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MICRONUTRIENTS: QUALITY BOOSTERS OF TROPICAL FRUITS- A REVIEW

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ABSTRACT

Mineral nutrition refers to the process by which plants acquire and utilise essential nutrients from the soil, including both macronutrients and micronutrients, for optimal growth and development. Micronutrients such as manganese (Mn), copper (Cu), boron (B), zinc (Zn), and molybdenum (Mo) play critical roles in enzyme activation, nutrient uptake, photosynthesis, pigment synthesis, fruit firmness, fruit set, size, colour, protein content, and bioactive compound accumulation. Deficiencies in these elements cause distinct physiological and quality-related disorders in tropical fruits. Appropriate supplementation at critical growth stages, using suitable application methods, can effectively correct such deficiencies. Studies have shown that micronutrient application enhances key fruit quality parameters, including total soluble solids (TSS), sugars, ascorbic acid, carotenoids, and shelf life. While conventional supplementation methods have proven effective, challenges related to soil-plant interactions persist. Emerging approaches such as precision nutrition, nano-formulations, chelated compounds, and AI-based management deserve further research for the improvement of tropical fruit micronutrient management.

Key words : Foliar, Post-harvest, Reducing Sugar, Sustainable nutrition, Total Sugar.

Introduction

India stands among the top fruit-producing countries in the world, but its fruit exports are still low compared to its production capacity. This gap is mainly due to difficulties in meeting international quality standards. Poor fruit quality is a major reason why Indian fruits are rejected in global markets, which reduces export opportunities and profits. Many related factors contribute to the decline in fruit quality in India. These include inadequacies in both pre-harvest and post-harvest practices, poor infrastructure and storage facilities, limited access to market information and export strategies and a lack of coordinated institutional support (Thulasiram, 2020). Collectively, these constraints not only reduce the export potential but also lead to a decline in domestic fruit prices due to reduced market competitiveness.

Fruit quality is generally evaluated based on two broad categories: extrinsic and intrinsic parameters. Extrinsic parameters refer to measurable physical attributes such as fruit size, shape, and colour. In contrast, intrinsic

parameters encompass organoleptic and biochemical characteristics determining consumer acceptance and nutritional value. These include titratable acidity, total soluble solids (TSS), reducing and non-reducing sugars, carotenoid and ascorbic acid content, pulp-to-peel ratio and firmness (Omar and Jafri, 2013).

A complex interplay of internal and external factors influences the expression of these quality attributes. Key determinants include mineral nutrition, Ecological conditions (e.g., light intensity, temperature, humidity), the application of plant growth regulators, the maturity stage at harvest, and postharvest handling techniques (Ramjan and Ansari, 2018). Among these, mineral nutrition, particularly the role of micronutrients, is increasingly recognised as a critical factor in enhancing fruit quality. Mineral nutrition encompasses the uptake and utilisation of essential nutrients from the soil, involving both macronutrients and micronutrients. Although, needed only in small quantities, micronutrients play vital roles in plant metabolism by supporting enzyme activation, chlorophyll formation, nutrient translocation and overall photosynthetic

efficiency.

Role of Micronutrients in Fruit Quality

Manganese (Mn) : Manganese is crucial for photosynthesis as an integral component of the oxygen-evolving complex in photosystem II, where it facilitates the splitting of water molecules and the release of oxygen. This process enhances electron transport, carbohydrate synthesis, and fruit sugar levels. Mn also participates in the phenylpropanoid pathway by activating phenylalanine ammonia-lyase (PAL), which converts phenylalanine to cinnamate, a precursor of anthocyanins, thereby improving fruit colour, antioxidant activity, and nutritional quality (Mousavi *et al.*, 2011).

Copper (Cu) : Copper plays a significant role in enhancing fruit texture by regulating lignin biosynthesis, a process crucial for maintaining cell wall strength and overall fruit firmness. It acts as a cofactor in the phenylpropanoid pathway, where it facilitates the conversion of phenylalanine to cinnamic acid *via* phenylalanine ammonia-lyase (PAL). Cinnamic acid then serves as a precursor for lignin, a key structural polymer that reinforces cell walls. Adequate Cu levels thus contribute to the mechanical strength and postharvest durability of fruits, helping reduce softening during storage and transit (Vargas *et al.*, 2018).

