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Research on the Role of Micronutrient Management in Improving Cotton Fiber Quality

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Abstract Cotton is an important fiber crop with significant global economic and industrial significance, and improving its fiber quality is essential to maintain competitiveness in the textile industry. This study explores the role of micronutrient management in improving cotton fiber characteristics such as length, strength, and fineness. We comprehensively study the physiological functions and agronomic importance of key micronutrients (i.e., boron, zinc, iron, and manganese) and analyze their effects on fiber development at the cellular and molecular levels. This review introduces effective soil and foliar application strategies, emphasizing an integrated nutrient management approach for optimal uptake and sustained productivity. A case study from India highlights the practical benefits and challenges of micronutrient interventions in cotton cultivation. We also discuss future directions, including nanotechnology applications, genetic advances to improve nutrient efficiency, and the integration of precision agriculture tools. This study highlights the need for micronutrient-centric agronomic practices, increased farmer awareness, and a supportive policy framework to achieve sustainable improvements in cotton fiber quality and overall crop performance.

Keywords Micronutrients; Cotton fiber quality; Boron and zinc; Nutrient management strategies; Sustainable cotton production

1 Introduction

Cotton is a vital global fiber crop, extensively cultivated in tropical and subtropical regions. It plays a crucial role in the textile industry, providing raw material for a wide range of products. The importance of cotton extends beyond its economic value, as it also contributes significantly to the livelihoods of millions of farmers worldwide (Wahid et al., 2020; Abbas et al., 2022). However, cotton production faces challenges such as climate change and nutrient imbalances, which can adversely affect yield and fiber quality (Ul-Allah et al., 2021; Abbas et al., 2023).

Micronutrients are essential for plant physiology, playing critical roles in various biochemical and physiological processes. Elements like boron, silicon, zinc, and magnesium are vital for the growth and development of cotton plants. These micronutrients are involved in processes such as photosynthesis, enzyme activation, and cell division, which are crucial for maintaining plant health and improving fiber quality (Swetha et al., 2020; De Souza Júnior et al., 2022). Despite their importance, micronutrient management in cotton cultivation has often been overlooked, leading to deficiencies that can impair plant growth and reduce fiber quality (Ahmed et al., 2020).

This study explored the role of micronutrient management in improving cotton fiber quality. It explored the effects of various micronutrients on cotton growth and fiber characteristics. Drawing on recent research results, it included analyzing different micronutrient application methods, such as foliar spraying, and their effects on cotton yield and fiber quality. By synthesizing current research results, this study aims to fully understand how to optimize micronutrient management to improve cotton production results.

2 Key Micronutrients Influencing Cotton Fiber Quality

Micronutrient management plays a crucial role in enhancing the quality of cotton fiber. Among the essential micronutrients, boron (B), zinc (Zn), iron (Fe), and manganese (Mn) are particularly significant in influencing cotton fiber quality.

2.1 Boron (B)

Boron is a vital micronutrient for cotton growth, significantly impacting fiber quality. It aids in the transfer of sugars and nutrients from leaves to fruit, which is crucial for plant functions and fiber development. Studies have shown that foliar application of boron improves cotton fiber quality by enhancing boll retention, lint yield, and fiber strength (Wahid et al., 2020; Abbas et al., 2023). Boron application is particularly beneficial in soils with low boron content, where it can improve fiber yield and quality traits such as micronaire index, strength, and uniformity (Cordeiro et al., 2024). Additionally, combining boron with other elements like silicon can further enhance fiber quality by improving tensile strength and reducing short fiber content (Table 1) (De Souza Júnior et al., 2022).

