Soil Application of Calcium, Zinc and Boron as a Safer Alternative to Foliar Application for Fruit Nutritional Quality and Human Health

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Abstract

Calcium (Ca), zinc (Zn), and boron (B) are essential plant nutrients that play critical roles in cell wall stability, membrane integrity, enzyme activation, hormonal regulation, pollen tube growth, fruit set, and postharvest quality. These nutrients are supplied to crops through soil and foliar application methods, each influencing nutrient uptake, translocation, and accumulation differently. Foliar application is widely used for rapid correction of deficiencies; however, several experimental studies across crops such as tomato, citrus, strawberry, and plum have demonstrated that excessive or repeated foliar sprays can lead to localized nutrient accumulation, leaf burn, fruit surface residues, and phytotoxicity, particularly in the case of boron due to its narrow deficiency-to-toxicity range. In contrast, soil application delivers nutrients through the root system, enabling gradual uptake regulated by plant physiological demand and soil buffering capacity, resulting in more balanced distribution among roots, stems, leaves, and fruits.

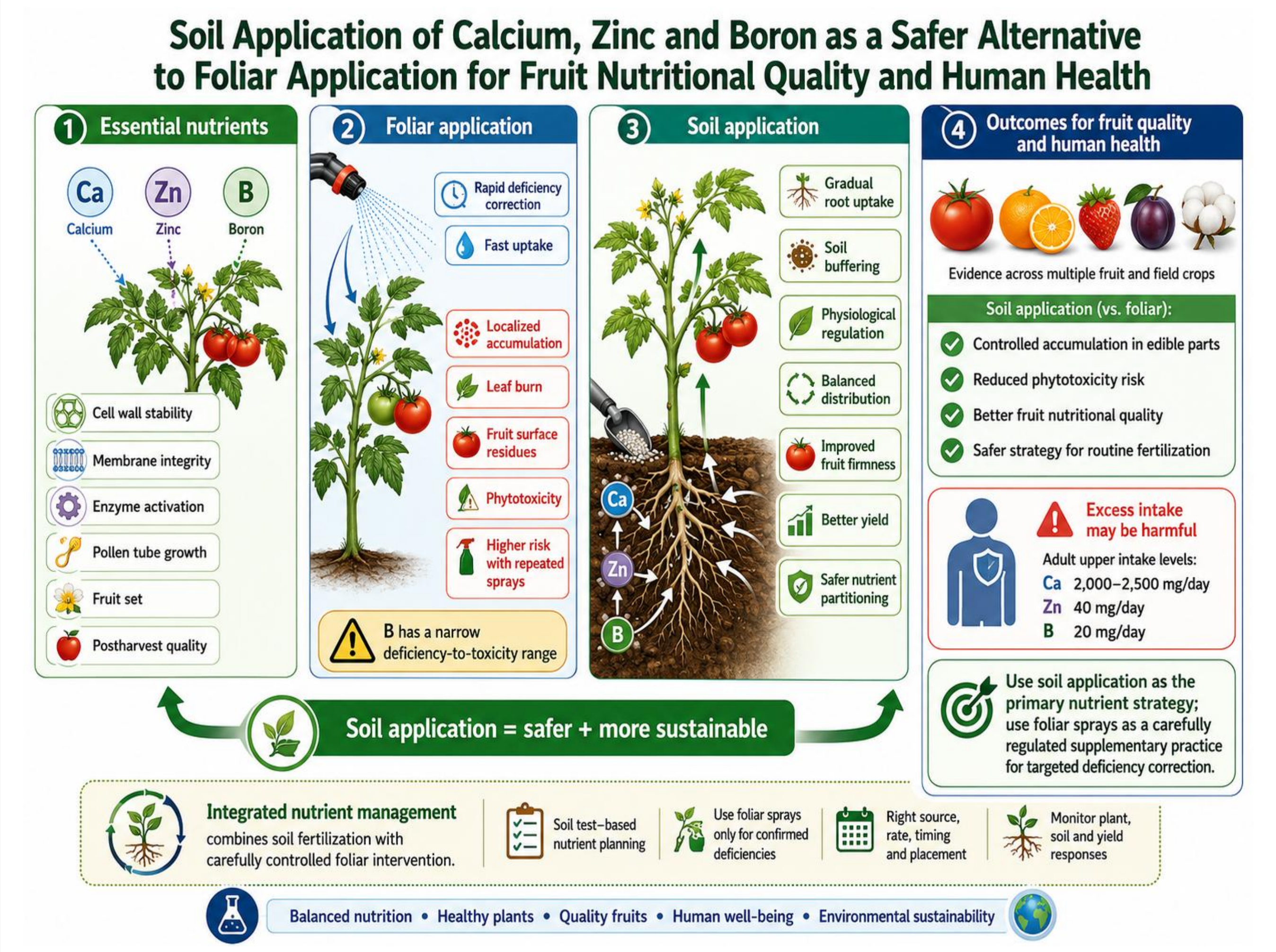
Global research indicates that soil-applied Ca, Zn, and B significantly improve crop growth, fruit firmness, yield, and nutritional quality under recommended doses. For instance, soil application of Zn and B in citrus increased fruit retention and yield, while boron application in cotton and tomato improved reproductive development and fruit quality when applied within optimal ranges. In contrast, foliar treatments often produce rapid increases in tissue nutrient concentration, which, although beneficial under deficiency conditions, may elevate the risk of excessive accumulation in edible plant parts if not carefully managed.

From a food safety perspective, this distinction is critical. While Ca, Zn, and B are essential micronutrients for human health, excessive intake may result in adverse physiological effects. The tolerable upper intake level for zinc is approximately 40 mg/day, whereas boron intake should generally not exceed 20 mg/day in adults (National Institutes of Health). Therefore, uncontrolled nutrient enrichment through repeated foliar application may have implications for dietary exposure and long-term health risk.

