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Agronomic Biofortification of Zinc and Iron in Pigeonpea: A Sustainable Approach for Hidden Hunger Mitigation

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Pigeonpea (*Cajanus cajan* L.) is an important pulse crop grown in tropical and subtropical regions and contributes significantly to food and nutritional security, especially in developing countries. However, micronutrient deficiencies, commonly referred to as hidden hunger, affect a large proportion of the global population due to inadequate intake of essential nutrients such as zinc (Zn) and iron (Fe). Agronomic biofortification, which involves the enhancement of micronutrient concentration in edible plant parts through soil and foliar nutrient management, has emerged as an economical and sustainable approach to address micronutrient malnutrition. In comparison to genetic approaches, agronomic interventions provide faster and more practical solutions through the use of micronutrient fertilizers, soil amendments and integrated nutrient management practices. In pigeonpea, enrichment with Zn and Fe not only improves grain nutritional quality but also positively influences crop growth, nodulation and stress tolerance. This review critically examines recent developments in agronomic biofortification of zinc and iron in pigeonpea, emphasizing fertilization strategies, nutrient dynamics, physiological mechanisms and their potential role in alleviating hidden hunger. The paper also discusses the Indian perspective, future research priorities and policy interventions for promoting nutrition-sensitive pulse production systems.

Key Words: Agronomic biofortification, Zinc, Iron, Pigeonpea, Hidden hunger, Micronutrients, Nutritional security

Introduction

Micronutrient deficiency, widely known as hidden hunger, has emerged as a serious global nutritional concern affecting billions of people, particularly in regions where diets are dominated by cereals and pulses. Among various micronutrients, zinc (Zn) and iron (Fe) deficiencies are most widespread and are associated with anemia, weakened immunity, impaired growth and reduced cognitive performance, especially among children and women. In countries like India, pulses serve as a major source of dietary protein and minerals for vegetarian populations, making their nutritional quality highly important.

Pigeonpea (*Cajanus cajan* L.) is the second most important pulse crop in India and occupies a substantial area under cultivation, contributing significantly to protein and micronutrient intake. Despite its inherent nutritional value, the concentration of bioavailable micronutrients in pigeonpea grains is often insufficient due to declining soil fertility, micronutrient depletion and imbalanced fertilizer application. Many Indian soils are inherently deficient in zinc and iron, which restricts their uptake, translocation and accumulation in edible plant parts.

Under such circumstances, agronomic biofortification, which focuses on enhancing micronutrient density in crops through external nutrient management, offers a practical, cost-effective and farmer-friendly strategy. Unlike conventional fortification and supplementation methods, agronomic biofortification enriches the crop during its growth period, ensuring nutrient delivery through the natural food chain and making it particularly suitable for resource-poor farming systems.

Concept of Agronomic Biofortification

Agronomic biofortification refers to the application of mineral fertilizers, soil amendments and nutrient management practices to increase the concentration and bioavailability of essential micronutrients in the edible parts of crops. It differs from genetic biofortification and transgenic approaches by providing immediate results without altering the crop's genetic makeup.

The primary objectives of agronomic biofortification include:

1. Enhancing Zn and Fe concentration in edible grains
2. Improving nutrient uptake efficiency
3. Increasing bioavailability of micronutrients
4. Sustaining crop yield and soil fertility

In pigeonpea, agronomic biofortification mainly focuses on zinc sulfate ($ZnSO_4$) and iron fertilizers through soil application, foliar spray, seed treatment and integrated nutrient management practices.

Importance of Zinc and Iron in Human Nutrition and Crop Physiology

Zinc and iron are essential micronutrients for both plant growth and human health. Zinc plays a critical role in enzyme activation, protein synthesis and hormone regulation, while iron is involved in chlorophyll synthesis, respiration and nitrogen fixation.

From a nutritional perspective, iron deficiency leads to anemia, fatigue, and reduced work capacity, whereas zinc deficiency causes impaired immune function, delayed growth and increased susceptibility to infections. Pulses like pigeonpea are naturally rich in protein but often contain suboptimal levels of bioavailable Zn and Fe, necessitating external enrichment through agronomic interventions.

Approaches to Agronomic Biofortification of Zinc and Iron in Pigeonpea

1. Soil Application of Zinc and Iron Fertilizers

Soil application is one of the most effective methods for micronutrient biofortification in pigeonpea. Zinc sulfate ($ZnSO_4 \cdot 7H_2O$) applied at 20–25 kg ha^{-1} significantly enhances grain Zn concentration and crop yield. Similarly, ferrous sulfate ($FeSO_4$) application improves iron availability in calcareous and alkaline soils where Fe deficiency is common.

Studies have shown that combined soil application of Zn and Fe increases nodulation, root growth, and nitrogen fixation in pigeonpea, thereby improving both yield and nutritional quality. Soil-applied micronutrients also improve residual soil fertility and benefit succeeding crops in pulse-based cropping systems.