Table 1 Analysis of variance for the influence of individual and combined application of silicon and boron on morphological and yield and fiber quality traits of transgenic cotton (Adopted from Abbas et al., 2023)

Mean sum of squares		
Source of variance	Treatment	Error
DF	9	20
Plant height	208.18**	23.05
Monopodial branches	0.72**	0.15170
Sympodial branches	15.65**	1.83
Open bolls	99.60**	12.12
Closed bolls	1.1813**	0.0398
Total bolls	26.25	0.76
Seed cotton yield	2258.92**	267.19
Ginning out turn	1.17**	0.01
Fiber length	0.26**	0.005
Fiber uniformity	3.69**	0.14
Micronaire	0.10**	0.003
Fiber strength	1.09**	0.05

2.2 Zinc (Zn)

Zinc is another essential micronutrient that directly affects cotton yield and fiber quality. It plays a role in enzyme activation, auxin synthesis, and maintaining biological membrane stability, all of which are critical for plant growth and fiber development (Swetha et al., 2020). Zinc deficiency can lead to poor crop production and fiber quality, making its adequate supply crucial for optimal cotton growth (Ahmed et al., 2020). Foliar application of zinc is often recommended in conditions where soil application is ineffective due to binding with soil particles.

2.3 Iron (Fe) and manganese (Mn)

Iron and manganese are also important micronutrients for cotton production. They are involved in various physiological processes, including chlorophyll synthesis and enzyme activation, which are essential for plant health and fiber quality (Bellaloui et al., 2021). Deficiencies in these micronutrients can lead to reduced fiber quality and yield. Ensuring an adequate supply of iron and manganese through foliar applications can help mitigate these deficiencies and improve cotton fiber quality.

3 Mechanisms by Which Micronutrients Enhance Fiber Quality

3.1 Cellular and molecular effects on fiber elongation

Micronutrients such as boron (B) and silicon (Si) play a crucial role in the cellular and molecular processes that enhance fiber elongation in cotton. Boron is essential for the development and growth of new cells in the growing meristem, which is critical for fiber elongation. It aids in the transfer of sugars and nutrients from leaves to fruit, directly impacting fiber development (Swetha et al., 2020). Additionally, the overexpression of certain genes, such as *GhACO1*, which is involved in ethylene biosynthesis, has been shown to improve fiber elongation by promoting cell wall loosening and cytoskeleton arrangement, thereby enhancing fiber quality (Wei et al., 2022).

3.2 Enhancement of boll set and retention

Micronutrients significantly influence boll set and retention, which are vital for improving cotton yield and fiber quality. Boron application has been shown to improve boll retention and increase the number of bolls per plant, which directly contributes to higher fiber yield (Abbas et al., 2023). The foliar application of boron and silicon, either individually or in combination, has been found to enhance boll retention and seed cotton production, indicating their role in stabilizing boll set under various environmental conditions (Abbas et al., 2022).

3.3 Impact on fiber fineness, strength, and length

The application of micronutrients such as boron and silicon has a profound impact on fiber fineness, strength, and length. Studies have demonstrated that the combined application of boron and silicon improves fiber length and tensile strength, while also reducing short fiber content, thereby enhancing overall fiber quality (De Souza Júnior et al., 2022). Boron application alone has been shown to improve fiber length and uniformity, contributing to better fiber quality traits (Wahid et al., 2020). Moreover, the use of biostimulants and micronutrient management strategies can lead to improvements in fiber characteristics such as length uniformity, micronaire, and strength (Silva et al., 2016).

4 Strategies for Effective Micronutrient Management

4.1 Soil-based management techniques

Soil-based management techniques for micronutrient management in cotton involve the application of essential nutrients directly to the soil to enhance plant growth and fiber quality. Boron (B) is a critical micronutrient for cotton, especially in calcareous saline soils where deficiencies are common. Soil application of boron has been shown to significantly improve growth, yield, and fiber quality traits. For instance, applying 2.60 mg/kg of boron to the soil improved plant height, leaf area, and boll characteristics, leading to enhanced seed cotton yield and fiber quality in the CIM-600 cotton cultivar (Atique-Ur-Rehman et al., 2020). This approach ensures that the micronutrients are available throughout the plant's growth stages, particularly during boll formation, which is crucial for fiber development.

4.2 Foliar application approaches

Foliar application is a widely used strategy for delivering micronutrients directly to the plant leaves, allowing for rapid absorption and utilization. This method is particularly effective for micronutrients like boron and silicon, which play vital roles in improving cotton fiber quality. Studies have demonstrated that foliar application of boron and silicon, either individually or in combination, can enhance fiber length, strength, and uniformity. For example, a combined foliar application of 4.0 mM silicon and 1.0 mM boron resulted in significant improvements in fiber quality traits such as ginning out turn and fiber uniformity (De Souza Júnior et al., 2022; Abbas et al., 2023). Additionally, foliar application of mepiquat chloride and nitrogen has been shown to improve boll weight, seed cotton yield, and fiber quality, highlighting the effectiveness of foliar nutrition in optimizing cotton production (Abbas et al., 2022).