Overall, evidence suggests that soil application provides a safer and more sustainable nutrient management strategy by promoting controlled uptake, internal partitioning, and reduced risk of excessive nutrient accumulation in fruits. Foliar application should be considered a supplementary practice for targeted deficiency correction rather than a primary fertilization approach. Integrated nutrient management, combining soil-based fertilization with carefully regulated foliar interventions, is recommended to optimize crop productivity, fruit quality, and human health safety.

Keywords: *Calcium; Zinc; Boron; Soil application; Foliar application; Nutrient partitioning; Fruit quality; Phytotoxicity; Food safety; Micronutrient toxicity*

Graphical Abstract



INTRODUCTION

Calcium (Ca), zinc (Zn), and boron (B) are essential plant nutrients required for normal growth, reproductive development, fruit quality, and postharvest performance. Calcium contributes to cell wall stability, membrane integrity, and fruit firmness, thereby reducing physiological disorders such as blossom-end rot, bitter pit, fruit cracking, and poor storage quality (Marschner, 2012). Zinc is required for enzyme activation, protein synthesis, auxin metabolism, chlorophyll formation, and stress tolerance, while boron is involved in cell wall formation, sugar transport, pollen germination, pollen tube growth, flowering, fruit set, and seed development (Alloway, 2008; Álvarez-Herrera *et al.*, 2025).

In agricultural systems, these nutrients are generally applied through soil or foliar methods. Soil application supplies nutrients to the rhizosphere, where roots absorb them gradually according to plant demand, soil moisture, pH, organic matter, microbial activity, and nutrient availability (Roy *et al.*, 2006). This method allows nutrients to pass through the root system before being transported to stems, leaves, flowers, and fruits, creating a more regulated pattern of nutrient distribution within the plant (Marschner, 2012). In contrast, foliar application supplies nutrients directly to leaves and fruits and is commonly used for rapid correction of deficiencies, especially where soil pH, salinity, drought, or nutrient fixation restricts root uptake (Roy *et al.*, 2006).

Although foliar application can be effective, it may also increase the risk of phytotoxicity when concentration, timing, or frequency is not properly controlled. FAO guidelines emphasize that foliar nutrients should be applied in dilute solutions because concentrated sprays may damage leaf tissues through osmotic stress (Roy *et al.*, 2006). This concern is especially important for boron because it has a narrow range between deficiency and toxicity (Qamar *et al.*, 2020). In cotton grown on calcareous saline soil, soil-applied boron at suitable levels improved growth, yield, physiological parameters, and fiber quality, whereas higher boron levels increased the risk of excessive accumulation and toxicity symptoms (Qamar *et al.*, 2020).

Several international studies have shown that calcium, zinc, and boron improve crop productivity and fruit quality when applied at recommended doses. In citrus, zinc and boron application significantly improved fruit retention and yield under calcareous soil conditions (Noor *et al.*, 2019). In tomato, foliar application of calcium, boron, and zinc improved growth and fruit production, but the response depended strongly on concentration and management (Haleema *et al.*, 2018). Similarly, boron application methods affected tomato growth, fruit quality, and flavor, showing that both dose and application method influence crop response (Xu *et al.*, 2021). In plum, foliar calcium and boron sprays affected fruit quality and storage behavior, indicating that foliar-applied nutrients can directly influence edible fruit tissues (Wójcik and Wójcik, 2003).

From a food safety perspective, nutrient accumulation in edible plant parts requires careful attention. Calcium, zinc, and boron are beneficial for human health when consumed in appropriate amounts. Calcium is essential for bone and teeth development, muscle contraction, nerve transmission, blood clotting, and normal cellular function. Zinc supports immune defense, wound healing, enzyme activity, protein synthesis, DNA synthesis, growth, and reproductive health. Boron, although not classified as an essential nutrient like calcium and zinc, has been associated with bone metabolism, hormone regulation, mineral utilization, and anti-inflammatory functions (NIH, 2026; Nielsen, 2014). However, excessive intake may cause adverse health effects. The tolerable upper intake level for calcium in adults is generally 2,000–2,500 mg/day, depending on age, while the adult upper intake level for zinc is 40 mg/day. For boron, the adult tolerable upper intake level is 20 mg/day, although the World Health Organization (WHO) suggests that a usual acceptable safe intake range for adults is approximately 1–13 mg/day (NIH, 2022, 2025, 2026; WHO, 1998). Excessive calcium intake may increase the risk of kidney stones and other complications, high zinc intake may interfere with copper absorption and immune function, and excessive boron intake may cause gastrointestinal and reproductive health concerns. Therefore, nutrient management should aim not only to improve crop yield and fruit nutritional quality but also to maintain safe nutrient concentrations in edible food products. Soil testing, tissue analysis, recommended fertilizer doses (Farid *et al.*, 2026), and controlled foliar application are necessary to reduce the risk of excessive nutrient accumulation in fruits and vegetables

Based on the available evidence, soil application may provide a safer and more sustainable approach for routine Ca, Zn, and B management because it promotes gradual uptake, soil buffering, root regulation, and internal nutrient partitioning. Foliar application should not be rejected completely, but it should be used as a supplementary or corrective practice under controlled conditions. This review, therefore, evaluates global research evidence on soil and foliar application of Ca, Zn, and B, with emphasis on crop performance, nutrient distribution, phytotoxicity, fruit quality, and human health safety.

