Afghan International Journal of Science (AIJS)

Publisher: Afghan International Islamic University

E-ISSN: 3134-5859

Website: https://aijs.aiiu.edu.af

Role of Micronutrients in Improving Yield and Fruit Quality in Grapes (*Vitis vinifera* L.): A Review

***Rahimullah Himatkhwah[1], Mohammad Sadiq Salihi[2], Ahmad Jawid Zamany[3]**

[1] Kabul University, Department of Horticulture, Faculty of Plant Sciences, Kabul, AF

[2] ANASTU University, Department of Soil Science and Irrigation, Faculty of Plant Sciences, Kandahar AF

[3] Kabul University, Horticulture Department, Faculty of Agriculture, Kabul University, Kabul, AF

Abstract

Although required in trace quantities, micronutrients play a crucial role in determining grapevine productivity and fruit quality. As a high-value horticultural crop, grapevines respond positively to well-balanced micronutrient management. Essential micronutrients, including iron, zinc, boron, manganese, copper, and molybdenum, are involved in key physiological and biochemical processes such as photosynthesis, enzyme regulation, flowering, fruit set, and berry development. Deficiencies of these elements often lead to impaired vine growth, reduced yield, inferior fruit quality, and increased susceptibility to physiological disorders. Numerous studies have demonstrated that appropriate micronutrient application through soil and foliar methods enhances grape yield and improves quality attributes, including total soluble solids, acidity, berry size, and coloration. This review highlights the importance of balanced micronutrient management for sustainable grape production and discusses the specific roles of selected micronutrients (Fe, Zn, B, and Cu) in influencing grape yield and fruit quality.

Article History

Published: Mar 31, 2026

Accepted: Mar 30, 2026

Revised: Mar 28, 2026

Received: Feb 02, 2026

Keywords: Fruit quality**,** Grapes**,** Growth**,** Micronutrients**,** Yield

Cite as: Himatkhwah, R., Salihi, M. S., & Zamany, A. J. (2026). Role of Micronutrients in Improving Yield and Fruit Quality in Grapes (Vitis vinifera L.): A Review. *Afghan International Journal of Science 2*(1), 100-114. DOI: https://doi.org/10.66546/zvsqtv83

Introduction

Grapevine (*Vitis vinifera* L.) is one of the most economically valuable fruit crops cultivated worldwide and exhibits considerable adaptation to drought stress (Gambetta et al., 2020). Grapes are among the most widely consumed fruits due to their favourable flavour, palatability, and high nutritional value. They are primarily consumed as fresh fruit and in processed forms such as juice and raisins. Grapes contain high levels of sugars in the form of monosaccharides, mainly glucose and fructose, along with a diverse range of phenolic compounds (Kandylis et al., 2021; Li et al., 2020). In addition, they are a rich source of essential minerals, including potassium, magnesium, iron, and calcium, as well as important vitamins such as C, B_6, and B_{12} (Conde et al., 2007; Pezzuto, 2008) Achieving an optimal balance between yield and fruit

***Correspondence:** rahimh21@gmail.com

Link to this Artilce: https://aijs.aiiu.edu.af/index.php/aijs/article/view/37

quality remains a key objective in viticulture, particularly under the increasing challenges posed by climate change and climatic variability. Among the factors influencing grape production, soil nutrient availability plays a critical role in determining vine productivity and fruit quality, underscoring the need for appropriate fertilization strategies. Micronutrients such as boron (B), zinc (Zn), copper (Cu), and iron (Fe) are especially important, as they are directly involved in grapevine physiological processes that regulate growth, yield, and fruit quality (Brunetto et al., 2015).

Micronutrients are defined as elements essential for plant growth that are required and accumulated in relatively small quantities, typically measured in milligrams per kilogram of soil or plant biomass, or in grams per hectare. Deficiencies of micronutrients in horticultural crops commonly arise from intensive agricultural practices, imbalanced macronutrient (NPK) applications, continuous nutrient depletion, and inadequate replenishment. Among micronutrient deficiencies, zinc is the most prevalent, followed by boron, copper, and iron. Copper and iron play critical roles in photosynthesis and enzyme-mediated processes, whereas boron is essential for carbohydrate metabolism and reproductive development. Adequate micronutrient availability promotes vegetative growth, flowering, fruit set, and overall crop yield (Ram and Bose, 2000). Improvements in fruit quality are often attributed to the catalytic functions of micronutrients, particularly when applied at optimal concentrations. Consequently, foliar application of micronutrients facilitates rapid nutrient uptake in plant tissues and enhances the assimilation of macronutrients, thereby improving fruit quality (Anees et al., 2011). A comprehensive understanding of micronutrient functions in grape cultivation is therefore essential for optimizing yield and fruit quality, making balanced micronutrient management a fundamental component of sustainable viticulture.

Given the critical roles of micronutrients in grapevine physiological processes, a thorough understanding of their effects on yield and fruit quality is essential for improving vineyard productivity. Balanced micronutrient management not only promotes vegetative growth, flowering, fruit set, and overall yield but also significantly influences key fruit quality attributes, including sugar accumulation, acidity, coloration, and shelf life, which are vital for market acceptance. Moreover, adequate micronutrient nutrition enhances grapevine tolerance to environmental stresses, pests, and diseases, thereby supporting more sustainable production systems. This review synthesizes current knowledge on the effects of micronutrients on grapevine yield and fruit quality, offering practical insights for grape growers, agronomists, and researchers. The findings are intended to support the optimization of nutrient management strategies and address emerging challenges such as climate change and soil degradation, ultimately contributing to improved productivity and sustainability in grapevine cultivation.

