Iron toxicity in plants: A Review

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ABSTRACT

Iron (Fe) is an essential micronutrient for plant growth and development, but excessive iron uptake can cause iron toxicity, leading to damage to plant cell membranes, reduced growth, yield, and overall health. This review paper discusses the issue of iron toxicity in plants, a common problem that affects crops such as rice, soybean, wheat, vegetables and is a common issue in Southeast Asia, Brazil, Africa, Australia, and the United States. Iron toxicity is more likely to occur in soils with high pH, high organic matter, or elevated levels of available iron. It discusses the various mechanisms that cause iron toxicity in plants, such as competition with other essential elements, oxidative stress, and changes in gene expression and phytohormones. The excess iron ions can cause damage to the root cells and the plasma membrane, leading to oxidative stress and increased production of reactive oxygen species (ROS). ROS can cause damage to cellular components, such as lipids, proteins, and DNA, leading to the death of root cells. Plants have specific mechanisms to take up iron, including transport proteins that are responsible for moving Fe^{2+} across the plasma membrane of root cells. Furthermore, it discusses the impact of iron toxicity on plant growth and development, including stunted growth, reduced root development, decreased water and nutrient uptake, and reduced photosynthetic activity. Highlights the importance of proper management of iron levels in soils to prevent iron toxicity and promote healthy plant growth.

Keywords: Iron toxicity, Cell membrane, Yield, Reducing growth, Oxidative stress

1. INTRODUCTION

Iron (Fe) is an essential micronutrient for plant growth and development, playing a critical role in various physiological processes, such as photosynthesis, respiration, and nitrogen metabolism [1]. Plants need to maintain iron (Fe) in the concentration of 10^{-4} to10^{-9} M to achieve optimal growth [2]. However, excessive iron uptake can lead to iron toxicity, causing damage to the plant's cell membranes, reducing growth, yield, and affecting the overall health of the plant [3]. Soils with low pH, low levels of organic matter, or low levels of available iron are not commonly associated with iron toxicity. In fact, these conditions are more likely to result in iron deficiency rather than iron toxicity in plants. Iron toxicity can occur in different soils, including those with high pH, high levels of organic matter, or elevated levels of available iron [4]. These conditions lead to an increase in the concentration of free Fe ions, which can bind to cellular components, disrupting cellular function and leading to plant stress. It is a common problem in many parts of the world, affecting crops such as rice, soybean, wheat, maize, and vegetables. Some of the regions with high iron toxicity in plants include Southeast Asia, Brazil, Africa, Australia, and United States. Iron toxicity can occur in both soil-grown and hydroponic systems, and it is especially common in calcareous soils, which have high pH levels [1].

Iron toxicity can occur in different plants if the levels of iron in the soil are too high [3]. Some plants are more sensitive to iron toxicity than others, such as most fruit trees, tomatoes, and peppers. On the other hand, some plants are less sensitive to iron toxicity and can tolerate high levels of iron in the soil, such as most grasses, some tree species like oak, pine, and eucalyptus [1]. High levels of iron in the soil can lead to the formation of toxic compounds, including hydroxyl radicals, which can cause oxidative damage to plant cells. This process is known as Fenton reaction, which involves the interaction between iron, hydrogen peroxide (H2O2), and other reactive oxygen species (ROS). $Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^-$.

High levels of iron in the soil can also lead to the formation of toxic compounds, such as hydroxyl radicals, that can cause oxidative damage to plant cells. Reactive Oxygen Species (ROS) are chemically reactive molecules containing oxygen that are generated during various metabolic processes in plants. Examples of ROS include superoxide radicals, hydrogen peroxide, hydroxyl radicals, singlet oxygen, and peroxyl radicals. While ROS play important roles in cellular signalling and defence mechanisms, their excess accumulation can lead to oxidative stress and damage to cellular components such as lipids, proteins, and DNA. The plant's antioxidant system, including enzymes such as superoxide dismutase, catalase, and ascorbate peroxidase, helps to reduce the levels of ROS in the plant cells and protect against oxidative stress [3]. Additionally, excess Fe accumulation can disrupt the nutrient balance of plants, leading to deficiencies in other essential nutrients such as zinc, copper, and manganese. Nutrient deficiencies can further increase the effects of Fe toxicity, leading to reduced plant growth, chlorosis, and necrosis. It can have a significant impact on crop productivity and quality [5]. In addition to reducing plant growth, it can also lead to a decline in yield and quality of harvested crops. The presence of excess Fe in the soil can also have negative effects on soil microbial communities, further impacting plant growth and productivity.