MATERIALS AND METHODS

Study Design

This study was designed as a narrative review based on published scientific literature related to calcium, zinc, and boron application in agricultural and horticultural crops. A narrative review approach was selected because the objective was to synthesize experimental findings from different crops, regions, and application methods rather than conduct a statistical meta-analysis. Similar review-based approaches are commonly used in plant nutrition research where studies vary in crop species, soil type, nutrient dose, climate, and experimental design (Marschner, 2012; Roy *et al.*, 2006).

Literature Search Strategy

Relevant literature was searched from scientific databases, including Google Scholar, ScienceDirect, Scopus, Web of Science, PubMed, and institutional sources such as FAO and NIH. Search terms included “calcium application in fruit crops,” “zinc soil and foliar application,” “boron toxicity in plants,” “soil versus foliar fertilization,” “micronutrient accumulation in fruit,” “calcium boron zinc fruit quality,” and “nutrient partitioning in plants.” The search strategy focused on studies dealing with nutrient uptake, crop yield, fruit quality, phytotoxicity, and human health implications (Alloway, 2008; Roy *et al.*, 2006).

Inclusion and Exclusion Criteria

Studies were included if they reported experimental or review-based evidence on Ca, Zn, or B application in crops, especially where soil and foliar application methods were compared. Priority was given to studies that provided quantitative information on yield, fruit set, fruit retention, nutrient concentration, fruit firmness, postharvest quality, or toxicity symptoms. Studies on tomato, citrus, cotton, strawberry, plum, mango, and related fruit crops were included because these crops have been widely used in Ca, Zn, and B nutrition research (Haleema *et al.*, 2018; Noor *et al.*, 2019; Qamar *et al.*, 2020; Xu *et al.*, 2021). Studies were excluded if they lacked clear application methods, did not report crop response, or were unrelated to plant nutrition and food safety.

Data Extraction

Data were extracted under the following categories: nutrient type, crop species, country or region, application method, fertilizer dose, growth response, yield response, fruit quality response, nutrient accumulation, and toxicity symptoms. Particular attention was given to experiments reporting differences between soil and foliar application. For example, citrus studies were reviewed for fruit retention and yield response to Zn and B application, tomato studies were reviewed for growth and fruit quality response, and cotton studies were reviewed for boron dose response and toxicity risk (Noor *et al.*, 2019; Qamar *et al.*, 2020; Xu *et al.*, 2021).

Comparative Evaluation Framework

The selected studies were analyzed using four major evaluation parameters. First, nutrient uptake efficiency was assessed by examining how soil and foliar applications influenced nutrient absorption and movement inside plants. Second, crop productivity was evaluated using yield, fruit set, fruit retention, and growth parameters. Third, fruit quality was assessed through firmness, cracking resistance, postharvest quality, biochemical quality, and storage behavior. Fourth, safety was evaluated by considering phytotoxic symptoms, excessive nutrient accumulation, and human dietary safety limits (Haleema *et al.*, 2018; NIH, 2026; Wójcik and Wójcik, 2003).

Human Health Safety Assessment

Human health implications were discussed using established dietary safety information for zinc and boron. Zinc was included because excessive intake may interfere with copper metabolism and immune function, while boron was included because of its narrow safe range in both plants and humans (NIH, 2026; Qamar *et al.*, 2020). The review, therefore, considered whether nutrient management practices could increase the concentration of Zn and B in edible crop tissues beyond desirable nutritional levels.

Limitations of the Review

This review is based on published literature and does not include new field experimentation. Differences among studies in soil type, crop species, climate, fertilizer source, nutrient concentration, and application timing may influence the interpretation of results. Therefore, the findings should be understood as a synthesis of global research trends rather than a universal rule for all crops and soils. Soil application is presented as a safer general strategy when properly managed, while foliar application is considered useful but more sensitive to dose, timing, and frequency (Roy *et al.*, 2006; Xu *et al.*, 2021).

RESULTS AND DISCUSSION

Effects of Ca, Zn, and B on Crop Growth and Yield

Across the reviewed studies, calcium, zinc, and boron consistently enhanced plant growth, reproductive development, fruit retention, and yield when applied at recommended doses. Calcium improves cell wall strength and membrane stability, which supports better fruit firmness, reduced cracking, and improved postharvest quality. Zinc contributes to enzyme activation, auxin synthesis, chlorophyll formation, and vegetative growth, while boron plays a major role in pollen germination, pollen tube growth, flowering, fruit set, and seed development (Alloway, 2008; Marschner, 2012).

In citrus, the application of zinc and boron has shown clear positive effects on reproductive development, fruit retention, and yield. Noor *et al.* (2019) reported that Zn and B application in sweet orange grown on calcareous soils improved fruit set, fruit retention, and yield, with the combined Zn + B treatment producing up to 14.34 t ha^{-1} fruit yield compared with 7.66 t ha^{-1} in the control. In that study, Zn and B were applied at 2.5 kg ha^{-1} each, either alone or in combination, and for foliar application the dose was divided into three sprays at important growth stages: before flower initiation, after fruit set at berry size, and 45 days after the second spray. The foliar spray was prepared using 13 g $ZnSO_4$ and 27 g H_3BO_3 in 6 L of water per tree per spray, and foliar application produced higher fruit yield than soil application under calcareous soil conditions (Noor *et al.*, 2019). However, these results should be interpreted carefully because boron has a narrow range between deficiency and toxicity, making dose control especially important in foliar nutrition (Noor *et al.*, 2019). Similarly, Sajid *et al.* (2010) found that foliar application of zinc sulphate at 0.5% and 1.0% and boric acid at 0.02% and 0.04% improved fruit yield and reduced physiological disorders in sweet orange cv. Blood Orange. The highest fruit yield was recorded with the higher zinc level combined with the lower boron level, specifically 1.0% Zn + 0.02% B, while 0.04% B should be used more cautiously because repeated boron sprays may increase the risk of nutrient imbalance or phytotoxicity. Therefore, for citrus foliar application, Zn may be applied within the tested range of 0.5–1.0%, but boron should preferably remain at the lower effective concentration around 0.02%, especially when sprays are repeated during the season. Higher boron concentrations, such as 0.04%, should only be used where deficiency is confirmed through soil or leaf analysis, because boron toxicity risk increases when concentration, frequency, or timing is not properly controlled (Sajid *et al.*, 2010; Roy *et al.*, 2006). This supports the broader conclusion of the attached review that foliar application is useful for rapid deficiency correction, but soil testing, plant tissue analysis, and controlled spray concentration are necessary to avoid excessive nutrient accumulation and phytotoxicity.

