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Foliar Application of Micronutrients in Orchards: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Applying micronutrients via foliar sprays has become increasingly important in modern orchard management as it addresses nutrient deficiencies that are often difficult to correct with conventional soil applications. This review summarizes existing research on the efficacy, methods, and benefits of foliar micronutrient application in different orchard systems. Particular emphasis is placed on key micronutrients such as iron, zinc, manganese, copper, boron, molybdenum, and chlorine to emphasize their importance to tree physiology, fruit quality, and overall orchard yield. It also examines the obstacles and best practices related to foliar fertilization, taking into account the timing of application, concentration and environmental aspects. By bringing together evidence from

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recent studies, this paper aims to provide fruit growers and researchers with a comprehensive understanding of foliar micronutrient strategies to optimize orchard well-being and overall productivity.

Keywords: Foliar application; micronutrients; orchards; nutrient deficiency; tree physiology; orchard management.

1. INTRODUCTION

Micronutrients, although required in minor amounts are indispensable for the optimal growth and productivity of orchard crops. Deficiencies in these trace elements can lead to physiological imbalances, compromising tree health and diminishing fruit quality. Traditional soil fertilization methods, while commonly used, often fall short in meeting the micronutrient needs of plants due to various soil-related factors, such as pH levels, organic matter content and microbial interactions, which influence nutrient availability (White and Broadley, 2003; Alloway, 2008a). To address these limitations, foliar application has emerged as a targeted and efficient approach for enriching orchard crops with essential micronutrients. By enabling direct absorption of nutrients through the leaves, foliar feeding offers a more immediate and effective means of correcting deficiencies and particularly under conditions that restrict soil nutrient uptake (Marschner, 2012). Foliar application is the practice of spraying nutrient solutions directly onto plant foliage, has gained considerable traction in orchard management. This method enables rapid nutrient absorption through the stomata and epidermis of leaves, bypassing the complexities of soil dynamics that often restrict micronutrient availability (Patil and Chetan, 2016; Fernández and Brown, 2013). The effectiveness of foliar feeding lies in its precision, as nutrient solutions can be tailored to address specific deficiencies and applied at critical stages of plant development (Fernández and Eichert, 2009; El-Jendoubi et al., 2011). Additionally, foliar fertilization is considered environmentally friendly, as it minimizes nutrient loss and leaching, which are common concerns in soil-based applications (Suman et al., 2017). This is especially beneficial in orchards, where micronutrient imbalances can significantly impact fruit yield, quality and resistance to insects, pests and diseases (Ram and Bose, 2000; Fageria et al., 2009).

Micronutrients such as zinc, boron, manganese, copper and iron are critical for various physiological processes in orchard crops including enzyme activation, photosynthesis and reproductive development (Suman et al., 2017; Shukla and Tiwari, 2016). Despite their importance, these elements are frequently deficient in soils due to pH fluctuations and interactions with other soil components (Masunaga and Fong, 2018). Foliar application provides a practical solution for correcting these deficiencies, ensuring that plants receive adequate amounts of these critical nutrients during key growth phases (Weinbaum, 1988; Zúñiga et al., 2018). Moreover, research has demonstrated that foliar feeding not only improves the immediate nutrient status of the plant but also enhances overall crop resilience to environmental stresses, such as drought and pest infestations (Tariq et al., 2007; Gautam et al., 2021).

In addition to addressing micronutrient deficiencies, foliar applications offer flexibility in nutrient management by enabling repeated, small-scale interventions throughout the growing season. This approach ensures nutrient delivery is synchronized with the crop's specific needs, promoting better growth, flowering, and fruit set (Annes et al., 2011; Khan et al., 2020a). Studies have shown that foliar feeding with micronutrients like zinc and boron significantly enhances fruit quality at harvest, with improvements observed in parameters such as firmness, color and sugar content (Davarpanah et al., 2016; Eichert and Burkhardt, 2001). However, the effects of foliar application vary depending on factors such as timing, concentration and formulation of nutrient solutions, as well as the physiological condition of the trees (Wojcik, 2007; Herrera et al., 2020). Thus, ongoing research is essential to refine foliar feeding strategies and optimize their impact on orchard productivity and sustainability.