Boron (B) : Boron plays a critical role in enhancing fruit set quality by influencing hormonal balance and reproductive development in plants. Boron inhibits the activity of indole acetic acid oxidase (IAAO), an enzyme responsible for degrading indole acetic acid (IAA), a key auxin involved in plant growth and fruit development. By suppressing IAAO, boron ensures higher levels of IAA, which promotes effective pollen tube growth and successful fertilisation by facilitating the transport of male germ cells to the ovary. This hormonal regulation significantly improves fruit set and ultimately enhances fruit quality. Thus, adequate boron availability is essential for optimising reproductive efficiency and fruit development in fruit crops (Hapuarachchi *et al.*, 2022)

Boron application has been shown to significantly enhance the fruit mass of avocado, contributing to improvements in overall fruit size and weight. In the experiment, avocado trees treated with boron at rates of 15 and 30 g/tree exhibited a notable increase in fruit mass compared to untreated controls, with gains of approximately 5-6%. The highest fruit weights were recorded in trees receiving boron supplementation, suggesting a positive correlation between boron availability and biomass accumulation. This effect can be attributed to boron's role in enhancing nutrient

translocation, cell wall formation, and hormonal regulation, collectively supporting robust fruit development (Thakur *et al.*, 2023).

Zinc (Zn) : Zinc is a vital micronutrient that plays a key biochemical role in enhancing fruit size by regulating the biosynthesis of indole acetic acid (IAA), a primary plant growth hormone. Zinc stimulates the activity of tryptophan synthetase, an enzyme that facilitates the conversion of serine and indole into tryptophan (Trp). Tryptophan serves as a critical precursor for the synthesis of IAA. Elevated IAA levels, in turn, promote cell division and elongation, directly contributing to increased fruit size. Thus, zinc indirectly supports fruit development through hormonal modulation, emphasising its importance in improving the yield and quality of fruit crops (Saleem *et al.*, 2022).

Zinc significantly contributes to the enhancement of protein content in fruits by acting as a crucial cofactor for RNA polymerase, the enzyme responsible for transcription. As a structural and catalytic component, zinc facilitates the accurate and efficient synthesis of messenger RNA (mRNA), which is essential for subsequent protein biosynthesis. This zinc-mediated regulation of gene expression ensures the production of various enzymes and structural proteins that are vital for fruit development and nutritional quality. In crops such as guava, adequate zinc availability has been linked to improved protein accumulation, thereby increasing the nutritional value of the fruit and supporting better postharvest quality and consumer health (Singh *et al.*, 2025)

Molybdenum (Mo) : Molybdenum plays a vital role in enhancing fruit quality by contributing to essential physiological and biochemical processes in plants. Molybdenum improves nitrogen content in fruits by facilitating the enzymatic activity of nitrate reductase, which converts nitrate into usable nitrogen, a key element for plant growth and fruit development. Furthermore, molybdenum contributes to the synthesis of bioactive compounds through the formation of molybdenum cofactors. These cofactors are derived from the interaction of molybdenum with pyranopterin-based proteins, enabling the activation of various enzymes involved in plant metabolism. Consequently, adequate molybdenum nutrition promotes nitrogen assimilation and supports the biosynthesis of health-promoting compounds, thereby enhancing the overall nutritional and functional quality of fruits (Abobatta *et al.*, 2024).

Iron (Fe) : Iron is an essential micronutrient that plays a key role in enhancing fruit quality by modulating

Table 1 : Micronutrient deficiencies in tropical fruits.

Tropical fruit	Micronutrient	Disorder	Symptoms
Pineapple	Zinc	Crookneck	Lateral emergence of inflorescence coupled with horizontal growth. Fruit fall due to premature yellowing
Guava	Zinc	Leaf bronzing	Brown patches, spots or streaks of dead tissue on the leaves and chlorosis between the leaf veins.
Pineapple	Copper	Drooping	Weak stem, narrow leaves, and dropping of fruit
Papaya	Boron	Bumpy disorder	Misshaped fruits with bumpy skin. Underdeveloped fruits and poor quality.
Mango	Boron	Fruit crack	Cracking of fruit
		Internal necrosis	Brown black patches near the stone.

Suman *et al.* (2017)

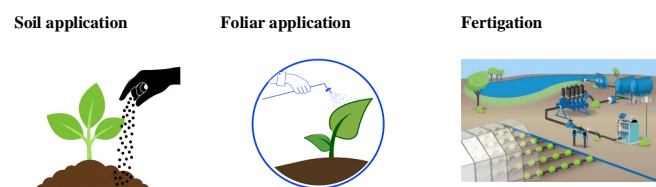


Fig. 1 : Different micronutrient application methods.

various physiological and biochemical processes in plants. Iron plays a vital role in chlorophyll synthesis through its involvement in the biosynthesis of aminolaevulinic acid, a key precursor in the chlorophyll production pathway. Enhanced chlorophyll synthesis directly contributes to increased photosynthetic efficiency, which in turn promotes fruit size and flavour development.