In tomato, foliar application of Ca, B, and Zn significantly improved growth and fruit production. Haleema *et al.* (2018) reported that calcium, boron, and zinc were applied as foliar sprays at different concentrations, including Ca at 0, 0.3, 0.6, and 0.9%; B at 0, 0.25, and 0.5%; and Zn at 0, 0.25, and 0.5%. Among these treatments, Ca at 0.6% produced the highest fruit number, reaching 66.15 fruits $plant^{-1}$, while B at 0.25% produced 67.78 fruits $plant^{-1}$, and Zn at 0.5% produced 63.78 fruits $plant^{-1}$. These results show that the optimum foliar levels increased fruit production compared with untreated plants, mainly through improved vegetative growth, flowering, fruit setting, and physiological activity (Haleema *et al.*, 2018). The response was concentration-dependent, as higher levels were not always superior, indicating that foliar application is effective only when the dose is properly regulated. Xu *et al.* (2021) also reported that boron application influenced tomato growth, fruit quality, and flavor attributes; in their study, leaf spray of 1.9 mg L^{-1} H_3BO_3 was more effective for improving plant growth and photosynthetic indices, while root application of 3.8 mg L^{-1} H_3BO_3 improved fruit quality and flavor-related traits. This confirms that boron plays an important role in reproductive growth and fruit development, but its method and concentration of application must be carefully managed (Xu *et al.*, 2021). Overall, the evidence suggests that foliar Ca, B, and Zn can improve tomato fruit production, but excessive or poorly regulated sprays may increase the risk of nutrient imbalance or phytotoxicity, particularly in the case of boron because of its narrow deficiency-to-toxicity range.

In strawberries, foliar application of calcium, zinc, and boron improved vegetative growth, fruit yield, and biochemical quality. Salman *et al.* (2022) evaluated foliar application of Ca, Zn, and B at three application timings: pre-flowering stage, post-fruit development stage, and combined application at both pre-flowering and post-fruit development stages. Their results showed that combined foliar application of Ca, Zn, and B improved leaf nutrient status, vegetative growth, average fruit weight, fruit yield, fruit size, fruit firmness, total soluble solids to titratable acidity ratio, ascorbic acid content, anthocyanin content, and antioxidant enzyme activities in 'Chandler' strawberry. The best response was associated with combined nutrient application at both growth stages, indicating that Ca, Zn, and B are important not only during vegetative growth but also during flowering, fruit development, and quality formation (Salman *et al.*, 2022). Similarly, Ibrahim *et al.* (2021) found that foliar application of boron and zinc at 100 ppm increased the number of leaves per plant, leaf area index, fresh weight, and dry weight of strawberry plants, showing that Zn and B support both vegetative and reproductive growth.

In cotton, boron has been reported as especially important during boll formation and reproductive development. Soil-applied boron improved growth, yield, and fiber-related traits in cotton grown under calcareous saline soil conditions, showing that boron availability is critical in soils where micronutrient deficiency is common. Qamar *et al.* (2020) reported that soil application of boron at 2.60 mg B kg^{-1} soil significantly improved cotton growth, yield, physiological traits, and fiber quality. However, higher boron levels became harmful; boron application at 5.52, 7.78, and 10.04 mg B kg^{-1} soil reduced the number of bolls per plant by 27%, 38.5%, and 49%, respectively, compared with the optimum treatment, indicating toxicity due to excessive boron supply (Qamar *et al.*, 2020). Earlier work on irrigated cotton also identified around 5 mg B kg^{-1} soil as a toxic critical level, where cotton leaves contained about 198 mg B kg^{-1} dry weight and toxicity symptoms appeared (Ahmed *et al.*, 2008). Therefore, boron must be applied carefully in cotton because the range between deficiency and toxicity is narrow, and soil or plant tissue testing should be used before increasing boron rates.

In addition to these crops, studies on mango and pomegranate also support the positive role of Zn and B in fruit production. Khan *et al.* (2022) reported that synchronized application of zinc and boron improved mango yield and quality attributes, suggesting that these nutrients support flowering, fruit retention, and fruit development. However, boron application must be carefully controlled because the range between deficiency and toxicity is narrow. In most crops, tissue boron concentrations of about 15–100 mg kg^{-1} dry matter are considered adequate for normal growth, while levels above 200 mg kg^{-1} dry matter may become excessive and can produce toxic effects such as leaf-tip burn, marginal chlorosis, necrosis, reduced growth, and yield loss (Alila *et al.*, 2023; Nable *et al.*, 1997). Therefore, boron sprays in mango and other fruit crops should be applied only at recommended concentrations and preferably after soil or leaf analysis. In pomegranate, foliar zinc and boron treatments reduced cracking and sunburn while improving yield-related traits, further confirming their role in fruit development and stress reduction. However, repeated or high-concentration boron sprays should be avoided because excessive boron accumulation may shift the plant from deficiency correction to toxicity, especially under dry, saline, or poorly leached soil conditions. This supports the need for balanced Zn and B fertilization to improve fruit quality while minimizing phytotoxicity and food safety risks.