2. ESSENTIAL MICRONUTRIENTS IN ORCHARDS

2.1 Iron (Fe)

Iron is crucial for chlorophyll synthesis and acts as a catalyst in various enzymatic processes within the plant (Marschner, 2012). Iron deficiency, often referred to as chlorosis, appears as yellowing of young leaves with green veins, severely affecting photosynthesis and growth (Kabata-Pendias and Pendias, 2001). Foliar application of iron chelates has proven effective in alleviating chlorosis in citrus orchards, enhancing leaf greenness and improving fruit quality (Tagliavini and Rombola, 2001).

2.2 Zinc (Zn)

Zinc plays a vital role in protein synthesis, growth regulation and hormone production (Alloway, 2008b). Zinc deficiency in orchard crops like apples and pears often results in stunted growth, leaf curling, and reduced fruit set (Mengel and Kirkby, 2001). Foliar applications of zinc sulfate quickly correct these deficiencies, promoting healthy tree growth and increasing yield (Swietlik and Faust, 1984).

2.3 Manganese (Mn)

Manganese is essential for photosynthesis, respiration, and nitrogen metabolism (Marschner, 2012). Deficiency symptoms, such as interveinal chlorosis and necrotic leaf spotting can negatively impact fruit development (Loneragan, 1988). Foliar spraying of manganese chelates restores normal physiological functions and enhances fruit quality in affected orchards (Hansch and Mendel, 2009).

2.4 Copper (Cu)

Copper is involved in lignin synthesis, enzyme activation and defense against pathogens (Broadley et al., 2012). Copper deficiency may cause dieback of shoots and reduce disease resistance in trees (Bowen, 1979). Foliar application of copper fertilizers helps maintain adequate levels, supporting tree structure and disease resistance (Karpinets et al., 2008).

2.5 Boron (B)

Boron is critical for cell wall formation, membrane integrity and reproductive processes (Marschner, 2012). In orchards, boron deficiency may lead to flower abortion, poor fruit set and brittle wood (Brown et al., 2002). Foliar applications of boron have shown improvements in fruit set and quality, especially in high-demand crops like apples and pears (Shorrocks, 1997).

2.6 Molybdenum (Mo)

Molybdenum is essential for nitrogen fixation and various enzyme functions (Kaiser et al., 2005). Symptoms of molybdenum deficiency include leaf curling, chlorosis and reduced nitrogen use efficiency (Gupta, 1997). Foliar application of molybdenum fertilizers enhances nitrogen metabolism and overall health of the tree. (Mendel and Hansch, 2002).

2.7 Chlorine (Cl)

Chlorine is essential for osmotic regulation and ionic balance within plant cells (White and Broadley, 2001). Although less frequently deficient, chlorine is crucial for water regulation and photosynthesis (Marschner, 2012). Foliar application of chloride salts can benefit trees in cases of water stress or ionic imbalance (Marschner, 1995).

2.8 Nickel (Ni)

Nickel plays a vital role in the metabolism of nitrogen, particularly in the urease enzyme system, which is essential for breaking down urea in plants. Nickel deficiency can result in reduced nitrogen utilization and slower growth rates in certain crops. Studies have also shown that nickel is critical for the synthesis of some plant hormones, thus influencing overall plant development and yield (zahed et al*.,* 2021; Kolbert et al*.,*2022).

2.9 Cobalt (Co)

Cobalt although required in trace amounts, is essential for plants involved in nitrogen fixation. It significantly enhances the activity of nitrogen-fixing bacteria such as Rhizobium and Frankia, which are crucial for leguminous plants. A cobalt deficiency can disrupt nitrogen fixation, leading to stunted growth and poor fruit yield in crops like beans and peas (Hu et al*.,* 2021).

2.10 Vanadium (V)

Vanadium while often overlooked, has been found to contribute to plant stress tolerance and antioxidant defense systems. It supports enzymes involved in oxidation-reduction processes, which are vital for plants' response to stress and environmental factors. Research has shown that vanadium application can improve the quality and yield of certain fruit crops, especially under adverse growing conditions (Zahed et al*.,* 2021).