Although iron, boron, copper, and zinc are essential for grapevine growth, yield, and fruit quality, existing studies focus mostly on individual micronutrients, specific cultivars, or single application methods. Foliar iron improves photosynthesis and sugar accumulation, boron enhances fruit set, copper increases berry weight and disease resistance, and zinc regulates enzymatic activity and phenolic content. However, there is no comprehensive synthesis on how combined micronutrient management affects both yield and quality traits across cultivars.

Optimal concentrations, timing, and interactions under varying conditions also remain unclear. This review aims to integrate current knowledge and highlight research gaps for effective micronutrient use in grape production.

Accordingly, this research aims to answer the following question:

1. How do iron, boron, copper, and zinc individually and collectively affect grapevine yield across different cultivars?
2. What is the impact of these micronutrients on key fruit quality traits, including sugar content, acidity, berry size, and anthocyanin levels?
3. Which application methods, concentrations, and timings are most effective for optimizing grape productivity and fruit quality under varying environmental conditions?

Methods and Materials

This narrative review synthesized published literature on the effects of micronutrients (iron, zinc, copper, and boron) on the yield and fruit quality of grapevine (*Vitis vinifera* L.). The primary aim was to integrate findings across studies and identify patterns, knowledge gaps, and best practices for micronutrient management in viticulture.

Data Collection Procedure

A comprehensive search of scientific literature was conducted using electronic databases, including Google Scholar, Scopus, Web of Science, and PubMed. Searches were performed for studies published between 2000 and 2025 to ensure contemporary relevance. The search employed combinations of keywords such as "grapevine micronutrients," "*Vitis vinifera* nutrition," "grape yield and quality," "micronutrient deficiency in grapes," and specific micronutrients (Fe, Zn, Cu, B). Reference lists of selected studies were also screened to identify additional relevant articles.

Inclusion and Exclusion Criteria

Studies were included if they:

1. Focused on *Vitis vinifera* L. and addressed the effects of Fe, Zn, Cu, or B on vine growth, yield, or fruit quality.
2. They were published in peer-reviewed journals, books, or technical reports.
3. Presented quantitative or qualitative data on yield components (e.g., berry size, cluster weight, number of bunches) or fruit quality traits (e.g., sugar content, total soluble solids, anthocyanin content).

Studies were excluded if they:

1. Investigated macronutrients only (N. P. K) without reference to micronutrients.
2. Were non-English publications or conference abstracts without full text.

3. Focused exclusively on post-harvest processing without linking to nutrient management.

Using these criteria, a total of 38 studies were initially identified and included in the analysis.

Data Extraction and Analysis

From each selected study, relevant data were extracted, including micronutrient type and concentration, application method (foliar or soil), growth stage of application, cultivar studied, measured yield components, and fruit quality parameters. The extracted data were organized into tables to allow comparison of treatment effects across studies. A qualitative synthesis approach was used to evaluate trends, identify consistent findings, and highlight discrepancies. In addition, the review critically assessed the methodological quality of the studies, including experimental design, replication, and statistical analysis, to provide evidence-based conclusions.

This approach enabled an integrated understanding of how Fe, Zn, Cu, and B influence grapevine performance and formulated practical recommendations for balanced micronutrient management in vineyards.

Findings

Effects of Micronutrients on the Yield of Grapes

Iron, boron, copper, and zinc are essential for grape yield, enhancing photosynthesis, fruit set, berry size, and cluster development. Foliar or soil applications of these nutrients at appropriate concentrations increase overall vine productivity. Effective micronutrient management is key to achieving higher yields across grape cultivars.

Iron

Iron (Fe) is an essential micronutrient required for chlorophyll synthesis and the activation of numerous enzymes involved in oxidation–reduction reactions during photosynthesis and respiration. Adequate iron nutrition enhances photosynthetic activity, carbohydrate synthesis, and reproductive development, with developing fruits acting as strong metabolic sinks within the plant (Sohrab et al., 2013). Because sugars are the primary products of photosynthesis, increased photosynthetic efficiency resulting from sufficient iron availability leads to higher sugar accumulation and increased total soluble solids in fruit juice (Ram and Bose, 2000). Iron also plays a critical role in several metabolic processes, including enzymatic reactions, respiration, and photosynthesis. Iron deficiency is rarely due to low total iron content in soils but is more commonly associated with reduced iron availability under alkaline or calcareous soil conditions, or due to antagonistic effects from excessive manganese or phosphorus. This condition, often referred to as lime-induced chlorosis, is prevalent in high-pH soils and is linked to a plant's limited capacity to absorb or utilize iron. Typical deficiency symptoms include interveinal chlorosis, where tissues between the veins become pale green or yellow while the veins remain green. In severe cases, chlorosis progresses to bleaching and necrotic lesions. Because iron has limited mobility within plants, deficiency symptoms are more pronounced in young leaves, whereas older foliage may remain green. Several studies have demonstrated the effectiveness of foliar iron application in improving grapevine nutrition, growth, and productivity. Application of chelated iron in combination with copper significantly enhanced iron uptake in grapevines, increasing leaf iron concentrations by 20.1–48.6% compared with conventional copper treatments and untreated controls. Improved iron availability resulted in enhanced photosynthetic performance, attributed to its role in chlorophyll formation and electron transport, while increased spray wettability further improved nutrient absorption (Ma et al., 2019).