Micronutrient application methods in tropical fruits

Micronutrients can be delivered to crops through various application methods, each with specific agronomic and physiological advantages. The most common approaches include soil application, foliar spraying, fertigation, and seed treatment. Soil application refers to adding micronutrient fertilisers to the soil, from where they are taken up by plant roots. This method is particularly effective for immobile nutrients such as zinc and copper and contributes to the long-term improvement of soil micronutrient reserves. Foliar application refers to the direct spraying of nutrient solutions onto plant foliage, enabling the rapid correction of nutrient deficiencies through swift absorption via the leaf surface and stomata. This method is especially advantageous under restricted root uptake, such as drought or high soil pH. Fertigation, the application of micronutrients through irrigation systems, ensures uniform distribution across the root zone and enhances nutrient use efficiency, particularly in high-value horticultural crops (Anitha and Kadalli, 2019).

Micronutrient application in tropical fruits

Mango : Krishnamoorthy and Hanif (2015) reported

that the application of NPK at 1:1:1.5 kg per tree, supplemented with farmyard manure (FYM, 50kg) and foliar spray of a micronutrient mixture (0.5 per cent), significantly improved vegetative growth, yield, and fruit quality. Supporting these findings, Pawar and Singh (2018) found that the use of the recommended dose of fertilisers (RDF) along with foliar sprays of zinc sulphate (0.4%), copper sulphate (0.2%) and boric acid (0.2%) applied before flowering and at the marble stage resulted in superior fruit quality, as reflected by higher TSS (18.51 °Brix), total sugars (12.88%), and ascorbic acid content (43.62 mg/100 g), along with reduced acidity (0.149). Comparable results were observed by Haldavnekar *et al.* (2018) in mango, where foliar application of zinc sulphate (0.4%), copper sulphate (0.2%) and borax (0.2%) enhanced fruit quality attributes.

Further evidence was provided by Dhotra *et al.* (2020), who demonstrated that foliar application of micronutrients significantly increased TSS levels (23.30% and 23.70%) when plants were treated with a combination of calcium nitrate [Ca(NO₃)₂] at 0.6 per cent, boric acid (0.2%), and zinc sulphate (0.8%), compared to the control. This treatment also led to a marked reduction in fruit acidity, while the highest acidity values (0.23% and 0.24%) were observed in untreated plants. Likewise, Singh *et al.* (2020) reported the highest TSS content (21.13 °Brix) in a treatment combining RDF with soil application of zinc sulphate (100 g), copper sulphate (50 g), and boric acid (50 g), along with two foliar sprays of zinc sulphate (0.2%) and boric acid (0.1%) applied just before flowering and at the marble stage. In contrast, the lowest TSS (20.07 °Brix) was recorded in the treatment receiving RDF alone.

Khan *et al.* (2022) observed that a combined soil (S) and foliar (F) nutrient management of boron (B) and zinc (Zn) of the treatment 75S B + 0.8F B + 150S Zn + 1.0F

Zn increased total soluble solids (45 %) and a decreased acidity (50%) over the control, thereby confirming its overall positive effect on fruit quality. In agreement with these findings, Maibam *et al.* (2024) reported that the highest TSS (18.57 °Brix) was achieved through foliar application of zinc sulphate (0.2%) combined with boric acid (0.2%), while the lowest acidity and highest reducing sugar content were recorded with zinc sulphate (0.2%) and copper sulphate (0.2%). Similarly, Vijayvargiya and Singh (2024) demonstrated that soil application of borax at 125 g per plant, followed by a 0.2 per cent foliar spray, significantly enhanced fruit yield and quality in mango cv. Dashehari.

Banana : Krishnamoorthy and Hanif (2017) observed that applying Arka Banana Special micronutrient formulation resulted in significant improvements in plant growth and fruit yield. Plants treated with this formulation showed the greatest girth (76 cm), stem height (2.48 m), number of leaves (18), leaf area index (4.72), finger weight (123 g), bunch weight (20.10 kg), and TSS (16.6 °Brix). Soil application Arka Banana Special solution, 250 ml at 45 days after planting, followed by four foliar sprays (0.5%) at the 5th, 6th, 7th month after planting and at shooting stage, recorded the highest yield (45.23 t/ha) compared to other micronutrient treatments.