Overall, the reviewed evidence shows that Ca, Zn, and B are essential for both vegetative and reproductive stages of crop development. Soil application provides a gradual and regulated nutrient supply, while foliar application produces quicker responses but requires careful dose control. Therefore, the best results are generally achieved when soil application is used as the primary nutrient source and foliar application is used as a supplementary method under deficiency or stress conditions.

Comparison of Soil and Foliar Application

The comparative analysis revealed clear differences between soil and foliar application methods in terms of nutrient uptake, movement, efficiency, and safety. Soil application resulted in gradual nutrient uptake through roots, which allowed internal regulation and distribution of nutrients across different plant organs. This mechanism ensured that nutrients were absorbed according to plant demand, soil moisture, pH, organic matter, and environmental conditions, thereby reducing the risk of excessive accumulation in specific tissues (Marschner, 2012; Roy *et al.*, 2006).

Soil application also provides a buffering effect because nutrients first interact with the soil system before entering the plant. In citrus, soil application of zinc and boron improved fruit set, fruit retention, and yield under calcareous soil conditions, showing that root-zone application can be effective even in soils where micronutrient availability is often limited (Noor *et al.*, 2019). Similarly, Zhang *et al.* (2015) reported that soil-applied Zn and B improved fruit yield and quality in satsuma mandarin, mainly by increasing fruit number and improving nutrient availability in the root zone. These findings suggest that soil application is useful for long-term nutrient management because it supports gradual uptake and balanced nutrient distribution.

In contrast, foliar application provided rapid nutrient absorption and was particularly effective in correcting deficiencies under adverse soil conditions. Foliar feeding is useful when high soil pH, salinity, drought, or nutrient fixation limits nutrient uptake through roots (Roy *et al.*, 2006). For example, foliar application of Ca, Zn, and B in tomato improved growth and fruit production, indicating its effectiveness as a short-term corrective strategy (Haleema *et al.*, 2018). Similarly, foliar application of Ca, Zn, and B in strawberry improved vegetative growth, yield, biochemical quality, and antioxidant attributes, especially when sprays were applied at suitable growth stages (Salman *et al.*, 2022).

However, the rapid uptake associated with foliar application may also result in higher nutrient concentrations in leaves and fruits. Studies on plum showed that foliar application of calcium and boron significantly increased their concentration in fruit tissues, demonstrating direct transfer to edible parts (Wójcik and Wójcik, 2003). Similarly, Xu *et al.* (2021) reported that different boron application methods in tomato produced different effects on plant growth, fruit quality, and flavor, confirming that the method and dose of nutrient application strongly influence nutrient accumulation and crop response.

Research on citrus further confirms that foliar application can improve growth and yield, but must be carefully managed. Sajid *et al.* (2010) found that foliar sprays of Zn and B significantly improved fruit yield and reduced physiological disorders in sweet orange cv. Blood Orange. In their study, the control treatment produced 71.17 kg fruit tree^{-1}, while the best treatment, 1.0% Zn + 0.02% B, produced 99.83 kg fruit tree^{-1}. This means that foliar application increased citrus yield by about 28.66 kg tree^{-1}, equal to an approximate 40.3% increase over the control. Other combined treatments also improved yield, including 0.5% Zn + 0.04% B, which produced 92.17 kg tree^{-1}, and 1.0% Zn + 0.04% B, which produced 94.67 kg tree^{-1}. However, the highest yield was achieved with higher zinc and lower boron, showing that nutrient concentration and balance are important for obtaining positive results without creating nutrient imbalance or toxicity risk. Therefore, foliar Zn and B can improve citrus productivity, but boron should be used carefully because repeated or high-concentration foliar sprays may increase the risk of localized accumulation and phytotoxic symptoms. In strawberry, Ibrahim *et al.* (2021) reported that foliar application of boron and zinc increased leaf number, leaf area index, fresh weight, and dry weight, confirming the rapid effect of foliar nutrition on vegetative growth. However, because foliar nutrients are directly deposited on plant surfaces, repeated applications may increase the risk of localized accumulation and phytotoxic symptoms.

Recent work on tomato also indicates that combined soil and foliar strategies may sometimes give better results than either method alone. Mal *et al.* (2025) evaluated five boron application protocols across seven tomato genotypes and examined their effects on 28 fruit quality attributes and two fruit quality indices related to fresh consumption and processing. The study found that boron application directly influenced important fruit traits, including pericarp thickness, fruit pH, phenolic content, zinc, copper, and boron concentration in tomato fruits. Among the tested treatments, the best response was obtained when boron was applied through soil at planting at 2.0 kg B ha^{-1}, followed by a foliar spray of 0.125 kg B ha^{-1} at the pre-flowering stage. This combined treatment improved tomato fruit quality more effectively than soil-only or foliar-only application methods (Mal *et al.*, 2025).

The combined soil-plus-foliar strategy improved physical fruit attributes by 6.1–33.1%, proximate composition by 7.8–49.0%, antioxidant-related traits by 16.7–207.5%, and mineral nutrient content by 9.6–146.8%. These improvements resulted in an overall improvement of about 31.0% in fruit quality indices for both fresh consumption and processing. The study also showed that tomato genotypes differed in their response to boron, with Pusa Ruby showing the highest boron responsiveness, followed by 2016/Res-3, Pathar Kuchi, 2016/Res-6, 2016/Res-5, 2016/Res-1, and 2016/Res-4 (Mal *et al.*, 2025).