Foliar application of iron has also been shown to influence yield and fruit quality parameters positively. In Flame Seedless grapevines, foliar iron treatments significantly increased yield, number of bunches per vine, bunch weight, bunch length, berry number per cluster, berry size, berry weight, and cluster compactness (Ali et al., 2021). Similarly, Thompson Seedless grapevines treated with ferrous sulphate (0.05–0.4%) at pre-bloom and post–fruit-set stages exhibited enhanced shoot growth, yield, cluster and berry size, juice content, and total soluble solids, with the 0.5% concentration producing the most favorable results (Rana and Sharma, 1979). In 'Perlette' grapes, foliar application of iron at 0.2% significantly increased yield primarily by increasing the number of berries per bunch, while having minimal effects on the number of fruit clusters per vine (Usha & Singh, 2001). Furthermore, a study evaluating foliar application of micronutrients (Fe, Zn, and Mn) on *Vitis vinifera* cv. Thompson Seedless demonstrated that applications at concentrations of 2000–5000 mg L^{-1}, applied before and after flowering, significantly improved both qualitative and quantitative traits. Applications in June resulted in the greatest increases in bunch length, berry number, berry length, and total soluble solids, whereas May applications produced higher bunch width, bunch weight, berry width, and berry weight. These findings suggest that foliar micronutrient application before flowering is an effective strategy for optimizing yield while reducing labor and production costs (Hosseinabad and Khadiv, 2019).

Boron

Boron (B) is an essential micronutrient involved in cell wall formation and the development of fruits and seeds, and it plays a critical role in pollen viability, pollination, and flowering processes (Malek and Rahim, 2011). One of the primary physiological functions of boron is to enhance calcium solubility, metabolism, and mobility within plant tissues, as well as to facilitate nitrogen uptake and utilization (Pandav et al., 2016). Because boron exhibits limited mobility within plants, deficiency symptoms typically appear first in actively growing tissues such as shoot apices, root tips, young leaves, and developing fruits. Boron deficiency can result in reproductive failure, poor fruit set, reduced berry size, fruit cracking, abnormal fruit development, and ultimately decreased yield (Harris, 2016). Common sources of boron used in agriculture include borax (sodium tetraborate, 10.5% B), boric acid (17.0% B), and disodium octaborate tetrahydrate (20% B). Boron is particularly important for fruit set and quality in grapevines, and several studies have demonstrated the beneficial effects of foliar boron application on grape yield and fruit quality attributes. Foliar application of boron (Solubor at 0.1%) significantly increased the number of fruitful shoots, bunch number, fruit yield, berry size, sugar content, and anthocyanin concentration in the grape cv. Sahebi (Khalil et al., 2018). Similarly, foliar boron treatments markedly improved bunch characteristics and yield components of Flame Seedless grapes, including bunch number, bunch weight and length, berry number, berry size and weight, and cluster compactness (Ali et al., 2021). In 'Perlette' grapevines, foliar application of boron at 0.4% enhanced yield primarily by increasing berry weight, while having minimal influence on the number of bunches per vine (Usha & Singh, 2001). Foliar sprays of boron as boric acid (H_3BO_3) at 2 g L^{-1} applied at pre-flowering, post-flowering, and veraison stages significantly improved berry characteristics (number, length, and weight), cluster length and weight, seed traits, and total soluble solids, although the magnitude of response varied among cultivars (Nikkhah et al., 2013).

The application of chelated boron throughout the growing season further enhanced grape yield and quality, increasing bunch weight by 3.9–18.2 g and yield by 5.4–18.9%. Treated grapes exhibited higher titratable acidity, increased anthocyanin concentration, and improved extractable anthocyanins, along with reduced seed tannins. Correspondingly, wines produced from treated grapes showed higher total dry extract and phenolic content, improved color intensity, enhanced varietal aroma, and a fuller palate, receiving sensory scores 5–7 points higher than those of untreated controls (Cherviak et al., 2021). Overall, boron deficiency severely disrupts grapevine growth and physiological functioning, underscoring the importance of balanced boron nutrition as a component of integrated mineral management strategies in sustainable viticulture (Zhao et al., 2025).

Copper

Copper-based formulations are widely used in grape production; however, their combination with chelated iron (Cu–Fe) has been shown to significantly reduce copper accumulation in plant tissues and soil. Application of Cu–Fe at 1.0 g L^{-1} reduced leaf copper concentration by 67.3% and lowered soil-available copper compared with the traditional Bordeaux mixture, thereby minimizing copper residues and toxicity risks while maintaining agronomic efficacy (Ma et al., 2019). Foliar application of copper-containing agrochemicals on Cabernet Sauvignon grapevines at rates of 0.5, 1.0, and 1.5 L ha^{-1} significantly increased berry weight, bunch mass, and sugar content (by 0.7–1.0 g 100 cm^{-2}) relative to untreated controls. The highest yield increase (26.2%) was observed at 0.5 L ha^{-1}, whereas all application rates enhanced resistance to powdery mildew, with the greatest disease suppression achieved at 1.5 L ha^{-1}. Accordingly, application rates of 0.5–1.0 L ha^{-1} are recommended for maximizing productivity, while higher rates are more suitable for improving disease resistance and reducing pesticide inputs (Arestova and Ryabchun, 2023). In another study, four foliar sprays of orthophosphoric acid and/or copper sulfate at 0.1 or 0.2% applied to mature Red Roomy grapevines significantly improved yield and berry quality, with no marked difference between the two concentrations. Orthophosphoric acid was more effective than copper sulfate, and their combined application at 0.1% each resulted in the highest yield increases, reaching 89.6% in 2018 and 123.0% in 2019 compared with untreated vines (Mansour et al., 2020). Both soil and foliar applications of copper fertilizers on Alkdarri grapevines increased yield and fruit quality compared with the control. Maximum berry diameter, 100-berry weight, and berry volume were achieved with soil application of calcium at 200 g $vine^{-1}$, while the highest cluster weight resulted from soil application of potassium at 150 g $vine^{-1}$. Foliar potassium at 20 g L^{-1} produced the greatest berry firmness, whereas foliar copper at 5 mg L^{-1} led to the highest juice pH and total soluble solids (Abo-Ahmedeh et al., 2020). Recent findings further indicate that nano-chelated copper applied at 1.0–1.5 g L^{-1} significantly increased the number of clusters per vine, cluster weight, and total yield in 'Taifi' grapevines, highlighting the potential of nano-formulations to enhance copper use efficiency and vineyard productivity (Alimam, 2024).

