chemical, physical, and biological strategies tailored to site specific soil conditions to optimize iron dynamics for improved crop productivity and environmental safety.

4.1. Role of microbial interactions and siderophores in iron mobilization

Microbial interactions are central to iron mobilization in soils, chiefly through the production of siderophores, high affinity with iron chelating compounds secreted by soil bacteria and fungi. These siderophores bind insoluble ferric iron (Fe^{3+}), converting it into soluble complexes accessible for microbial and plant uptake (Singh et al., 2022; Gomes et al., 2024). By enhancing iron solubility in iron-limited soils, especially those with high pH or heavy metal contamination, siderophores improve iron bio availability, which is critical for plant growth and nutrition. Furthermore, the iron siderophore complex serves as a competitive mechanism to limit pathogenic organisms by depriving them of essential iron (Majewska et al., 2024; Ahmed & Holmstrom, 2014). Microbes help iron mobilization in the soil and play their role in nutrient cycling and help plants to withstand tough conditions.

Microorganisms like Pseudomonas, Bacillus, and Rhizobium that produce siderophores play important role in reclaiming soils by binding and immobilizing toxic metals with iron which help in reducing metal toxicity in the rhizosphere soils (Gomes et al., 2024; Ghazanfar et al., 2024). Under metal contaminated conditions these microbes increase their production of siderophores, this shows their natural ability to survive harsh environmental conditions while also helping plants in nutrient uptake (Sultana et al., 2021; Majewska et al., 2024). Using these beneficial microbes in soil management such as bio fertilizers provides promising and sustainable ways to improve iron nutrition and reduce soil toxicity.

4.2. Reclamation of iron affected or degraded soils for sustainable production

Mining and industrial activities often cause iron toxicity which cause challenges for sustainable agriculture because they tend to have poor soil structure and nutrient imbalance. Recent efforts in soil reclamation mainly focus on using amendments like iron mining waste. These materials improve soil physical condition and moisture retention without causing environmental hazards. Jin et al. (2022) showed that using iron tailing under the topsoil can improve soil porosity and water holding capacity which greatly improve crop production in the arid and semi-arid regions.

New soil health approaches like the use of iron modified biochar have shown positive results in immobilizing heavy metals and microbial activity, thus maintaining soil fertility and plant health over long term (Ashraf and Hasnain, 2019). In addition, use of green remediation methods that use iron nano particles for detoxification of contaminated soils in ecofriendly way (Wang and Huang, 2021).

Use of mining products and advanced iron-based materials provide positive pathway in restoring degraded land. These strategies help improve soil quality, improve crop yield and restore ecosystem without causing further damage (Mukhopadhyay, Singh, & Pandey, 2021). long term monitoring shows that proper management of these reclaimed soils can sustainably support agricultural production which make these methods highly valuable for the areas suffering from land degradation due to iron toxicity (Cao, Wu, & Zhou, 2023; Li, Zhang, & Zhang, 2024).

5. The Human Nutrition Paradox: Iron in Diet vs. Iron Deficiency

Iron nutrition presents a complex paradox for humans that links soil science and health outcomes. While soils rich in iron might suggest sufficient iron availability, iron deficiency remains a widespread global nutrition problem affecting approximately two billion people (Table 2). This paradox arises because the iron in soils is often present in forms unavailable or poorly absorbed by plants and, consequently, by humans through diet (Abbaspour et al., 2014). Iron is essential for oxygen transport in the blood and many metabolic processes, but its bioavailability is limited by soil chemistry, pH, and interactions with other minerals, which restrict crop iron uptake and reduce its nutritional quality in edible parts (Schmidt et al., 2020).

Table 2. Iron Concentration and its deficiency symptoms

Iron Concentration	Deficiency Symptoms	References
Adults: ~8-18 mg/day	Fatigue, weakness, pale skin, shortness of breath, dizziness.	Abbaspour et al., 2014; Healthline, 2024; NHS, 2025
Women (including pregnant): 18 mg/day	heavy menstrual bleeding increases iron requirement. symptoms include fatigue, anemia	Healthline, 2024; Better Health, 2003
Children: 7-10 mg/day	Irritability, poor growth, behavioral problems, developmental delay	Abbaspour et al., 2014; Healthdirect, 2025.

In many calcareous and alkaline soils, which cover over 30% of arable land worldwide, iron tends to form insoluble compounds, causing iron chlorosis in plants and diminishing crop yield and nutritional value. Efforts to bio fortify crops with iron, using agronomic practices or novel iron fertilizers such as iron amino chelates, have shown promise in enhancing iron content and bio availability but face barriers due to soil properties and plant physiology (Alipour Babadi et al., 2025). Meanwhile, excessive iron in some environments can cause toxicity, thus careful management is required to maintain iron homeostasis in plants and prevent negative effects on growth (Wu et al., 2019).

This paradox highlights the need for integrated approaches combining soil management, crop breeding, and nutritional interventions to resolve iron deficiency anemia a major health challenge especially in women and children in developing countries. Improving the bio availability of dietary iron through better soil and plant iron nutrition can provide sustainable solutions to this global Issue (Abbaspour et al., 2014; Schmidt et al., 2020).

6. Conclusion

Iron dynamics in Pakistani agroecosystems reveal a complex interplay between soil properties, plant physiological responses, and nutritional outcomes. Although iron is abundantly present in many soils, the prevalent calcareous nature, high pH levels, and low organic matter content significantly limit iron bioavailability to plants. This leads to widespread iron deficiency in crops, adversely affecting growth, yield, and nutritional quality. Such soil constraints require targeted reclamation strategies, including soil amendments, iron fertilization, and biofortification approaches to enhance iron uptake by plants and ensure sustainable productivity. At the physiological level, iron deficiency induces chlorosis and disrupts vital plant metabolic processes, underscoring the importance of optimal iron nutrition for healthy crop development. Addressing iron deficiency not only supports crop health but also impacts human nutrition, given the central role of staple crops as dietary iron sources. Therefore, integrated soil-plant management practices are essential for improving iron availability in soils and crops, which can contribute to resolving iron nutritional deficiencies in human populations. Sustainable iron management in Pakistani agriculture demands a multidisciplinary approach that connects soil science, crop physiology, and nutrition. This approach aims to reclaim degraded soils, optimize crop production, and improve dietary iron intake, enhancing both food security and public health in the region.

7. Funding

This research received no external funding.

8. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

9. Authors' Contribution

Muhammad Hanzala Mansha and Hafiz Tanvir Ahmad conducted the initial data collection. Syed Kazim Ali, Arisha, and Rana Asad Jabbar contributed to the investigation and literature synthesis. Hafsa Rameen, Ijaz Mehboob, and Ayesha Irum handled the technical review and final manuscript editing.

10. SDGs Addressed

This study directly contributes to SDG 2 (Zero Hunger) by promoting sustainable carrot production and food security and supports SDG 12 (Responsible Consumption and Production) through eco-friendly biopriming practices that reduce reliance on chemical inputs.

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