2. Foliar Application: A Rapid Biofortification Strategy Foliar spray of micronutrients is a highly efficient method for enhancing Zn and Fe concentration in pigeonpea grains due to direct absorption through leaves. Foliar application of 0.5% $ZnSO_4$ and 0.5% $FeSO_4$ at flowering and pod formation stages significantly increases grain micronutrient content.

Foliar feeding ensures:

- Higher nutrient use efficiency
- Quick correction of deficiencies
- Enhanced translocation to seeds
- Improved grain quality

This method is particularly useful under rainfed and micronutrient-deficient soil conditions.

3. Seed Priming and Seed Treatment

Seed priming with zinc and iron solutions is an emerging agronomic biofortification technique that enhances early seedling vigor and micronutrient uptake. Zn and Fe seed treatment improves germination, root proliferation and nutrient absorption efficiency in pigeonpea. This approach is cost-effective and suitable for smallholder farmers.

4. Integrated Nutrient Management (INM)

Integrated application of organic manures, biofertilizers, and micronutrients significantly enhances Zn and Fe biofortification in pigeonpea. The use of farmyard manure (FYM), vermicompost and micronutrient-enriched compost improves soil microbial activity and micronutrient availability. Rhizobium inoculation combined with Zn and Fe fertilization enhances biological nitrogen fixation and micronutrient uptake, leading to better grain enrichment and sustainable soil health.

Physiological and Molecular Mechanisms of Zn and Fe Uptake in Pigeonpea

The uptake and accumulation of zinc and iron in pigeonpea involve complex physiological and molecular mechanisms. Root transporters such as ZIP (Zinc-regulated transporter/Iron-regulated transporter proteins), YSL (Yellow Stripe-Like proteins) and NRAMP transporters play a key role in micronutrient absorption and translocation. Zinc enhances auxin synthesis and enzyme activity, while iron is essential for electron transport and chlorophyll formation. Adequate supply of Zn and Fe improves photosynthesis, protein synthesis and carbohydrate metabolism, ultimately increasing grain micronutrient density.

Nutrient Interactions and Soil Factors Affecting Biofortification

Micronutrient availability in pigeonpea is influenced by several soil factors such as pH, organic matter, soil texture, and nutrient interactions. High soil pH and phosphorus levels often reduce Zn and Fe availability due to antagonistic interactions. Conversely, organic matter and chelating agents enhance micronutrient solubility and uptake. Balanced fertilization and site-specific nutrient management are essential to achieve effective agronomic biofortification.

Achievements and Research Advances in India

India has made significant progress in micronutrient management in pulse crops under ICAR and AICRP-Pigeonpea programs. Several field studies have reported that combined soil and foliar application of Zn and Fe increases pigeonpea grain yield by 10–25% and significantly enhances micronutrient concentration. Research conducted at ICAR-IIPR, Kanpur and various State Agricultural Universities has demonstrated that application of 25 kg $ZnSO_4$ ha^{-1} along with recommended NPK and foliar spray improves grain Zn and Fe content while maintaining yield stability. Agronomic biofortification practices are now being promoted under national initiatives such as the National Food Security Mission (NFSM-Pulses) and Nutri-Smart Agriculture programs.

Socioeconomic and Nutritional Impacts

Agronomic biofortification of pigeonpea offers dual benefits of improving crop productivity and nutritional quality. Adoption of Zn and Fe fertilization enhances farmer income through higher yield and better market value of nutritionally enriched pulses. From a public health perspective, increased consumption of micronutrient-rich pigeonpea can significantly reduce anemia and zinc deficiency in vulnerable populations. Integration of biofortified pulses into government nutrition programs such as Mid-Day Meal Scheme, ICDS, and Public Distribution System (PDS) can amplify their nutritional impact and contribute to achieving Sustainable Development Goals (SDG 2 and SDG 3).

Challenges and Future Perspectives

Despite its potential, agronomic biofortification faces several challenges including low awareness among farmers, limited access to micronutrient fertilizers, soil heterogeneity, and variability in nutrient response across environments. Future research should focus on:

- Nano-fertilizers for enhanced micronutrient use efficiency
- Precision agriculture and site-specific nutrient management
- Integration of agronomic and genetic biofortification
- Climate-resilient nutrient management strategies

- Development of micronutrient-efficient pigeonpea varieties

Advancements in omics technologies, nutrient diagnostics and decision support systems will further strengthen agronomic biofortification programs.

Conclusion

Agronomic biofortification of zinc and iron in pigeonpea represents a sustainable, economically viable, and scalable strategy to combat hidden hunger and micronutrient malnutrition. The combined application of soil and foliar micronutrients, integrated nutrient management, and improved agronomic practices can significantly enhance grain micronutrient concentration without compromising yield. Given the widespread Zn and Fe deficiencies in Indian soils and diets, promoting micronutrient fertilization in pigeonpea cultivation can substantially improve nutritional security and public health. Future efforts should focus on policy support, farmer awareness, and integration of biofortified pulses into national nutrition programs to achieve long-term food and nutritional sustainability.

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