Zinc

Zinc (Zn) is a vital micronutrient involved in enzyme activation, protein synthesis, and auxin metabolism, thereby regulating both vegetative growth and reproductive development in grapevines. Adequate zinc nutrition plays a crucial role in pollen viability, fruit set, and balanced vine growth. Foliar application of zinc sulfate ($ZnSO_4$) at 0.4% has been shown to improve yield components and berry quality while reducing physiological disorders such as shot berries, particularly in the grape cv. Sahebi, underscoring the importance of zinc in reproductive success (Khalil et al., 2018). Numerous studies have reported positive effects of foliar zinc application on yield and fruit quality in different grape cultivars. In Flame Seedless grapes, zinc sprays significantly increased the number of bunches per vine, bunch weight and length, berry number per cluster, berry size, berry weight, and cluster compactness (Ali et al., 2021). Similarly, foliar application of zinc at 0.4% improved yield in 'Perlette' grapes, although its effects on berry number and bunch characteristics were less pronounced compared with other micronutrients (Usha & Singh, 2001). Foliar zinc applications at 0.20% and 0.40% significantly enhanced yield and fruit quality attributes, including total soluble solids, juice content, pH, and acidity, with effects significant at the 1% level. Moreover, combined foliar application of magnesium and zinc exhibited a significant synergistic interaction, resulting in higher yields than individual nutrient applications (Bybordi and Shabanov, 2010). Application of zinc as $ZnSO_4{\cdot}H_2O$ at 2 g L^{-1} significantly improved berry traits (number, length, and weight), cluster characteristics (length and weight), seed attributes (number and size), and total soluble solids. Foliar sprays applied at pre-flowering, post-flowering, and veraison stages enhanced fruit set and quality, although cultivar-dependent responses were observed (Nikkhah et al., 2013). The use of chelated zinc during the growing season further increased grape bunch weight by 3.9–18.2 g and yield by 5.4–18.9%. Zinc-treated grapes exhibited higher titratable acidity, increased anthocyanin and extractable anthocyanin concentrations, and substantially reduced seed tannin content. Correspondingly, wines produced from treated grapes showed higher total dry extract and phenolic content, improved color intensity, enhanced varietal aroma, and a fuller palate, achieving sensory scores 5–7 points higher than those of untreated controls (Cherviak et al., 2021). A study evaluating the foliar application of micronutrients (Fe, Zn, and Mn) on *Vitis vinifera* cv. Thompson Seedless demonstrated that applications at concentrations of 2000–5000 mg L^{-1}, applied before and after flowering, significantly improved both qualitative and quantitative traits. Applications in June produced the greatest increases in bunch length, berry number, berry length, and total soluble solids, whereas May applications resulted in higher bunch width, bunch weight, berry width, and berry weight. These findings indicate that foliar micronutrient application before flowering optimizes yield while reducing labor and production costs (Hosseinabad and Khadiv, 2019). Evidence from Mohebbi et al. (2022) indicated that foliar application of 0.3% Zn EDTA significantly enhanced grapevines' performance.

Effects of Micronutrients on the Quality of Grape

Micronutrient application has increasingly been recognized as a vital strategy to improve grape quality and yield (Ekbic et al., 2018). Micronutrients are as essential as macronutrients for optimizing plant growth, yield, and overall productivity. In garden plants, zinc deficiency is the most prevalent, followed by deficiencies in boron, manganese, iron, and molybdenum (Ekbic et al., 2018). Foliar fertilization serves as an effective method to enhance nutrient uptake and correct deficiencies during the growing season (Ekbic et al., 2018). In a two-year study, application of a micronutrient formulation M1 (0.1%) resulted in the highest fruit nitrogen content (1.040% and 1.106%) and increased phosphorus concentrations in both leaf petioles (0.401% and 0.429%) and fruit tissue (0.062% and 0.067%) (Khalil et al., 2021). Moreover, the combined application of micronutrient M3 (0.1% + $ZnSO_4$ 0.4%) yielded the highest fruit boron concentrations, measuring 8.69 and 9.05 ppm, respectively (Khalil et al., 2021).