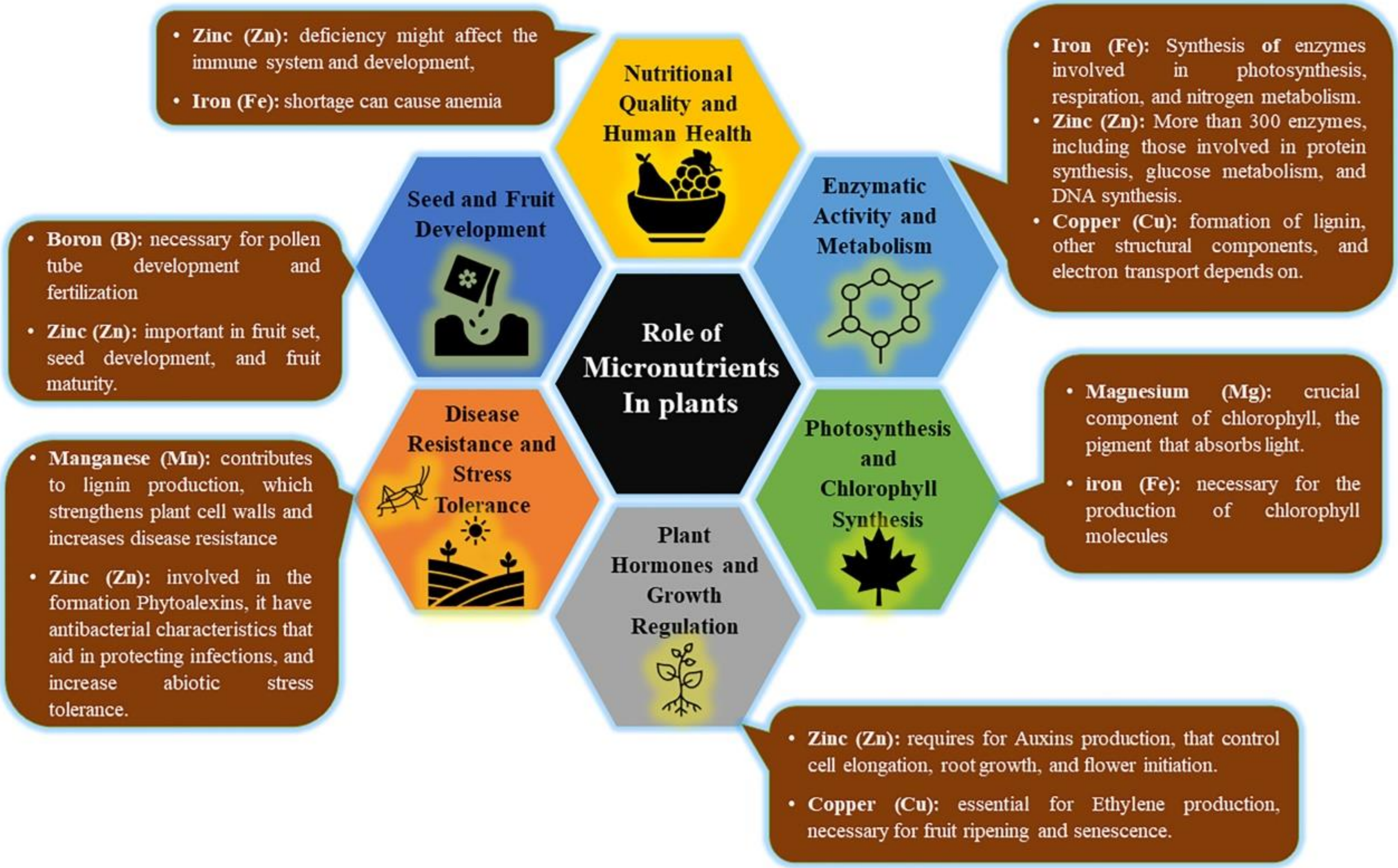

Fig. 1. The essential role of micronutrients in enhancing growth and yield of orchard crops (Ahmed et al., 2023)

3. PATHWAY AND MECHANISM OF NUTRIENT UPTAKE IN FOLIAR APPLICATIONS

Green leaves, primarily recognized for their role in photosynthesis, also serve as crucial sites for the absorption of both inorganic and organic materials. Studies indicate that leaf surfaces can effectively absorb a variety of nutrients, promoting plant growth and overall health (Baker and Tibbitts, 2006; Muthukumar et al., 2020). The practice of foliar spraying micronutrients is widely employed to address nutrient deficiencies, thereby enhancing fruit quality and overall plant vigor (Kumar et al., 2018; Singh et al., 2021).