2. Impact on plant growth and development

Iron toxicity in plants is believed to be associated with the regulation of iron uptake and transport. Iron uptake in plants is facilitated by specific transporters that are regulated by the concentration of iron in the soil [6]. It is a serious problem for plants as it can negatively affect various aspects of their growth and development. It can cause stunted growth and reduced root development, which leads to decreased water and nutrient uptake and reduced photosynthetic activity [7]. In addition, iron toxicity can result in decreased chlorophyll content, which affects the plant's ability to perform photosynthesis, leading to reduced growth and productivity [40]. In severe cases, leaf necrosis may occur, leading to the death of the plant [8]. Leaf yellowing is another common symptom of iron toxicity, which is associated with chlorosis [1]. Furthermore, iron toxicity can cause reduced seed production, which affects plant reproduction and survival [5].

3. Mechanisms of iron toxicity in plants

Iron toxicity in plants occurs when the concentration of iron in the soil solution exceeds the plant's ability to absorb and transport it to the roots. The form of iron that is taken up by plants is usually Fe^{2+} (ferrous iron) ion. Fe^{3+} (ferric iron) is the most common form of iron in aerobic soils, but it is not easily absorbed by plant roots because it forms insoluble precipitates [9]. In anaerobic soils, Fe^{2+} is more prevalent as it is formed by reduction of Fe^{3+} by microorganisms, and this form of iron can be more easily absorbed by plant roots. Plants have specific mechanisms to take up iron, including transport proteins that are responsible for moving Fe^{2+} across the plasma membrane of root cells. Plants also secrete compounds called "siderophores," which bind to Fe^{3+} and help to solubilize it, making it more available for uptake by plant roots [10]. Once inside the plant, iron is used in several processes, including the formation of chlorophyll for photosynthesis and in the production of enzymes that are involved in respiration and nitrogen fixation.

The excess iron ions can cause damage to the root cells and the plasma membrane, leading to oxidative stress and increased production of reactive oxygen species (ROS). ROS can cause damage to cellular components, such as lipids, proteins, and DNA, leading to the death of root cells [11]. Excess iron can also affect the uptake of other essential elements, such as phosphorus and zinc, by competing with the transporters that facilitate their uptake by the roots. This interference can lead to nutrient imbalances, reduced growth, and overall plant health [1].

Recent research studies have shown that excess iron can lead to alterations in the expression of genes involved in iron uptake, transport, and homeostasis [12]. These changes in gene expression can further increase the physiological and biochemical changes associated with iron toxicity. Another mechanism involved in iron toxicity in plants is the production of phytohormones, such as ethylene and auxin. Excess iron can stimulate the production of ethylene and auxin in plants, leading to various physiological and biochemical changes [13]. These changes can further contribute to the toxic effects of excess iron on plant growth and development.

4. Effects of iron toxicity on plant

Iron toxicity can have detrimental effects on plant growth and development, [14] found that elevated iron concentration caused a boost in the antioxidant enzyme activity in both roots and leaves, but lowered the levels of photosynthetic pigments, leaf gas exchange, and overall plant growth. Similarly, [15] reported that iron toxicity can cause poor growth, tillering, reduction in crop spike number, spikelet sterility, and flowering delay or even failure and severe yield reductions, associated with leaf discoloration. It can reduce crop yields dramatically, such as that of rice, by up to 78% in West Africa.

The presence of excess iron in submerged paddy fields with low pH, often leads to iron toxicity in rice, which can disrupt cell homeostasis and impair growth and yield due to the significant increase in ferrous ion concentration as reported by [16]. Iron toxicity symptoms in rice manifest due to the excessive absorption of Fe^{2+} by the roots, which is then transported upwards to the leaves through acropetal translocation. This results in an increased production of harmful oxygen radicals, which can harm cell structural components and disrupt physiological functions [17]. Excess iron can trigger a rise in polyphenol oxidase activity, resulting in the synthesis of oxidized polyphenols. Additionally, iron toxicity can induce leaf bronzing and decrease root oxidation capacity. Excessive levels of Fe^{2+} ions increase the generation of ROS ($O_2^{\bullet-}$, H_2O_2, $^1O_2$, HO_2, $OH^\bullet$, OH^-, and RO), which are extremely toxic and reactive and can cause protein oxidation, lipid peroxidation, carbohydrate, and DNA damage, which can result in cell death [18]. Fe toxicity in the medicinal plant *Bacopa monnieri* L. leads to the production of MDA in the leaves and shoots [19].

Iron toxicity can have adverse effects on the uptake and balance of other vital nutrients in plants, as reported by [20]. Their study revealed that iron toxicity reduced the uptake of nitrogen (N), phosphorus (P), and potassium (K). The reduced uptake of these essential nutrients can cause nutrient imbalances, leading to growth inhibition and reduced yield.