The biochemical quality parameters of grape berries, including reducing and non-reducing sugars, total sugar content, ascorbic acid concentration, pH, and total soluble solids (TSS), reached their highest levels following supplementation with iron (Fe), zinc (Zn), and boron (B) at 200 ppm (Ali et al., 2021). The application of micronutrient fertilizers containing boron and zinc positively influenced wine quality attributes, enhancing red color intensity, varietal aroma related to berry characteristics, and contributing to a fresher, fuller palate (Cherviak et al., 2021). The use of these micronutrient fertilizers also improved phenolic ripeness, as evidenced by an increase in the proportion of extractable anthocyanins in the must (by 3–8%) and a substantial reduction in seed tannin content (by two- to threefold) compared to untreated controls (Cherviak et al., 2021). Experimental grape samples treated with these micronutrients exhibited elevated titratable acidity (increased by 0.8–1.8 g/L), higher anthocyanin concentrations in berries (by 12–39%), enhanced extractable anthocyanin proportions (by 3–8%), and reduced seed tannins (by 2–3 times) (Cherviak et al., 2021). Additionally, the highest TSS values were observed with treatments combining NPK fertilizer and either 10 ppm selenium or 10% chamomile extract (Ekbic et al., 2018).

Iron

Iron treatments positively influence grape berry quality by modulating sugar, acid, and flavonoid profiles (Zhang et al., 2022). Foliar application of iron increases sugar levels while reducing berry acidity. Furthermore, certain flavonoid monomers in the grape peel significantly increase following iron supplementation (Zhang et al., 2022). However, foliar sprays of ferrous sulfate, EDTA-Fe, ferric gluconate, and ferric sugar alcohol have been observed to decrease total anthocyanin, flavanol, and flavonol contents in the peel (Zhang et al., 2022). Importantly, foliar application of ferric citrate restores balance to the sugar-to-acid ratio in berries and elevates anthocyanin, flavanol, and flavonol concentrations in the peel, thereby enhancing both grape quality and the nutritional value of the berries and final wine (Zhang et al., 2022).

Boron

Boron is mobile in the xylem and exhibits limited mobility in the phloem, playing a vital role in pollination and fruit set (Álvarez-Herrera et al., 2025). Its application reduces mass loss, maintains fruit firmness, enhances color, and promotes the development of larger and heavier fruits. Additionally, boron increases soluble solids, regulates total titratable acidity and pH, lowers respiration rates, and stabilizes ascorbic acid by delaying its degradation (Álvarez-Herrera et al., 2025). It also mitigates physiological disorders such as fruit splitting, cork spot, internal rot, shot berries in grapes, blossom end rot, and segment drying in citrus. Both foliar and soil applications of boron improve fruit yield and post-harvest quality (Álvarez-Herrera et al., 2025). Adequate boron levels are therefore essential for optimal fruit quality, given their multifaceted functions. Furthermore, foliar sprays of boric acid have been shown to positively affect yield and quality parameters, with 0.3% treatments notably enhancing fruit appearance, size, and color uniformity (Ekbic et al., 2018).

Copper

Copper is a critical micronutrient in grapevine cultivation, contributing both to disease management and essential physiological and metabolic processes (Dobrei et al., 2024). The dosage and timing of copper applications significantly affect grape yield, fruit quality, and overall vine health (Dobrei et al., 2024). Increased copper levels have been associated with proportional enhancements in carbohydrate accumulation in one-year-old canes, wood maturation rates, and bud fertility (Dobrei et al., 2024). Principal component analysis (PCA) revealed notable relationships between copper treatments and vitamin accumulation across various grape cultivars, underscoring varietal differences in response and emphasizing copper's role in enhancing vitamin content in grapes (Dobrei et al., 2024).

Zinc

Zinc is a vital micronutrient that plays a central role in numerous physiological and biochemical processes in grapevines, thereby directly influencing berry development and fruit quality. Adequate zinc fertilization has been shown to enhance key quality parameters, including sugar accumulation, coloration, phenolic content, and berry size, particularly when appropriate application rates and formulations are used. In zinc-deficient vineyards, foliar application of zinc sulfate improves photosynthetic activity and promotes berry growth, especially during the critical period from veraison to full ripening. Zinc supplementation has been associated with increased total soluble solids and phenolic compounds, along with a reduction in titratable acidity, effects supported by the upregulation of genes involved in phenolic biosynthesis (Song et al., 2015). Comparative studies indicate that foliar zinc treatments significantly increase yield and fruit quality relative to untreated controls, with nano zinc oxide applied at 2 ppm demonstrating the greatest efficacy, followed by zinc sulfate and chelated zinc at 100 ppm, suggesting these concentrations as optimal for improving grape productivity and quality (Shaaban et al., 2024). Similarly, foliar application of iron, zinc, and boron at key stages of berry development markedly enhanced yield components, berry physical characteristics, and biochemical quality attributes, with the highest responses observed at 200 ppm (Ali et al., 2021). The combined application of zinc (4 g L^{-1}) and salicylic acid (150 mg L^{-1}) substantially improved fruit quality of Halawani grapevines by increasing cluster number and weight, berry size, total soluble solids, total sugars, juice percentage, density, and concentrations of β-carotene, zinc, nitrogen, and proline, while concurrently reducing total acidity and total phenolic content (Al-Atrushy, 2021). Moreover, nano-zinc application at 1.2 ppm enhanced total carbohydrate content, leaf iron concentration, cluster number, cluster weight, and overall yield. All evaluated nano-zinc concentrations (0.4, 0.8, and 1.2 ppm) resulted in higher yields than conventional zinc fertilizers while reducing zinc input, indicating improved nutrient-use efficiency (Saleh et al., 2019). Finally, foliar application of zinc at 100 mg L^{-1} significantly increased berry weight, total soluble solids, and glucose and fructose concentrations, whereas application at 200 mg L^{-1} effectively reduced total acidity and malic acid content compared with the control treatment (Alimam, 2022).