For foliar-applied nutrients to be utilized effectively by the plant, they must first penetrate the leaf's outer cuticle and walls of the underlying epidermal cells before entering the cytoplasm. The cuticle, a waxy layer serving as a protective barrier, poses the greatest resistance to nutrient penetration. Once nutrients breach this barrier, their absorption mimics that of roots, where the surrounding environment significantly influences uptake (Sinha et al., 2019; Zeng et al., 2021). Research shows that both stomatal and cuticular pathways are involved in absorption process, with cuticle being the primary entry point for most nutrients. While stomatal uptake does occur, it is generally less significant than cuticular uptake (Khan et al., 2020b; Tranquillo et al., 2022).

The primary aim of foliar application is not to replace soil fertilization but to complement it, especially for secondary nutrients (calcium, magnesium, and sulfur) and micronutrients (zinc, manganese, iron, copper, boron, and molybdenum). This approach is particularly advantageous through growth stages characterized by reduced photosynthesis rates and limited root growth, allowing targeted nutrient translocation into seeds, fruits, tubers, or vegetative tissues (Gogosz et al., 2020; Novak et al., 2021). Furthermore, early foliar applications can stimulate vigorous growth and maximize yield potential during critical growth phases, making foliar feeding an effective management strategy to combat environmentally induced stresses and nutrient deficiencies (Yang et al., 2021). The benefits of foliar feeding extend beyond immediate nutrient absorption, leading to improved crop responses through enhanced growth rates and higher yields, ultimately contributing to more sustainable agricultural practices (Wang et al., 2019; Hossain et al., 2021).

4. METHODS OF FOLIAR APPLICATION

Foliar fertilizers play a crucial role in the precise management of micronutrient deficiencies in orchard crops. These fertilizers can be broadly categorized based on their solubility and chemical composition, which significantly affect their stability, bioavailability, and efficacy (Fageria et al., 2016; Shen et al., 2020). Chelated micronutrients are predominantly favored in foliar applications due to their superior stability and enhanced bioavailability. Chelating agents such as EDTA (ethylenediaminetetraacetic acid) and EDDHA (ethylenediamine-N,N′-bis (2-hydroxyphenylacetic acid)) are commonly employed to form stable complexes with micronutrients, thereby preventing precipitation and facilitating efficient uptake by foliage (Gupta et al., 2014; Wang et al., 2017). These chelated forms ensure that micronutrients remain soluble under varying environmental conditions, enhancing their accessibility to plant tissues (Sharma and Singh, 2018).

In addition to chelated forms, non-chelated micronutrient fertilizers are also utilized, although they are less common due to their tendency to react with other foliar-applied substances, which can reduce bioavailability and potentially cause foliar burn (Badejo et al., 2019; Reddy et al., 2021). Organic foliar fertilizers, derived from natural sources such as seaweed extracts and compost teas, offer an eco-friendly alternative by providing micronutrients in a readily assimilable form while also enhancing soil health and microbial activity (O'Brien et al., 2021; Rahman et al., 2020). These organic formulations contain a complex mixture of micronutrients and beneficial compounds that can synergistically enhance plant growth and resilience (Benson et al., 2022).

Furthermore, micronutrient fertilizers can be formulated as liquid concentrates or ready-to-use sprays, allowing for flexibility in application based on orchard size and management practices. Liquid concentrates enable precise mixing and customization of nutrient solutions to address specific deficiencies, while ready-to-use sprays offer convenience and time efficiency, especially in large-scale operations (Gonzalez et al., 2020; Tiwari et al., 2019). The choice of fertilizer type depends on factors such as the specific micronutrient requirements of the orchard crop, the existing soil nutrient profile, and the desired speed of nutrient correction (Zhang et al., 2020; Hossain et al., 2021).