These findings suggest that soil application provides a stable boron supply during early crop growth, while foliar application at pre-flowering gives an additional boron supply at a critical reproductive stage. This is important because boron supports pollen germination, pollen tube growth, fruit set, cell wall development, and fruit quality formation. Therefore, the results support the idea that foliar application should not be completely rejected; rather, it should be used as a carefully regulated supplementary practice along with soil-based fertilization. However, because boron has a narrow range between deficiency and toxicity, such combined application should be based on recommended doses, soil testing, and crop requirements to avoid over-accumulation and phytotoxicity.

Overall, soil application appears safer and more sustainable for routine nutrient management because it allows controlled uptake through roots, soil buffering, and internal partitioning across plant organs. Foliar application is faster and more effective for deficiency correction, but it carries a greater risk of tissue accumulation, leaf burn, and fruit surface residues if concentration, frequency, and timing are not carefully controlled. Therefore, the most balanced approach is to use soil application as the primary nutrient source and foliar application only as a corrective or supplementary method under specific deficiency conditions.

Nutrient Partitioning and Internal Distribution

One of the key differences between soil and foliar application lies in nutrient partitioning within the plant. Soil-applied nutrients are absorbed by roots and transported through xylem and phloem, resulting in gradual distribution among roots, stems, leaves, flowers, and fruits. This internal partitioning reduces the likelihood of sudden nutrient accumulation in edible plant tissues and promotes balanced plant growth (Marschner, 2012). Since soil acts as a buffering medium, nutrient availability is influenced by pH, organic matter, cation exchange capacity, soil moisture, and microbial activity, which further regulates nutrient uptake and movement inside the plant (Roy *et al.*, 2006).

Calcium is mainly transported through the xylem and moves with the transpiration stream. Therefore, it tends to accumulate more in highly transpiring organs such as leaves, while fruits often receive less calcium because they have lower transpiration rates. This explains why calcium-related disorders such as blossom-end rot in tomato, bitter pit in apple, and fruit cracking may occur even when soil calcium is present in sufficient amounts (Farid and Razzaq, 2026; Marschner, 2012). However, soil-applied calcium improves root-zone calcium availability and supports overall plant structure, cell wall stability, and membrane integrity, thereby indirectly improving fruit firmness and postharvest quality (White and Broadley, 2003).

Zinc shows moderate mobility within plants and is involved in enzyme activation, protein synthesis, auxin metabolism, and chlorophyll formation. Soil-applied zinc is absorbed by roots and distributed across vegetative and reproductive organs, supporting balanced plant growth. Alloway (2008) reported that zinc availability in soil strongly influences root uptake and internal transport, especially in alkaline and calcareous soils where zinc deficiency is common. In citrus, soil-applied zinc and boron improved fruit yield and quality, suggesting that root uptake supported better nutrient distribution and reproductive development (Zhang *et al.*, 2015).

Boron mobility is more complex than calcium and zinc because its movement inside plants depends strongly on plant species, transpiration flow, and the type of carbohydrates produced by the crop. In many crops, boron has limited phloem mobility, which means that once boron is deposited in older leaves, it cannot easily move again to younger growing tissues, flowers, or developing fruits. As a result, boron deficiency often appears first in actively growing parts of the plant, such as shoot tips, young leaves, flower buds, pollen grains, and developing fruits. This happens because these tissues have high boron demand but cannot receive enough boron from older leaves when internal redistribution is poor (Brown and Shelp, 1997).

This limited mobility has important practical implications for crop production. Since boron is closely involved in cell wall formation, membrane stability, sugar transport, pollen germination, pollen tube elongation, flowering, fruit set, and seed development, even a short period of boron shortage during flowering or early fruit development can reduce reproductive success. Poor boron supply may lead to weak pollen tube growth, poor fertilization, flower drop, poor fruit set, malformed fruits, fruit cracking, and reduced fruit quality. Therefore, boron must be available at the right time, especially during reproductive stages when flowers and young fruits are forming (Marschner, 2012).

However, boron behavior is not the same in all crops. In some plant species that produce sugar alcohols, such as sorbitol, mannitol, or dulcitol, boron can form complexes with these compounds and move more freely through the phloem. In such species, boron can be redistributed from mature leaves to young tissues and fruits more effectively. This explains why boron deficiency symptoms and fertilizer responses vary among crops. For example, crops with poor boron mobility may require more careful and timely boron application, while crops with better boron mobility may distribute boron more efficiently within the plant (Brown and Shelp, 1997).

From a nutrient management perspective, this means that boron application should be carefully timed and controlled. Soil application can provide a gradual boron supply through the root system, while foliar application may be useful during critical stages such as pre-flowering, flowering, and early fruit development. However, boron has a narrow range between deficiency and toxicity, so excessive application can quickly become harmful. Therefore, boron fertilization should be based on soil testing, tissue analysis, crop requirements, and recommended doses. Balanced boron distribution is essential not only for better flowering and fruit set but also for improving fruit firmness, reducing cracking, and maintaining overall fruit quality.

In tomato, different boron application methods affected plant growth, fruit quality, and flavor, showing that nutrient movement and accumulation depend strongly on both method and dose (Xu *et al.*, 2021). Soil application promoted more gradual uptake, while foliar application produced faster changes in shoot nutrient status. Similarly, Qamar *et al.* (2020) reported that soil-applied boron improved growth and yield in cotton, but excessive boron levels increased the risk of toxicity, showing that even soil application must be carefully regulated.