Discussion

Chlorophyll synthesis in plant metabolism requires iron. Application of iron through fertilizers, especially at favorable levels, increases photosynthesis, thereby boosting carbohydrate output, promoting plant growth, and leading to fruit development. The increases in yield parameters across different grape varieties may be due to the availability and proper function of iron in chlorophyll synthesis, photosynthesis, and the activation of enzymes in plant metabolism. Ali et al. (2021) reported similar findings: foliar iron application increased yield significantly in Flame Seedless grapevines.

Boron plays a crucial role in plant growth and development. For instance, boron plays a critical role in cell wall formation, pollination, flowering, and fruit development. Application of boron to grapevines increased related yield parameters, such as the number of bunches, bunch weight and length, berry size, and fruit yield. The increases in the yield parameters of grapefruit development of the berry may be due to the active physiological function of absorbed boron in the plant that stimulated nitrogen uptake and increased yield. As well as, based on the limited movement of boron in plants, foliar application on the grapevine may provide a favorable amount of boron during growth and fruit development periods. Similar findings were reported by Khalil et al. (2018), who found that foliar application of boron increased berry yield characteristics.

Furthermore, grape yield improvement was involved in copper application. Different application methods and copper types increased yield parameters in grapes, such as the number of clusters per vine, cluster weight, and total yield. These yield and yield-related parameter increases may be due to copper's significant role in crop metabolism and enzyme activation. As Alimam (2024) confirmed, nano-chelated copper application at 1-1.5 g L^{-1} increased grape yield parameters.

An adequate amount of zinc is essential for plant growth and development; for instance, it plays an important role in pollen viability, fruit set, and balanced vine growth. Yield increases with Zn may also be due to Zn's involvement in enzyme activation, protein synthesis, and auxin stimulation, which increase grape yield. The findings are consistent with those of Khalil et al. (2018).

Fruit plants, including grapevines, commonly suffer from micronutrient deficiencies, primarily in the following order: Zinc, Boron, Magnesium, Iron, and Molybdenum. Thus, the application of micronutrients improved grape quality and nutrient content. Improvement in grape quality parameters and nutritional values may be due to the application, availability, active physiological and metabolic functions, and involvement in the activation of micronutrient enzymes, especially iron, boron, copper, and zinc. The findings of the review align with those of Dobrei et al. (2024), Shaaban et al. (2024), and Song et al. (2015).

Conclusion

This review underscores the pivotal roles of key micronutrients—iron (Fe), zinc (Zn), boron (B), and copper (Cu)—in modulating grapevine yield and fruit quality. Iron is indispensable for chlorophyll biosynthesis, photosynthesis, respiration, and enzymatic activation; adequate iron supply enhances photosynthetic efficiency, carbohydrate synthesis, and sugar accumulation in berries, thereby improving yield and total soluble solids, especially in calcareous and high-pH soils prone to iron deficiency. Boron is crucial for cell wall formation, carbohydrate transport, pollen viability, flowering, and fruit set; its deficiency manifests as poor fruit set, berry cracking, and diminished yields. Conversely, foliar boron applications consistently enhance bunch number, berry size, sugar content, anthocyanin concentration, and post-harvest traits such as firmness, color stability, and acidity regulation. Zinc is involved in enzyme activation, protein synthesis, and auxin metabolism, thereby impacting both vegetative growth and reproductive development. Empirical evidence demonstrates that zinc supplementation improves pollen viability, fruit set, cluster compactness, yield components, and key berry quality parameters, including total soluble solids, acidity, and phenolic content. Copper contributes to photosynthesis, carbohydrate metabolism, wood maturation, bud fertility, vitamin accumulation, and disease resistance. Applied at optimal levels, copper enhances yield, berry weight, and sugar content, although excessive accumulation may induce phytotoxicity and environmental concerns. Collectively, the literature supports those foliar applications of these micronutrients—whether individually or in balanced combinations—during critical phenological stages such as pre-flowering, post-flowering, and veraison, effectively correcting deficiencies and improving both yield and fruit quality. Accordingly, integrated, site-specific micronutrient management strategies for Fe, Zn, B, and Cu are essential to optimize grape productivity, enhance berry composition and wine quality, and promote sustainable viticulture amidst challenges posed by soil nutrient depletion and climate variability.

Limitations and Future Research Directions

Despite extensive research demonstrating the importance of iron, boron, copper, and zinc in grapevine growth, yield, and fruit quality, several limitations remain. Most studies focus on individual micronutrients, specific cultivars, or limited environmental conditions, making it difficult to generalize findings across different grape-growing regions. The interactions among multiple micronutrients and their combined effects on yield and fruit quality remain poorly understood. Additionally, optimal concentrations, application timing, and application method (foliar vs. soil) vary widely across studies, and long-term effects on soil health and sustainability are rarely evaluated.

Future research should focus on:

- Integrated micronutrient management: Investigating combined applications of Fe, B, Cu, and Zn to understand synergistic or antagonistic effects.

- Cultivar-specific responses: Assessing how different grape varieties respond to micronutrient treatments under diverse soil and climatic conditions.
- Standardized application strategies: Determining optimal concentrations, timings, and methods for maximizing yield and quality.
- Long-term and environmental impacts: Evaluating the effects of repeated micronutrient applications on soil health, nutrient interactions, and sustainable viticulture practices

Authors Contributions

- Rahimullah Himatkhwah and Mohammad Sadiq Salihi conceptualized the review topic, conducted the literature review, and were responsible for writing and editing the original manuscript.
- Ahmad Jawid Zamany provided technical guidance, critical review, and suggestions for manuscript improvement, and assisted in literature collection, formatting, and reference management. All authors reviewed and approved the final version of the manuscript.