5. APPLICATION TECHNIQUES

Effective foliar application requires proper spraying techniques to ensure uniform coverage and optimal absorption. Common methods include:

5.1 Hand Spraying

This traditional method involves manually applying nutrient solutions using handheld sprayers. While labor-intensive and best suited for small orchards or targeted applications, hand spraying allows for precise control over the quantity and distribution of the fertilizer. This method is particularly useful for addressing localized deficiencies or applying spot treatments in specific areas of the orchard (Khan et al., 2020c; Reddy et al., 2021). However, scalability and consistency can be challenging, making it less feasible for large-scale operations (Badejo et al., 2019).

5.2 Mechanical Spraying

For larger orchards, mechanical sprayers mounted on tractors or other machinery provide a more efficient and consistent application of foliar fertilizers. These sprayers can cover extensive areas rapidly, ensuring uniform nutrient distribution across the orchard canopy. Advances in spray technology, such as precision nozzles and variable rate controllers, have enhanced the effectiveness of mechanical spraying by allowing for adjustable spray patterns and application rates based on real-time data (Sharma and Singh, 2018; Gonzalez et al., 2020). This method reduces labor costs and increases operational efficiency, making it a preferred choice for commercial orchard management (Hossain et al., 2021).

5.3 Aerial Spraying

In expansive orchards where ground-based spraying is impractical, aerial spraying using aircraft or drones are employed. This method enables the rapid coverage of large areas with minimal labor. However, it requires careful calibration to prevent nutrient drift and ensure target coverage. Precision aerial spraying technologies, such as GPS-guided systems and advanced nozzle designs, have mitigated some challenges associated with this method by enhancing accuracy and reducing off-target deposition (O'Brien et al., 2021; Zhao and White, 2008). Additionally, drones equipped with multispectral sensors can facilitate site-specific applications by identifying areas with nutrient deficiencies, thereby optimizing resource use efficiency and minimizing environmental impact (Tan and Huang, 2018).

5.4 Advanced Spraying Technologies

Emerging technologies, such as electrostatic spraying and thermal fogging, offer innovative solutions to improve foliar fertilizer application. Electrostatic spraying imparts a positive charge to fertilizer droplets, enhancing their adhesion to the negatively charged plant surfaces and reducing drift. Thermal fogging produces ultra-fine droplets that can penetrate dense canopies and reach the undersides of leaves, ensuring comprehensive nutrient coverage. These advanced techniques contribute to higher application efficiency and reduced nutrient loss, thereby maximizing the benefits of foliar feeding (Gupta et al., 2014; Liu et al., 2021).

5.5 Timing and Frequency

The timing of foliar applications is critical for maximizing nutrient uptake. Applications are typically scheduled during periods of active growth when stomatal openings facilitate nutrient absorption (Marschner, 2012). The frequency depends on the specific micronutrient, deficiency severity and orchard crop with some requiring multiple applications throughout the growing season (Gupta and Bansal, 2014).

6. FACTORS INFLUENCING EFFICACY

a. **Environmental Conditions:** Temperature, humidity and wind speed significantly affect foliar nutrient uptake. Optimal environmental conditions typically include moderate temperatures, high humidity and low wind to enhance leaf wetness duration and nutrient absorption (White and Broadley, 2003). Adverse weather conditions can reduce efficacy by increasing nutrient runoff or volatilization (Gupta and Bansal, 2014).
b. **Leaf Surface Characteristics:** Leaf anatomy and surface properties influence nutrient uptake. Younger leaves with more stomata are generally more receptive to foliar nutrients compared to older leaves (Marschner, 2012). Additionally, the presence of waxy cuticles can impede nutrient absorption, necessitating the use of surfactants or adjuvants to enhance penetration (White and Broadley, 2003).

c. **Nutrient Formulation:** The chemical form of micronutrient impacts its stability and bioavailability. Chelated forms are preferred for their superior stability and reduced tendency to react with other foliar-applied substances, ensuring higher uptake efficiency (Gupta and Bansal, 2014). Non-chelated forms may precipitate on leaf surfaces, decreasing their availability for absorption (White and Broadley, 2003).