Foliar application may bypass part of the root-regulated uptake system and deliver nutrients directly to leaves, shoots, and fruit surfaces. This can be useful for rapid correction of deficiency, but it may also cause localized accumulation when sprays are applied repeatedly or at high concentrations. For example, foliar calcium and boron application in plum increased Ca and B concentration in fruit tissues, demonstrating direct movement into edible fruit parts (Wójcik and Wójcik, 2003). Similarly, foliar application of Ca, Zn, and B in strawberry improved growth and biochemical quality, but the response depended on application timing and concentration, indicating that foliar nutrient movement is sensitive to management practices (Salman *et al.*, 2022).

Overall, nutrient partitioning patterns strongly support soil application as a safer and more balanced nutrient delivery method for routine fertilization. Soil application allows root-mediated uptake and internal distribution across plant organs, reducing the chance of sudden excessive accumulation in fruits. Foliar application remains valuable for correcting deficiencies, but it requires strict control of concentration, frequency, and timing to avoid localized nutrient accumulation and phytotoxicity.

Phytotoxicity and Toxicity Risks

Phytotoxicity was observed as a major limitation of foliar application, particularly for boron. Boron has a narrow range between deficiency and toxicity, and even slight over-application can result in leaf burn, chlorosis, necrosis, reduced growth, and yield loss (Marschner, 2012; Qamar *et al.*, 2020). In cotton, excessive boron application significantly reduced crop performance, confirming that precise dose management is essential to avoid toxicity (Qamar *et al.*, 2020). Similar responses have been reported in other crops, where boron toxicity first appears as marginal leaf burn and progresses to severe tissue damage when concentrations exceed critical thresholds (Nable *et al.*, 1997).

Foliar application increases the risk of such toxicity because nutrients are delivered directly to plant surfaces, bypassing soil buffering and root regulation mechanisms. High concentrations of foliar-applied nutrients can cause osmotic stress, leading to dehydration of leaf cells, disruption of membrane integrity, and reduced photosynthetic efficiency (Roy *et al.*, 2006). Fernández and Eichert (2009) further explain that foliar nutrient uptake depends on cuticular penetration and environmental conditions, and excessive solution concentration can damage epidermal cells, resulting in phytotoxic symptoms.

In addition to osmotic effects, micronutrient toxicity may occur due to over-accumulation within plant tissues. Zinc toxicity, for example, can interfere with metabolic processes, inhibit root growth, and disrupt nutrient balance by inducing deficiencies of other elements such as iron and copper (Alloway, 2008). Broadley *et al.* (2007) reported that excessive zinc accumulation can impair plant physiological functions and reduce biomass production. Similarly, boron toxicity affects cell wall structure, enzyme activity, and membrane function, ultimately reducing plant growth and yield (Nable *et al.*, 1997).

Experimental evidence also shows that repeated foliar sprays increase the likelihood of localized accumulation when concentrations are not properly controlled. In plum, foliar application of calcium and boron during early fruit growth significantly increased their concentration in fruit tissues, indicating direct deposition and possible risk of over-accumulation in edible parts; therefore, such sprays should be used carefully and preferably according to crop-specific recommendations, because the attached review notes that foliar-applied nutrients can directly influence edible fruit tissues and may increase phytotoxicity risk when repeated excessively. In tomato, Haleema *et al.* (2018) reported that the most effective foliar levels were Ca at 0.6%, B at 0.25%, and Zn at 0.5%, applied as foliar sprays; higher levels, especially Ca at 0.9% and B at 0.5%, should be treated carefully because the response was concentration-dependent and excessive foliar nutrition may cause leaf injury or nutrient imbalance. In citrus, Sajid *et al.* (2010) evaluated foliar Zn at 0.5–1.0%, and B at 0.02–0.04%, and the best yield response was obtained with 1.0% Zn + 0.02% B, showing that a higher zinc level with a lower boron level was safer and more effective than increasing boron concentration. Therefore, boron around 0.02% may be considered the safer effective foliar level in citrus, while 0.04% B should be used cautiously and only where deficiency is confirmed. In strawberry, Ibrahim *et al.* (2021) reported that foliar application of boron + zinc at 100 ppm improved vegetative growth, and repeated spraying of 100 ppm boron-zinc at 30, 45, and 60 days after transplanting increased fruit yield and quality. Similarly, Salman *et al.* (2022) showed that Ca, Zn, and B application was most useful when applied at suitable stages, particularly pre-flowering and post-fruit development, confirming that timing is as important as concentration. Overall, foliar application should remain within tested optimum ranges, especially for boron, because the attached review emphasizes that foliar feeding is more sensitive to dose, timing, and frequency than soil application.

Simple caution can be for practical safety - foliar boron should be kept at the lower effective level wherever possible, such as 0.02% in citrus, 0.25% in tomato, and 100 ppm in strawberry, because boron has a narrow deficiency-to-toxicity range and repeated sprays may cause leaf burn, localized accumulation, and phytotoxicity.

In contrast, soil application generally presents a lower risk of phytotoxicity because soil acts as a buffering medium. Nutrients applied to soil undergo processes such as adsorption, precipitation, and microbial interaction before being absorbed by plant roots, thereby reducing the likelihood of sudden exposure to high nutrient concentrations (Marschner, 2012). However, it is important to note that even soil application can lead to toxicity if excessive doses are applied over time, particularly in poorly drained or saline soils where nutrient accumulation may occur (Alloway, 2008).

Overall, the findings suggest that while foliar application is highly effective for rapid correction of nutrient deficiencies, it carries a higher risk of phytotoxicity compared to soil application, especially when concentration, frequency, and timing are not properly managed. Soil application, by contrast, provides a more controlled and gradual nutrient supply, making it a safer option for routine fertilization. Therefore, foliar feeding should be applied cautiously, following recommended doses and schedules, to minimize toxicity risks while maintaining crop productivity.