References

Abo-Ahmedeh, H., Mhasneh, A., & Rawashdeh, H. (2020). Using soil and foliar applications of some fertilizers to improve the yield and quality parameters of table grapes (*Vitis vinifera* L.). *Bulletin UASVM series Agriculture* 77(1), 1-6. https://doi.org/10.15835/buasvmcn-agr:2019.0016.

Al-Atrushy, S. M. (2021). Effect of foliar application of zinc and salicylic acid on vegetative growth and yield characteristics of Halawani grape cultivar (*Vitis vinifera* L.). *Iraqi journal of agricultural sciences*, 52(4), 989-998. https://doi.org/10.36103/ijas.v52i4.1410.

Ali, I., Wang, X., Abbas, W., Hassan, M., Shafique, M., Tareen, M., Fiaz, S., Ahmed, W., & Qayyum, A. (2021). Quality responses of table grapes' Flame Seedless' as affected by foliarly applied micronutrients. *Horticulturae*, 7(11), 462. https://doi.org/10.3390/horticulturae7110462.

Alimam, N. M. A. (2022). Impact of foliar application of chelated zinc on the seasonal changes of growth and development of grape berries (*Vitis vinifera* L.). *MINAR International Journal of Applied Sciences and Technology*, 4(3), 19–34. https://doi.org/10.47832/2717-8234.12.3.

Álvarez-herrera, J. G., Jaime-guerrero, M., & Fischer, G. (2025). The Effect of Boron on Fruit Quality : *A Review. Horticulture*, 11(992), 1–19. https://doi.org/10.3390/horticulturae11080992.

Ameen Abdullah Alimam, N. M. (2024). Effect of foliar application of chelated Nano copper on vegetative growth and productivity of the Taifi grape cultivar. *International Journal of Modern Agriculture and Environment*, 4(1), 79-90. https://doi.org/10.21608/ijmae.2024.329408.1038.

Arestova N. O., Ryabchun I. O. (2023). Influence of Copper-Containing Agrochemical On Grape Productivity Indicators. *Vestnik of Kazan State Agrarian University*. (1), 5-11. https://doi.org/10.12737/2073-0462-2023-5-11.

Brunetto, G., Miotto, A., Ceretta, C. A., Schmitt, D. E., Heinzen, J., de Moraes, M. P., ... & Girotto, E. (2014). Mobility of copper and zinc fractions in fungicide-amended vineyard sandy soils. *Archives of Agronomy and Soil Science*, 60(5), 609-624. https://doi.org/10.1080/03650340.2013.826348.

Bybordi, A., & Shabanov, J. A. (2010). Effects of the foliar application of magnesium and zinc on the yield and quality of three grape cultivars grown in the calcareous soils of Iran. *Notulae Scientia Biologicae*, 2(2), 81-86. https://doi.org/10.15835/nsb223575.

Cherviak, S., Anikina, A., Ermikhina, M., Aleinikova, N., & Didenko, P. (2021). Evaluation of the effect of characteristics Evaluation of the effect of micronutrient fertilizers based on chelates on grape and wine quality characteristics. IOP Conference Series: *Earth and Environmental Science*, 699(01), 1–5. https://doi.org/10.1088/1755-1315/699/1/012024.

Conde, C., Silva, P., Fontes, N., Dias, A. C. P., Tavares, R. M., Sousa, M. J., ... & Gerós, H. (2007). Biochemical changes throughout grape berry development and fruit and wine quality. *Global Science Books*, 1-18. Link

Dobrei, A., Nistor, E., Dobrei, A. G., Mălăescu, M., Constantinescu, D. G., Cristea, T., & Drăgunescu, A. (2024). The Impacts of Copper Application Timing and the Frequency of Treatments on Physiological, Biochemical and Productive Parameters in a Vine Yard. *Scientific Papers*, LXVIII(2). Link

Ekbic, H. B., Gokdemir, N., & Erdem, H. (2018). Effects of Boron on Yield Quality and Leaf Nutrients of Isabella (*Vitis labrusca* L) Grape Cultivar. *Acta Sci. Pol*, 17(1), 149–157. https://doi.org/10.24326/asphc.2018.1.14.

Gambetta, G. A., Herrera, J. C., Dayer, S., Feng, Q., Hochberg, U., & Castellarin, S. D. (2020). The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance. *Journal of experimental botany*, *71*(16), 4658-4676. https://doi.org/10. 1093/jxb/eraa313

Harris, K. D., & Lavanya, L. (2016). Influence of Foliar Application of Boron the quality of Tomato. *Research Journal of Agriculture and Forest*, 4(7), 1-5. Link

Hosseinabad, A., & Khadivi, A. (2019). The effect of microelements on qualitative and quantitative characteristics of *Vitis vinifera* cv. Thompson Seedless. *Erwerbs-Obstbau*, *61*(Suppl 1), 41-46. https://doi.org/10.1007/s10341-019-00449-x.

Kandylis, P., Dimitrellou, D., & Moschakis, T. (2021). Recent applications of grapes and their derivatives in dairy products. *Trends in Food Science & Technology*, 114, 696-711. https://doi.org/10.1016/j.tifs.2021.05.029

Khalil, A., Nazir, N., Din, S., Sharma, M. K., & Kumar, A. (2021). Effect of Fertilizer and Micronutrients on Leaf and Fruit Mineral Status of Grapes cv. Sahebi. *Biological Forum- An International Journal*, 13(1), 270–276. Link

Khalil, A., Sharma, M., Nazir, N., Bhat, R., Sundouri, A., Banday, S., & Javied, K. (2018). Impact of fertilizer and micronutrients levels on Growth, Yield and Quality of Grape cv. Sahebi. *Current Journal of Applied Science and Technology*, *27*(5), 1-9. https://doi.org/10.9734/CJAST/2018/41912.

