

performance (Bai et al., 2021). In commercial orchards, combinations of N-P-K adjusted by phenological stage have been shown to increase total yield and improve fruit size, weight, and soluble solids, particularly when N is emphasized around flowering and K during fruit development and ripening (Maatallah et al., 2024). However, high P supply can be negatively correlated with total sugar content, underscoring the need for balanced P inputs. (Maatallah et al., 2024). Foliar potassium (often combined with silicon) additionally enhances sugar translocation, coloration, soluble solids, firmness, and postharvest quality when applied at fruit set, stone hardening, and physiological maturity (Abidi et al., 2023).

3.2 Micronutrient supplementation

Calcium, boron, and zinc play crucial roles in fruit set, structural integrity, and quality formation. Soil and foliar Ca supply influences cell wall strength and postharvest behavior across Rosaceae fruits (Bai et al., 2021). In peaches and nectarines, foliar Ca applications increase fruit Ca content, especially when applied in late fruit development, with Ca retained mainly in the flesh and skin, which are critical for eating quality and shelf life (Carrasco-Cuello et al., 2024).

Boron is indispensable for cell wall formation, flowering, and fruit set; its imbalance reduces pollination success, fruit set, yield, and quality, and can increase acidity and physiological disorders (Thakur et al., 2023). Foliar B or Zn sprays in peach increase fruit set, yield, and quality traits such as TSS, TSS:acidity ratio, ascorbic acid, and firmness, while raising leaf B and Zn concentrations (Ali et al., 2019b; Muradi and Godara, 2020).

Deficiency symptoms of these micronutrients can manifest as poor flowering, low fruit set, small or deformed fruits, and increased physiological disorders. Boron deficiency is highlighted as one of the most widespread trace-element problems, producing a wide range of symptoms in young tissues and substantially reducing yield and quality (Thakur et al., 2023). In soil-based surveys of peach orchards, available B and Ca strongly influence single fruit weight and soluble solids, emphasizing the importance of maintaining adequate levels to avoid hidden deficiencies (Sun et al., 2022a). Foliar fertilization is generally considered 10-20 times more efficient than soil application for correcting micronutrient deficiencies in fruit trees, because it delivers nutrients directly to metabolically active leaves and developing fruit (Muradi and Godara, 2020).

3.3 Fertilization methods and timing

Basal soil fertilization and in-season topdressing form the backbone of macronutrient supply in many peach orchards. Early soil applications rich in N (often in 2-1-1 N:P:K ratios) before blossom are widely recommended to support spring growth and flower initiation, followed by additional N (e.g., ammonium sulfate) at early fruit set to sustain ovary growth and fruit retention (Tsoumanis et al., 2025). Multi-year trials combining intra-row spacing with N-P-S blends show that intermediate spacing and moderate basal rates (e.g., 150 kg/ha) can maximize yield, fruit weight, and economic return (Mosie et al., 2025).

Split N applications targeted to reproductive growth stages improve uptake and reduce environmental losses; isotope tracing in high-input orchards reveals that only about one-third of applied N is taken up by the tree, with substantial portions remaining in soil or lost to the environment, suggesting that total rates can be reduced by about 30% while focusing on reproductive stages (Yang et al., 2024). Foliar fertilization during key growth stages complements soil applications and allows rapid correction or strategic boosting of particular nutrients.

Foliar N-fixing biofertilizers applied at fruit appearance and full development can enhance chlorophyll content, shoot growth, and fruit weight while decreasing reliance on synthetic N sources (Tsoumanis et al., 2025). Foliar K (often as potassium-silicon) at fruit set, stone hardening, and maturity improves fruit weight, firmness, soluble solids, titratable acidity, and postharvest resistance, illustrating the value of stage-specific sprays (Abidi et al., 2023). Similarly, foliar B, Zn, and Fe sprays applied once or twice from early spring significantly increase yield, fruit size, TSS, ascorbic acid, and leaf micronutrient content while reducing acidity, with double sprays outperforming single applications (Ali et al., 2019a; Muradi and Godara, 2020).