7. BENEFITS OF FOLIAR MICRONUTRIENT APPLICATION

a. Enhanced Nutrient Uptake: Foliar application effectively bypasses soil-related constraints, providing direct access to essential micronutrients and ensuring their timely availability to orchard trees. This method enhances nutrient use efficiency and reduces the likelihood of deficiencies (Zhang et al., 2021; Ghosh et al., 2022).

b. Improved Tree Health and Yield: An adequate supply of micronutrients through foliar feeding supports various physiological processes, leading to healthier trees with enhanced growth rates and increased yields. Improved photosynthesis and respiration rates contribute significantly to overall vigor and productivity (Ranjan et al., 2020; Arora et al., 2021).

c. Superior Fruit Quality: Trees enriched with micronutrients produce fruits with improved size, color, flavor, and shelf life. For example, sufficient zinc and boron levels are associated with better fruit set and reduced fruit drop, thereby enhancing both the quantity and quality of the harvest (Mishra et al., 2021; Sarker et al., 2023).

d. Disease Resistance: Proper micronutrient nutrition enhances tree defenses against pathogens and pests. Copper for instance, plays a crucial role in lignin synthesis, contributing to the structural integrity of trees and their resistance to fungal infections (Choudhary et al., 2020; Akhtar et al., 2022).

8. CHALLENGES AND CONSIDERATIONS

a. Cost and Labor: Foliar application is an effective method for targeted nutrient delivery but can be costly and labor-intensive, particularly in large-scale orchards. While the use of premium foliar fertilizers, often containing specialized chelating agents, can strain financial resources, there are more cost-effective alternatives. For example, zinc oxide has been shown to produce similar results to the commonly used zinc sulfate, offering a more affordable solution. Additionally, applying nutrients fewer times throughout the growing cycle may reduce labor costs, as multiple fertilizers can be applied simultaneously, streamlining the process and reducing workload (Gupta and Bansal, 2014; White and Broadley, 2003). These alternatives present an opportunity for growers to maintain the benefits of foliar application while mitigating associated costs and labor demands (Singh and Kaur, 2015).

b. Risk of Over-Application: One of the foremost challenges with foliar fertilization is the risk of over-application, which can precipitate nutrient toxicity and result in adverse physiological effects such as leaf burn and tissue damage. Unlike soil applications, where excess nutrients may leach or become bound within the soil matrix, foliar-applied nutrients are readily available for immediate uptake, heightening the risk of phytotoxicity if applied in excess (Marschner, 2012; Gupta and Bansal, 2014). This is particularly critical for micronutrients like copper and manganese, which are required in trace amounts but can become toxic when over-applied, disrupting essential physiological processes (Davarpanah et al., 2016). Additionally, excessive application can lead to nutrient imbalances, where the uptake of one micronutrient interferes with the absorption of others, exacerbating deficiencies rather than alleviating them. To mitigate these risks, precise calibration of nutrient formulations and adherence to recommended application rates are imperative, necessitating meticulous monitoring and management practices (Suman et al., 2017). Failure to do so not only compromises plant health but also diminishes the overall efficacy of foliar fertilization strategies (Singh and Kaur, 2015).

c. Environmental Impact: While foliar fertilization offers advantages such as reduced soil nutrient runoff and minimized groundwater contamination, it presents its own set of environmental challenges.

Improper application techniques, such as aerial spraying under unfavorable weather conditions, can lead to off-target deposition, adversely affecting non-target plants, insects and surrounding ecosystems (Gupta and Bansal, 2014). Drift from aerial applications can result in nutrient deposits in unintended areas, potentially causing soil and water contamination, disrupting local biodiversity (Masunaga and Fong, 2018). Furthermore, the volatilization of certain foliar-applied micronutrients can contribute to atmospheric pollution, posing risks to both human health and the environment (Zhao and White, 2008). To address these issues, adherence to best practices, such as precise equipment calibration, optimal timing based on weather forecasts, and the establishment of buffer zones, is essential to minimize environmental impact. Additionally, the development and use of eco-friendly adjuvants and surfactants can enhance nutrient adherence to leaf surfaces, reducing the likelihood of drift and off-target effects (Tan and Huang, 2018). Ongoing research into sustainable application methods and formulations is crucial to balance the benefits of foliar fertilization with environmental stewardship (Hawkesford, 2009).