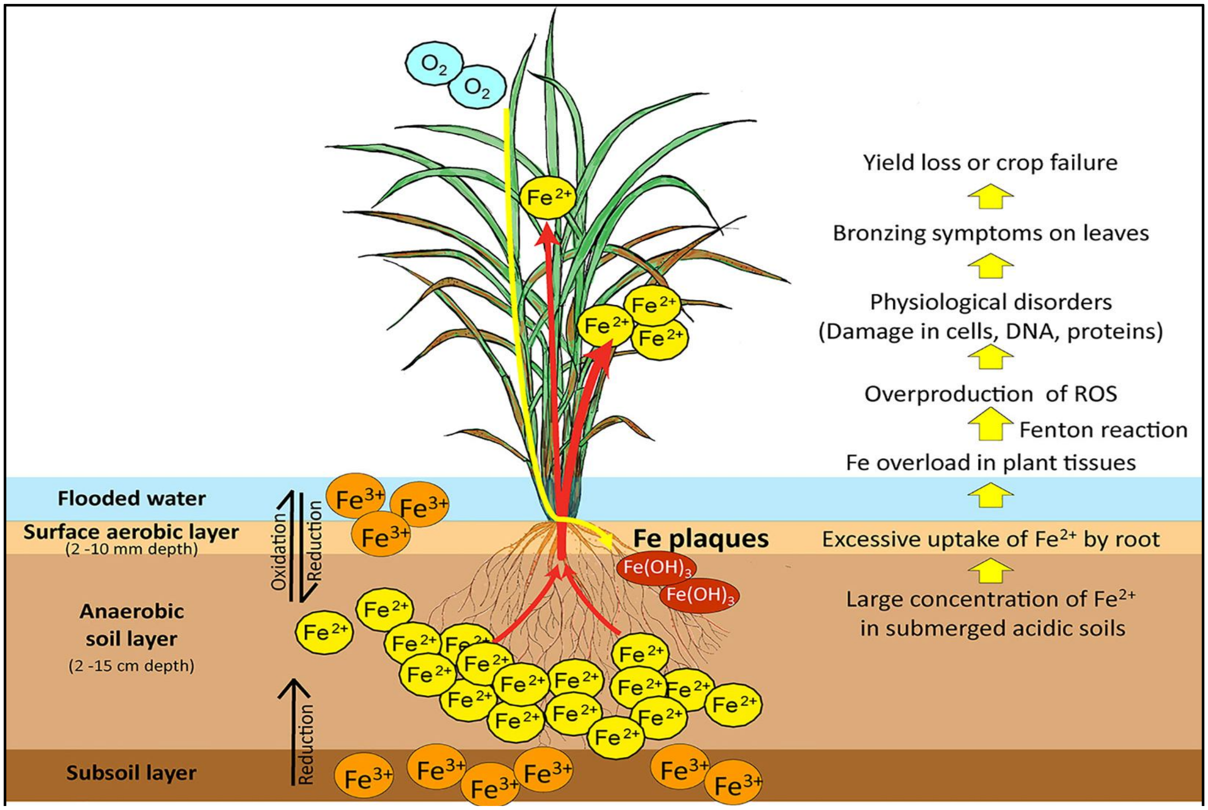

Figure 1. *Iron reduction in submerged low-pH soils and the effects of Fe toxicity on rice plants. In submerged soils with anaerobic and low pH conditions, ferric ion (Fe^{3+}) is reduced to the more soluble ferrous ion (Fe^{2+}).*

5. Strategies for mitigating iron toxicity

Iron toxicity in plants can be a significant problem in areas with high soil iron levels. To mitigate its effects, several strategies have been developed. One approach is to modify the soil environment by adjusting the soil pH can reduce the availability of iron to the plant. For example, adding lime to alkaline soils or sulphur to acidic soils can help to lower the soil pH and decrease the uptake of iron [8]. Elevating the pH of the soil by lowering the concentration of free hydrogen ions can promote the binding of iron ions to negative sites in the soil, leading to a reduction in free iron and subsequently decreasing its bioavailability to plants. Another strategy is to select iron-tolerant plant species. certain plant species are more tolerant to iron toxicity and can be used in areas with high soil iron levels. Additionally, chelation can be used to reduce the toxicity of excess iron. Chelation is the process of binding metal ions with chelating agents, such as organic molecules called chelators or chelating agents [34]. The resulting complex formed between the chelator and the metal ion is called a chelate. In biological systems, chelation is involved in the transport and storage of metal ions, such as iron, copper, and zinc, and is critical for the proper functioning of enzymes and other proteins that require these metals as cofactors. Chelation can also be used to remove excess metal ions [35].