4.3 Integrated nutrient management (INM)

Integrated nutrient management (INM) combines soil and foliar applications to optimize nutrient availability and improve cotton fiber quality. This approach involves the strategic use of both soil-applied and foliar-applied nutrients to address deficiencies and enhance plant growth. For instance, combining soil application of potassium with foliar sprays of potassium nitrate has been shown to significantly improve plant morphology, seed cotton yield, and boll characteristics (Tariq et al., 2018). INM practices also include the use of nano-calcium and potassium humate foliar sprays, which have been found to enhance growth, yield, and fiber quality in cotton grown on alluvial non-saline soils (Rabeh and Elsokkary, 2022). By integrating various nutrient management strategies, INM aims to maximize the efficiency of nutrient use, leading to improved cotton productivity and fiber quality.

5 Challenges and Knowledge Gaps in Micronutrient Research

5.1 Variability in soil and climatic conditions

The effectiveness of micronutrient management in cotton production is significantly influenced by the variability in soil and climatic conditions. Micronutrients like boron and silicon are essential for cotton growth, but their availability can be limited by soil characteristics such as pH and texture, which affect nutrient solubility and uptake by plants (Ahmed et al., 2020; Abbas et al., 2023). Additionally, climatic factors such as temperature and rainfall patterns can alter the nutrient dynamics in the soil, further complicating the management of micronutrients (Ul-Allah et al., 2021). This variability poses a challenge in developing standardized micronutrient management practices that are effective across different regions.

5.2 Limited understanding of genotype-nutrient interactions

There is a limited understanding of how different cotton genotypes interact with micronutrients, which is crucial for optimizing nutrient management strategies. Different cotton cultivars may respond variably to micronutrient applications, affecting growth, yield, and fiber quality (Wahid et al., 2020; Wahid et al., 2021). For instance, certain genotypes may have a higher affinity for specific micronutrients, influencing their uptake and utilization efficiency. This knowledge gap hinders the development of targeted nutrient management practices that can maximize the genetic potential of different cotton varieties (Swetha et al., 2020).

5.3 Inadequate farmer awareness and adoption

Despite the proven benefits of micronutrient application in improving cotton yield and fiber quality, there is inadequate awareness and adoption among farmers. Many farmers lack knowledge about the specific roles of micronutrients and the appropriate application techniques, such as foliar feeding, which can enhance nutrient uptake and efficiency (Kaur et al., 2024). Additionally, economic constraints and limited access to micronutrient products further impede the widespread adoption of these practices. Addressing these challenges requires concerted efforts in farmer education and the development of cost-effective micronutrient solutions (Abbas et al., 2022; De Souza Júnior et al., 2022).

6 Case Study: Micronutrient Management in Cotton Cultivation in India

6.1 Background and regional context

Cotton cultivation in India, particularly in regions like Central India and Maharashtra, faces challenges due to soil nutrient imbalances and climate change impacts. The soils in these areas, such as the swell-shrink soils of Central India, have been experiencing a decline in essential nutrients like potassium (K) due to the overuse of nitrogen (N) and phosphorus (P) fertilizers without adequate K supplementation (Gabhane et al., 2023). Additionally, the semi-arid regions, such as those in Maharashtra, are characterized by Vertisols, which require careful nutrient management to maintain soil quality and crop productivity. The agricultural soils across India also show widespread deficiencies in micronutrients such as zinc (Zn), boron (B), and sulfur (S), which are crucial for sustaining crop yields and quality (Figure 1) (Shukla et al., 2021).