9. BEST PRACTICES FOR FOLIAR APPLICATION

9.1 Proper Diagnosis

Accurate diagnosis of micronutrient deficiencies through soil and leaf tissue testing is essential for targeted and effective foliar interventions. Regular monitoring allows for timely adjustments to nutrient management strategies, optimizing plant health and yield (Rafiq et al., 2021; Sharma et al., 2022).

Table 1. Case studies on foliar application of micronutrients in various orchards

Orchard Type	Micronutrients Applied	Benefits Observed	Reference
Citrus orchards	Iron, zinc, Magnesium	Corrected chlorosis, improved fruit size and quality, enhanced tree vigor, increased marketable yield	Mahmoud et al., 2023
Apple orchards	Boron, zinc and manganese	Significant improvements in fruit set, reduction in fruit drop, robust tree performance during flowering	White and Broadley, 2003
Pear orchards	Copper and molybdenum	Enhanced disease resistance, improved nitrogen metabolism, healthier trees with better growth rates	Gupta and Bansal, 2014
Cherry orchards	Zinc and iron	Improved fruit quality, increased yield, and enhanced color development in fruits	Annes et al., 2011
Peach orchards	Boron	Enhanced flowering and fruit set, leading to increased marketable yield	Davarpanah et al., 2016
Mango orchards	Magnesium and zinc	Improved fruit size and weight, enhanced resistance to pests and diseases	Tariq et al., 2007
Grape orchards	Calcium and boron	Better fruit development, improved flavor profile, and increased resistance to disease	Shoeib and Sayed, 2003
Avocado orchards	Manganese and copper	Increased yield, improved fruit quality, and enhanced tree health	Masunaga and Fong, 2018
Almond orchards	Iron and zinc	Correction of deficiency symptoms, improved nut quality and size	Ram and Bose, 2000
Walnut orchards	Iron and manganese	Enhanced growth rates, improved yield, and better fruit quality	Suman et al., 2017
Pomegranate orchards	Zinc and molybdenum	Increased fruit weight, improved quality, and enhanced disease resistance	Wojcik, 2004

9.2 Use of Adjuvants

Incorporating surfactants or other adjuvants can enhance nutrient penetration and absorption, particularly in plants with waxy leaf surfaces. Adjuvants reduce surface tension, facilitating better nutrient distribution and uptake, ultimately improving the effectiveness of foliar applications (Martinez et al., 2021).

9.3 Integrated Nutrient Management

Combining foliar application with soil fertilization and other nutrient management practices ensures a balanced and comprehensive approach to orchard nutrition. Integrated strategies enhance overall nutrient availability and utilization efficiency, leading to healthier plants and better yields (Ahmad et al., 2023).

9.4 Timing Optimization

Scheduling foliar applications during optimal growth phases, such as early spring or late summer, maximizes nutrient uptake and minimizes losses due to environmental factors. Avoiding application during extreme weather conditions is crucial for maintaining efficacy and achieving the desired results (Mollah et al., 2023).