Bashma *et al.* (2018) reported that the combined application of 100 per cent recommended dose of fertilisers (RDF) along with foliar spray of a micronutrient mixture (1 per cent) at 3 months after planting (MAP) resulted in significant improvement in fruit quality of banana cv. Nendran. This treatment recorded the highest total soluble solids (34.67 °Brix), TSS/acid ratio (114.92) and pulp-to-peel ratio (2.58), while also producing the lowest titratable acidity (0.31 per cent). Panigrahi *et al.* (2018) demonstrated that the combined use of RDF + ZnSO₄ (0.5%) + FeSO₄ (0.5%) in banana cv. Grand Naine produced the highest total sugar (18.40%), TSS (23.85%), reducing sugar (11.92%), non-reducing sugar (6.48%) and ascorbic acid (12.98 mg/100 g), while significantly reducing fruit acidity compared to the control. Premalatha and Suresh (2019) further noted that foliar spraying of micronutrient mixtures (2% and 3%) at 2, 4, and 6 months after planting improved TSS, reducing sugar, non-reducing sugar, pulp peel ratio and reducing acidity in banana cv. Nendran.

Papaya : Parmar *et al.* (2017) documented that the application of 100 per cent RDNK (200:250 g per plant) in eight equal splits beginning from the second month after planting, together with foliar sprays of Grade-IV micronutrient (1 per cent) applied at the 2nd, 4th, 6th,

and 8th months, significantly improved plant growth attributes such as plant height, stem girth, and leaf area, while also reducing the duration required for first flowering in papaya cv. Red Lady.

In support of these findings, Monika *et al.* (2018) observed that foliar application of calcium [0.5% Ca(NO₃)₂], sulphur (0.5% K₂SO₄) and micronutrients (0.5% ZnSO₄ + 0.1% boric acid) along with the recommended dose of fertilisers resulted in the maximum number of fruits per plant (34.21), fruit weight (1.39 kg), fruit length (29.96 cm), and fruit circumference (41.34 cm). This treatment also produced a higher yield, 47.54 kg per plant, which was 28.21 per cent greater than the control.

Similarly, Anju *et al.* (2022) reported that foliar spraying of borax (0.5%), zinc sulphate (0.5%), and calcium nitrate [0.5% Ca(NO₃)₂] at the 4th and 7th months after planting recorded the highest total soluble solids (14.5 °Brix), total sugar content (9.80%), ascorbic acid (65.3 mg/100 g), carotenoids (2.2 mg/100 g), and shelf life (7 days) in papaya cv. Arka Surya. Likewise, Kumar *et al.* (2022) found that plants treated with K₂SO₄ at 1 per cent + borax at 0.25 per cent + ZnSO₄ at 0.25 per cent showed improved quality parameters, including total soluble solids (13.52 °Brix), ascorbic acid (54.42 mg 100 g⁻¹), total sugar (5.64%), reducing sugar (4.60%), and the lowest acidity (0.13%) compared to the control, thereby enhancing yield and fruit quality in papaya cv. Red Lady.

Recently, Kumar *et al.* (2024) reported that foliar application of borax (0.5%) combined with zinc sulphate (0.5%) resulted in the highest total soluble solids (12.83 °Brix) and the lowest acidity (0.140%) when compared with the control in papaya cv. Red Lady.

Guava : Zagade *et al.* (2017) revealed that the application of zinc sulphate (1 per cent) resulted in the maximum number of fruits per tree (170), yield per tree (35.57 kg), yield per hectare (14.22 t ha⁻¹), TSS (11.80 °Brix), reducing sugar (4.52%), and total sugar (7.40%). However, the highest fruit weight (193 g) and pulp weight (153.60 g) were obtained with a combined foliar spray of CuSO₄ (1%) + FeSO₄ (1%) + ZnSO₄ (1%) + borax (0.5%), while the lowest acidity (0.35%) was recorded with foliar application of FeSO₄ (1 per cent).

In a similar study, Janaki *et al.* (2020) observed that the application of RDF along with enriched micronutrient mixture (MNM) through soil at a rate of 2 kg per tree, combined with a foliar spray of MNM (0.3 per cent), resulted in the highest TSS (12.8 °Brix), reducing sugars (8.02%), non-reducing sugars (6.93%), and the lowest

acidity (0.42%) in guava cv. Lucknow 49. Likewise, Mondal *et al.* (2023) found that foliar spraying of sodium tetraborate ($\text{Na}_2\text{B}_4\text{O}_7$) at 0.3 per cent significantly improved fruit quality traits such as TSS (11.03 °Brix), TSS/acid ratio (57.3), ascorbic acid (181.99 mg per 100 g pulp), and total sugars (7.87%), while also enhancing fruit set (69.56%) and number of fruits per tree (24.66) in Thai guava. The same treatment effectively reduced fruit drop and acidity (0.20%).