Implications for Human Health

The accumulation of nutrients in edible plant parts has direct implications for human health because fruits and vegetables are major dietary sources of minerals. Calcium, zinc, and boron are essential for human nutrition; however, excessive intake may cause adverse effects. Calcium is important for bone development, muscle contraction, nerve transmission, and blood clotting, while zinc supports immune function, wound healing, enzyme activity, and DNA synthesis (NIH, 2026). Boron is not classified as an essential nutrient in the same way as zinc and calcium, but it is associated with bone metabolism, hormone regulation, and inflammatory responses when consumed in small amounts (Nielsen, 2014).

Although these nutrients are beneficial at appropriate levels, excessive intake can be harmful. For adults, the tolerable upper intake level is 2,000–2,500 mg/day for calcium, depending on age; 40 mg/day for zinc; and 20 mg/day for boron, while the WHO suggests an acceptable safe boron intake range of approximately 1–13 mg/day for adults (NIH, 2022, 2025, 2026; WHO, 1998). Excessive calcium intake may increase the risk of kidney stones and other complications, while long-term excessive zinc intake may cause nausea, vomiting, reduced copper absorption, anemia, and impaired immune function. Boron also has a narrow safety margin, and excessive intake may cause gastrointestinal disturbance, reproductive toxicity, and metabolic imbalance. Therefore, nutrient enrichment of edible crops must be carefully managed so that it improves nutritional quality without increasing dietary risk.

Foliar application may increase nutrient concentration in edible tissues because nutrients are deposited directly on leaves and fruit surfaces. This is especially important when sprays are applied repeatedly or close to harvest. Wójcik and Wójcik (2003) reported that foliar application of calcium and boron increased their concentration in plum fruit tissues, showing that foliar-applied nutrients can move into edible parts. Similarly, foliar application of Ca, Zn, and B in tomato and strawberry improved fruit quality but also demonstrated that nutrient concentration depends strongly on dose, timing, and frequency of application (Haleema *et al.*, 2018; Salman *et al.*, 2022).

In contrast, soil application allows nutrients to enter through the root system, where uptake is regulated by plant demand and soil buffering processes. Nutrients are then distributed among roots, stems, leaves, flowers, and fruits, reducing the chance of sudden excessive accumulation in edible fruit tissues (Marschner, 2012). This makes soil application comparatively safer from a food safety perspective, particularly for nutrients such as boron and zinc, where excessive levels may create both plant toxicity and dietary concerns (Abalist and Ukoroije, 2026; Alloway, 2008; Qamar *et al.*, 2020).

These findings highlight the need to integrate crop productivity goals with human nutritional safety. Fertilizer management should not aim only to maximize yield or nutrient concentration but should maintain minerals within safe and beneficial ranges. Soil testing, plant tissue analysis, controlled fertilizer doses, and avoidance of repeated foliar sprays near harvest are necessary to ensure that improved crop production does not compromise human health (Roy *et al.*, 2006).

Overall Evaluation

Based on the reviewed studies, soil application provides a more stable, regulated, and sustainable approach to calcium, zinc, and boron management. It ensures gradual uptake through roots, internal distribution among plant organs, and reduced risk of localized nutrient accumulation. Soil application also benefits from soil buffering mechanisms, which regulate nutrient availability and reduce sudden exposure to high concentrations (Marschner, 2012; Roy *et al.*, 2006).

Foliar application, while effective for rapid deficiency correction, should be used selectively and carefully. It is useful where soil conditions such as high pH, salinity, drought, or nutrient fixation restrict root uptake. However, repeated or high-concentration foliar sprays can increase the risk of leaf burn, fruit surface residues, phytotoxicity, and excessive nutrient accumulation in edible tissues (Fernández and Eichert, 2009; Wójcik and Wójcik, 2003).

Overall, the evidence supports an integrated nutrient management approach. Soil application should serve as the primary source of Ca, Zn, and B because it provides long-term nutrient stability and safer uptake. Foliar application should be used only as a supplementary or corrective method under specific deficiency conditions. This balanced strategy can improve crop yield, fruit quality, postharvest performance, and food safety while reducing environmental and human health risks.

CONCLUSION

The present review demonstrates that calcium, zinc, and boron are essential nutrients that significantly influence plant growth, fruit development, and crop productivity. Both soil and foliar application methods play important roles in nutrient management; however, their effectiveness and safety differ substantially.

Soil application provides a controlled and sustainable nutrient delivery system by allowing gradual uptake through roots and balanced distribution among plant organs. This method reduces the risk of excessive nutrient accumulation in fruits and minimizes phytotoxic effects. In contrast, foliar application offers rapid correction of nutrient deficiencies but carries a higher risk of localized accumulation, phytotoxicity, and potential food safety concerns when not properly managed.

Experimental evidence from multiple crops, including citrus, tomato, cotton, and strawberry, indicates that soil application improves yield, fruit quality, and nutrient balance when applied at recommended doses (Noor *et al.*, 2019; Qamar *et al.*, 2020; Xu *et al.*, 2021). Foliar application remains valuable as a supplementary strategy, particularly under nutrient-deficient conditions or when soil factors limit nutrient availability.

From a human health perspective, maintaining safe levels of nutrient accumulation in edible plant parts is critical. Excessive intake of Ca, zinc and boron can lead to adverse health effects, emphasizing the need for controlled fertilization practices (NIH, 2026).

Overall, the findings support the adoption of integrated nutrient management strategies in which soil application forms the foundation of nutrient supply, while foliar application is used selectively and cautiously. Such an approach ensures optimal crop productivity, improved fruit quality, and enhanced food safety.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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