Table 1: Effects of iron toxicity on different crops

Crop	Iron Concentration in Plant	Effect	Reference
Wheat	>100 mg kg^{-1}	Inhibition of root, shoot growth, reduced yield, and oxidative stress	[21]
Rice	>300 mg kg^{-1}	Leaf bronzing, stunted growth, reduction in yield, and biomass	[22]
Cherry	>1300 mg kg^{-1}	Reduced relative growth rate (RGR) of roots and leaves, leaf chlorosis and darkening of roots	[23]
Soybean	>30 mg kg^{-1}	Leaf chlorosis, stunted growth, reduced yield, reduced biomass, oxidative stress, and change in gene expression	[24]
Arabidopsis	>350 µM Fe L^{-1}	Reduced growth, chlorosis, and oxidative stress	[25]
Pepper tree	>250 µM Fe L^{-1}	Leaf chlorosis, dark roots, and plant growth reduction	[26]
Green gram	>200 µM Fe L^{-1}	Seed germination is significantly reduced	[27]
Cucumber	>10 µM Fe L^{-1}	Decrease in chlorophyll content, growth, and yield	[28]
Common reed	>50 mg L^{-1}	Reduced growth of the seedlings	[29]
Cowpea	>400 mg L^{-1}	Retarded growth, decreased chlorophyll concentration, reduced yield and oxidative stress.	[30]
Pea	>40 mg L^{-1}	Reduced growth, chlorosis, and yield reduction	[31]
Potato	>0.1 Mm Fe	Reduced growth, decreased chlorophyll concentration, reduced tuber yield, deterioration of quality by lowering the concentration of sugars, starch.	[32]
Ashwagandha	>200 mM Fe	Thickened cell wall, folding and shrinkage of cell wall, damage of cell membranes	[33]

According to [1], chelating agents like EDTA or DTPA can be added to the soil to solubilize excess iron and reduce its toxicity. Limiting waterlogging can also help to mitigate the effects of iron toxicity. As reported by [36], waterlogging reduces oxygen levels in the soil, creating anaerobic conditions that promote the reductive dissolution of iron, leading to increased concentrations of soluble iron ions (Fe2+) in the soil solution. This increased availability of iron can exacerbate iron toxicity in plants. While FeO forms can develop under reducing conditions, they are not highly mobile or bioavailable compared to the soluble ferrous iron ions (Fe^{2+}). Finally, using iron-efficient cultivars can be an effective strategy for reducing the effects of iron toxicity. [37] investigated the effectiveness of using chelating agents, such as citric acid and ethylenediamine tetra acetic acid (EDTA), to reduce the bioavailability of iron in the soil and reduce the symptoms of iron toxicity in rice plants. Other studies have focused on genetic engineering to increase the plant's tolerance to iron toxicity, such as by overexpressing genes involved in iron uptake and transport [38].

The use of iron-deficient soils or hydroponic solutions has also been shown to reduce the symptoms of iron toxicity. Additionally, the application of iron-solubilizing bacteria, such as *Bacillus* spp., has been shown to increase the bio-availability of iron in the soil and reduce the symptoms of iron toxicity in various crops [39]. These approaches have shown promise in mitigating iron toxicity in plants and could be used to improve crop yield and reduce the negative effects of iron toxicity on plant growth and development.

4. CONCLUSION

Iron toxicity is a widespread problem that can seriously affect plant growth and development in soils with high iron concentrations. This condition leads to reduced productivity and increased susceptibility to diseases. Several studies have highlighted the damaging effects of iron toxicity on photosynthesis, chlorophyll content, antioxidant defence systems, and nutrient uptake and balance in plants [42]. To alleviate the negative effects of iron toxicity, several strategies have been suggested. One of the most effective ways is to modify soil conditions by adjusting the pH and/or adding organic matter, such as compost or manure, to the soil. The impact of adjusting pH and adding organic matter on Fe bioavailability depends on the existing biogeochemical conditions and compounds in the soil. It is essential to consider factors such as soil composition, iron forms, and nutrient interactions when implementing pH adjustments or incorporating organic matter to manage iron toxicity. Soil testing and assessment of specific soil conditions are important to determine the appropriate remedial measures for mitigating iron toxicity. Another strategy is to use iron-tolerant plant species, which have developed mechanisms to withstand high levels of iron in their environment. Other methods include chelation, limiting waterlogging, and using iron-efficient cultivars. Despite these strategies, further research is necessary to gain a better understanding of the mechanisms of iron toxicity in plants and to develop new and more effective approaches for mitigating its negative effects. Research could help identify the genetic and physiological factors that influence iron tolerance in plants and develop better soil management practices for iron-contaminated soils.

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