10. FUTURE DIRECTIONS

a. **Precision Agriculture:** The future of foliar nutrient application in orchards is poised for transformation through advancements in precision agriculture technologies. Integrating tools such as remote sensing, drones, and satellite imagery offers unprecedented opportunities to monitor and analyze plant health and nutrient status in real-time. These technologies enable the identification of specific areas within an orchard exhibiting nutrient deficiencies, allowing for targeted and efficient nutrient delivery through foliar spraying (Raju et al., 2020). For instance, multispectral imagery can assess leaf chlorophyll content and other physiological indicators, while the Normalized Difference Vegetation Index (NDVI) can be used to assess overall plant vigor, enabling further refinement of nutrient application strategies (Tucker et al., 2015). This approach enhances nutrient use efficiency and reduces costs associated with excessive or unnecessary applications, yielding both economic and environmental benefits. Additionally, data analytics and machine learning can predict nutrient needs based on historical trends, optimizing application schedules and amounts (Kumari et al., 2020). By integrating these advanced technologies into orchard management, growers can achieve higher yields while minimizing resource wastage (Zhang et al., 2019).
b. **Sustainable Practices:** Future research is increasingly focused on integrating foliar micronutrient applications with sustainable orchard management practices. This includes developing eco-friendly chelating agents that are less harmful to the environment compared to traditional synthetic chelates (White and Broadley, 2003). Biodegradable adjuvants are also being investigated to enhance the efficacy of foliar sprays without contributing to soil or water contamination. Additionally, implementing practices like cover cropping and organic amendments can enhance soil health and micronutrient availability, complementing foliar feeding strategies (Gahoonia and Nielsen, 2004). This holistic approach aims to improve crop yield and quality while aligning with the growing demand for sustainable agricultural practices in the face of climate change. Moreover, the adoption of integrated pest management (IPM) strategies can synergistically work with foliar fertilization, reducing pesticide reliance and enhancing overall orchard health (Srinivasan et al., 2018).
c. **Genetic Improvement:** A promising direction for the future of foliar micronutrient application lies in the genetic improvement of orchard crops. Breeding programs that focus on developing varieties with enhanced nutrient use efficiency and resilience to micronutrient deficiencies can significantly complement foliar application strategies (Gupta and Bansal, 2014). By identifying and selecting traits related to micronutrient uptake and utilization, researchers can develop tree varieties that require fewer supplemental nutrients, reducing dependence on external inputs and lowering production costs (Berg et al., 2013). Advances in genomic techniques, such as CRISPR and marker-assisted selection, are poised to accelerate the identification of beneficial traits, allowing for the rapid development of

improved orchard varieties (Zhou et al., 2020). Additionally, exploring symbiotic relationships between root systems and beneficial soil microorganisms can enhance nutrient uptake efficiency in orchard crops. Ultimately, this genetic approach, combined with effective foliar application practices, can contribute to more sustainable and productive orchard systems, addressing both current challenges and future demands in agriculture (Sharma et al., 2018).

d. Climate Resilience: As climate change poses increasing challenges to agriculture, future research should focus on enhancing the resilience of orchards to abiotic stresses such as drought, salinity, and temperature extremes. Foliar applications of certain micronutrients can improve plant stress tolerance by enhancing physiological processes like photosynthesis, transpiration, and antioxidant production (Akkar et al., 2019). Studies have shown that applying micronutrients like zinc and boron can strengthen cellular structures and improve overall plant resilience under stress conditions (Hussain et al., 2018). Research efforts should also aim to develop integrated approaches that combine foliar nutrition with practices such as soil moisture management and drought-resistant rootstocks. Additionally, monitoring climate variability and its impacts on nutrient dynamics will be essential for fine-tuning foliar application schedules and nutrient formulations (Thompson et al., 2020). This focus on climate resilience will enhance orchard productivity and ensure the long-term sustainability of fruit production systems under changing environmental conditions.

e. Consumer Education and Awareness: The future success of foliar application practices will also depend on educating consumers and stakeholders about the benefits and safety of foliar fertilization. Transparent communication regarding the methods and rationale behind foliar nutrient applications can foster greater acceptance among consumers increasingly concerned about food safety and environmental sustainability (Gao et al., 2019). Providing resources and training for growers on best practices in foliar nutrition can enhance adoption rates and optimize outcomes in fruit quality and yield (Schmidt et al., 2020). Furthermore, establishing collaborations between researchers, extension services, and agricultural organizations will be crucial in disseminating knowledge and facilitating the exchange of innovative practices among orchard managers. Promoting the understanding of micronutrient roles in human health and nutrition will support consumer demand for high-quality produce, thereby benefiting orchard profitability and sustainability.

11. CONCLUSION

Foliar application of micronutrients is a valuable tool in orchard management, offering rapid and efficient correction of nutrient deficiencies that soil applications may not address promptly. By ensuring optimal micronutrient levels, growers can achieve healthier trees, higher yields, and superior fruit quality. However, successful implementation requires careful diagnosis, precise application techniques, and integration with broader nutrient management strategies. Continued research and technological advancements will further enhance the efficacy and sustainability of foliar micronutrient applications in orchards.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

1. Paper pal and Grammerly for paraphrasing and grammatically correction.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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