6.2 Implemented micronutrient strategies

To address these challenges, several strategies have been implemented. In Central India, the use of green manuring with gliricidia has been explored to supplement K requirements, improving soil quality and cotton productivity. In semi-arid regions, integrated nutrient management (INM) practices have been adopted, which include the use of organic amendments like farmyard manure (FYM) and gliricidia to partially substitute for chemical fertilizers, thereby enhancing soil organic carbon and nutrient availability. Additionally, foliar applications of micronutrients such as silicon (Si) and boron (B) have been shown to improve boll retention and fiber quality in transgenic cotton. These strategies are complemented by advanced irrigation techniques like sub-surface drip irrigation (SSDI), which optimize water and nutrient use efficiency (Kaur et al., 2024).

6.3 Observed impacts and lessons learned

The implementation of these micronutrient management strategies has led to significant improvements in cotton yield and fiber quality. For instance, the use of gliricidia in nutrient management packages has resulted in higher seed cotton yields and improved soil physical properties in Central India. In Maharashtra, INM practices have enhanced the productivity of cotton-green gram intercropping systems, demonstrating the importance of balanced fertilization for sustainable agriculture. Foliar applications of Si and B have been particularly effective in enhancing fiber quality traits, such as ginning out-turn and fiber length, while also improving plant growth and yield (Abbas et al., 2023). These case studies highlight the critical role of micronutrient management in addressing nutrient deficiencies and improving the resilience and economic viability of cotton cultivation in India. The lessons learned emphasize the need for region-specific nutrient management strategies that integrate both organic and inorganic inputs to optimize soil health and crop performance.

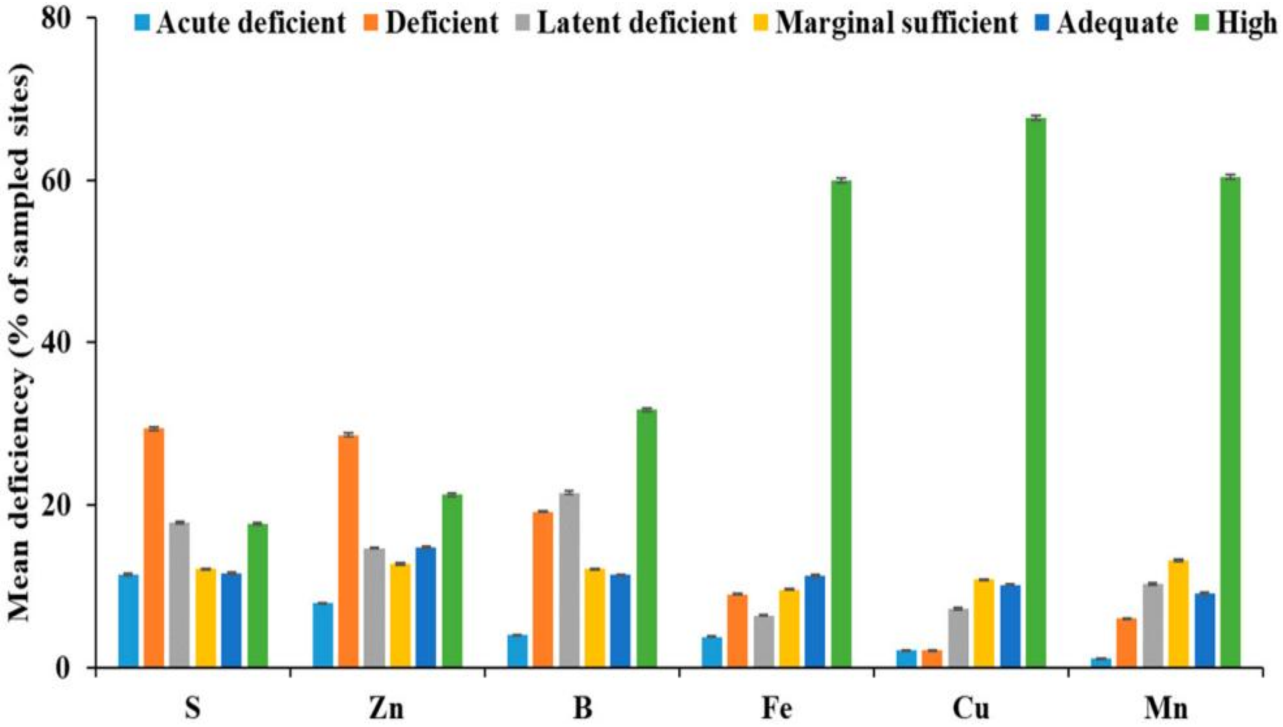

Figure 1 Mean deficiency of available S and micronutrients in agricultural soils of India. Error bars indicate stand error of the means (Adopted from Shukla et al., 2021)