Further supporting these findings, Mor *et al.* (2024) reported that combined foliar application of FeSO_4 (0.5%), H_3BO_3 (0.5%), and MgSO_4 (0.5%) resulted in superior fruit quality, characterised by the highest TSS, TSS/acidity ratio, ascorbic acid, total sugars, reducing and non-reducing sugars, and pectin content, along with the lowest titratable acidity in guava cv. Hisar Surkha. Similarly, Shukla *et al.* (2024) concluded that foliar application of zinc sulphate at 0.4 per cent improved fruit quality in terms of TSS (11.78 °Brix), acidity (0.4%), total sugars (6.34%), and sugar–acid ratio (15.91), whereas boric acid at 0.4 per cent recorded the highest ascorbic acid content (173.373 mg per 100 g pulp) and pectin content (1.650) in guava cv. Allahabad Safeda.

More recently, Sharma *et al.* (2025) demonstrated that the combined foliar application of FeSO_4 (0.2%) + ZnSO_4 (0.25%) + H_3BO_3 (0.2%) + KNO_3 (1.5%) was most effective in improving fruit quality parameters, including TSS (10.23 °Brix), acidity (0.38%), ascorbic acid (150.03 mg per 100 g), and total sugars (7.86%) in guava cv. Allahabad Safeda.

Challenges in micronutrient application in fruit crops

Despite their vital role in the enhancement of fruit quality and yield, the effective use of micronutrients in fruit crops faces several challenges. A major concern is soil-plant interaction, as micronutrient availability depends on soil pH, organic matter, texture, and antagonistic ions. For instance, high soil pH often causes iron and zinc deficiencies in calcareous soils. Application methods such as soil application, foliar spray, and fertigation also vary in effectiveness depending on nutrient mobility and the crop's growth stage (Subramani *et al.*, 2021).

Incorrect application methods can lead to poor absorption, toxicity, or nutrient wastage. Timing and dosage also pose challenges, as micronutrient needs vary with the crop's growth stage. Both deficiency and excess can cause toxicity or metabolic issues. Site-specific management, diagnostic tools, and precision agriculture are essential for improving micronutrient use in fruit production. Site-specific management considers variations

in soil, crop nutrient demand, and environmental conditions within an orchard to ensure that micronutrients are applied in the correct amount, at the optimal time, and in the most effective location. Diagnostic tools such as soil testing, leaf and fruit analysis, and visual symptom assessment help to detect micronutrient deficiencies accurately. Precision agriculture techniques, such as GPS mapping, sensor-based fertiliser application, and variable-rate technology, further improve nutrient use efficiency. These methods reduce nutrient wastage and prevent over- or under-application. As a result, micronutrients are utilised more effectively by the crop. This leads to improved fruit yield and quality. Overall, these approaches lower production costs and environmental risks, making fruit production more sustainable. (Khatun *et al.*, 2024).

Emerging trends and future directions in micronutrient management in fruit crops

Recent advancements in agricultural technology have opened new avenues for improving micronutrient management in fruit crops. One such trend is the adoption of precision nutrition, which leverages tools like fertigation units to deliver targeted nutrient doses according to real-time crop requirements and growing conditions. This approach minimises nutrient losses and enhances nutrient use efficiency. Another promising development is the use of nano and chelated formulations, which improve the solubility, stability, and bioavailability of micronutrients. Nano-sized particles and chelated compounds facilitate better absorption and translocation within the plant system, reducing application frequency and environmental impact.

Furthermore, the integration of artificial intelligence (AI) in crop management, exemplified by digital platforms such as E-crop systems, enables the collection and the analysis of field data to facilitate informed decision-making. These AI-driven technologies can monitor plant health, predict nutrient deficiencies, and automate nutrient application. Together, these innovations represent a shift towards more sustainable, efficient and data-driven nutrient management strategies in fruit production systems.

Conclusion

Micronutrients, though required in minute quantities, play a pivotal role in enhancing the growth, productivity, and quality of tropical fruits. Their involvement in critical physiological and biochemical processes such as photosynthesis, enzyme activation, and hormonal regulation directly influences fruit size, colour, flavour, nutritional content and shelf life. Despite their importance, micronutrient deficiencies are widespread in tropical

regions due to soil imbalances, inappropriate application methods and limited awareness. Recent advancements, including precision nutrition, nano-chelated formulations, and AI-assisted crop management, offer promising solutions to overcome these challenges and ensure efficient micronutrient delivery. A strategic and science-based approach to micronutrient management is essential to unlock the genetic potential of tropical fruits, enhance their market value and contribute to sustainable horticultural production. Continued research, farmer education, and policy support are crucial to mainstreaming these innovations and realising the full benefits of micronutrients as quality boosters in tropical fruit cultivation.

Disclosure statement

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