Li, Z., Howell, K., Fang, Z., & Zhang, P. (2020). Sesquiterpenes in grapes and wines: Occurrence, biosynthesis, functionality, and influence of winemaking processes. *Comprehensive reviews in food science and food safety*, 19(1), 247-281. https://doi.org/10.1111/1541-4337.12516.

Ma, J., Zhang, M., Liu, Z., Chen, H., Li, Y. C., Sun, Y., ... & Zhao, C. (2019). Effects of foliar application of the mixture of copper and chelated iron on the yield, quality, photosynthesis, and microelement concentration of table grape (*Vitis vinifera* L.). *Scientia Horticulturae*, *254*, 106-115. https://doi.org/10.1016/j.scienta.2019.04.075.

Malek, M. A., & Rahim, M. A. (2011). Effect of boron fertilizer on yield and quality seed production of two varieties of carrot. *Journal of Agro Forestry and Environment*, 5(1), 91-94. Link

Mansour, A. E. M., Hagagg, L. F., Merwad, M. A., & El-Shamma, M. S. (2020). Response of red roomy grapevines to spray of orthophosphoric acid and copper sulphate. *Middle East Journal of Applied Sciences*, 10(4), 715-720. https://doi.org/10.36632/mejas/2020.10.4.63

Moazzam Anees, F.M. Tahir, J. Shahzad and N. Mahmood (2011). Effect of foliar application of micronutrients on the quality of mango (*Mangifera indica* L.) cv. Dusehri fruit. *Mycopath*, 9(1), 25-28. Link

Mohebbi, H., Ebadi, A., Taheri, M., Zarabi, M., & Bihamta, M. R. (2022). The effect of different levels of foliar application of zinc, iron, and manganese micronutrients on reproductive characteristics and yield of *Vitis vinifera* grapes in some vineyards of Zanjan province. *Journal of Horticultural Science*, 36(2), 443-457. https://doi.org/10.22067/JHS.2021.71776.1078

Nikkhah, R., Nafar, H., Rastgoo, S., & Dorostkar, M. (2013). Effect of foliar application of boron and zinc on qualitative and quantitative fruit characteristics of grapevine (*Vitis vinifera* L.). *International Journal of Agriculture and Crop Sciences*. 6, (9), 485–492. Link

Pandav, A. K., Nalla, M. K., Aslam, T., Rana, M. K., & Bommesh, J. C. (2016). Effect of foliar application of micronutrients on growth and yield parameters in eggplant cv. HLB 12. *Environment and ecology*, 35(3), 1745-1748. Link

Pezzuto, J. M. (2008). Grapes and human health: a perspective. *Journal of agricultural and food chemistry*, 56(16), 6777-6784. https://doi.org/10.1021/JF800898P.

Ram, R. A., & Bose, T. K. (2000). Effect of foliar application of magnesium and micro-nutrients on growth, yield and fruit quality of mandarin orange (*Citrus reticulata* Blanco). *Indian journal of Horticulture*, 57(3), 215-220. Link

Rana, R. S., & Sharma, H. C. (1979). Effect of iron sprays on growth, yield and quality of grapes. *Punjab Horticultural Journal*, 19, 31–34. Link

Saleh, M., El, R., El, S., El-Gazzar, A., & Shaaban, E. (2019). Efficiency of nano-zinc foliar spray on growth, yield, and fruit quality of Flame Seedless grape. *Journal of Applied Sciences*, 19(10), 612–617. https://doi.org/10.3923/jas.2019.612.617.

Shaaban, M. M., Mahboob, M. M., & Abou-Zaid, E. A. (2024). Effect of zinc applications on the productivity of thompson seedless grapevines. *Assiut journal of agricultural sciences*, 55(1), 169-180. https://doi.org/10.21608/ajas.2024.251515.1312.

Song, C., Liu, M., Meng, J., Chi, M., Xi, Z., & Zhang, Z. (2015). Promoting Effect of Foliage Sprayed Zinc Sulfate on Accumulation of Sugar and Phenolics in Berries of *Vitis vinifera* cv. Merlot Growing on Zinc Deficient Soil. *Molecules*, 20, 2536 – 2554. https://doi.org/10.3390/molecules20022536.

Usha, K. & Singh, B. (2001). Effect of macro and micro-nutrient spray on fruit yield and quality of grape (Vitis vinifera L.) cv. Perlette. In International Symposium on Foliar Nutrition of Perennial Fruit Plants 594 (pp. 197-202). Link

Zhang, S., Chen, H., Gao, M., Gu, C., & Wang, R. (2022). Effects of different iron treatments on wine grape berry quality and peel flavonoid contents. *Food Science and Nutrition*, 3598–3607. https://doi.org/10.1002/fsn3.2957.

Zhao, M., He, J., Suolang, J., Liu, L., Hayat, F., Wang, S., Umer Javed, H., & Wang, L. (2025). Consequences of Micro- and Macronutrient Deficiencies on Physiological and Growth Metrics in Hydroponic' Thompson Seedless' Grapevines. *Horticulturae*, 11(5), 543. https://doi.org/10.3390/horticulturae11050543