7 Future Directions and Innovations

7.1 Micronutrient nanotechnology and precision agriculture

The integration of nanotechnology in micronutrient management presents a promising avenue for enhancing cotton fiber quality. Nanoparticles (NPs) offer unique properties such as high surface area and reactivity, which can improve the efficiency of nutrient uptake in plants. This approach, known as nanonutrition, has been shown to enhance the growth and yield of crops more effectively than conventional fertilizers (Ditta and Arshad, 2016). Additionally, the convergence of precision agriculture with nanotechnology and artificial intelligence can optimize nutrient delivery and uptake, thereby improving crop productivity and sustainability (Zhang et al., 2021). The use of nano-silicon and boron has already demonstrated improvements in cotton growth and fiber quality, suggesting that further exploration of nanotechnology in micronutrient management could yield significant benefits (Rabeh et al., 2023).

7.2 Genetic approaches to improve nutrient efficiency

Advancements in cotton genomics have opened new possibilities for improving nutrient efficiency through genetic approaches. The sequencing of cotton genomes has provided insights into fiber biogenesis and the genetic basis for fiber quality traits (Yang et al., 2020). By identifying genomic variations and loci associated with fiber quality and yield, researchers can target specific genes for molecular selection and genetic manipulation (Ma et al., 2018). This genomic information can be leveraged to develop cotton varieties with enhanced nutrient use efficiency, potentially reducing the need for external nutrient inputs and minimizing environmental impacts (Khan et al., 2017).

7.3 Climate resilience and sustainable cotton quality

As climate change continues to impact cotton production, developing climate-resilient cotton varieties is crucial. Micronutrient management plays a vital role in enhancing the resilience of cotton plants to abiotic stresses such as drought and heat (Abbas et al., 2023). Practices like sub-surface drip irrigation combined with optimized fertigation have shown to improve cotton productivity and quality in water-scarce environments, highlighting the importance of efficient water and nutrient management in building climate resilience (Kaur et al., 2024). Furthermore, the application of micronutrients can enhance the plant's resistance to environmental stresses, contributing to sustainable cotton production (Dimkpa and Bindraban, 2016).

8 Concluding Remarks

Research on micronutrient management in cotton production has highlighted the significant role of micronutrients such as boron (B) and silicon (Si) in enhancing cotton fiber quality and yield. Studies have shown that the foliar application of B and Si, either individually or in combination, can improve fiber quality traits such as fiber length, strength, and uniformity, as well as increase boll retention and seed cotton yield. The combined application of B and Si has been particularly effective in improving fiber tensile strength and reducing short fiber content. Additionally, the use of plant growth regulators like mepiquat chloride, in conjunction with nitrogen, has been found to enhance yield and fiber quality by optimizing plant growth and physiological processes.

The findings suggest that integrating micronutrient management into cotton cultivation practices can significantly improve both yield and fiber quality. Agronomic practices should consider the foliar application of B and Si as a viable strategy to enhance cotton production, especially in regions with micronutrient-deficient soils. Policymakers should promote research and development of micronutrient-based fertilizers and support training programs for farmers to implement these practices effectively. Additionally, the adoption of sustainable irrigation practices, such as sub-surface drip irrigation, can further optimize water use efficiency and improve cotton quality in water-scarce regions.

The research underscores the importance of micronutrient management in cotton production, offering a pathway to improve fiber quality and yield sustainably. Future research should focus on optimizing the application rates and combinations of micronutrients to maximize benefits across different environmental conditions and cotton cultivars. Implementing these findings at the farm level requires collaboration between researchers, extension services, and policymakers to ensure that farmers have access to the necessary resources and knowledge. By doing so, the cotton industry can enhance its resilience to climate change and meet the growing demand for high-quality fiber.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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