firmness, shelf life, and resistance to physiological and abiotic stresses. Most Ca in plants accumulates in vegetative organs, and insufficient Ca supply is common in commercial production systems, often associated with reduced fruit formation and quality decline.

Magnesium is an important component of chlorophyll and also acts as an activator for many enzymes. It is distributed between leaves and fruits, and its uptake is positively correlated with plant height and the number of fruits per plant (Quddus et al., 2025).

Elements such as Fe, Zn, Mn, Cu, and B are essential for photosynthesis, respiration, enzyme activation, and hormone balance. Application of Fe, Zn, and Ca through foliar spray or substrate can improve vegetative growth, flowering, yield, and fruit quality (such as vitamin C content and firmness) (Marchenko et al., 2024; Singh et al., 2024).

Long-term investigations of leaf nutrient status in commercial plantations show that although N, P, K, and Mg are usually sufficient, deficiencies of Ca, S, Zn, and Cu occur in more than half of the samples, which may limit yield and fruit quality under both open-field and protected conditions (Osvalde et al., 2023). Typical deficiency symptoms include chlorosis and poor growth caused by Fe and Mg deficiency, weak pedicels and soft fruits caused by Ca deficiency, and reduced fruit set, smaller fruit size, or lower sugar content due to insufficient Zn, B, and other micronutrients, ultimately reducing marketable yield and economic returns (Sangeeta et al., 2019; Sayğı, 2022).

4.3 Nutrient uptake dynamics

Under greenhouse soilless cultivation, nutrient uptake is influenced not only by root physiological characteristics but also by the interaction between substrate and nutrient solution. The uptake of most macronutrients is lowest in the early stage after autumn planting and reaches a peak from flowering to fruit maturity. Among these, K shows the highest uptake rate, followed by N, Ca, Mg, and P. Roots and crowns store nitrogen during autumn and winter, and about 40% of the stored nitrogen is remobilized for new growth during flowering.

Analysis of leaves, crowns, roots, and fruits indicates that during fruit maturation, N, P, and K are mainly transported to fruits, while Ca is largely retained in leaves and roots, and Mg is distributed between vegetative organs and fruits. This suggests that continuous nutrient supply is required during the reproductive growth stage (Ikegaya et al., 2020).

In hydroponic and low-substrate-volume systems, root uptake patterns are strongly affected by the composition of the nutrient solution (such as N/K and K/Ca ratios), electrical conductivity (EC), pH, and cultivar-specific uptake characteristics. Adjusting these ratios at different growth stages can improve photosynthetic efficiency, promote earlier fruit ripening, increase yield by about 20%~26%, and improve the sugar-acid ratio and vitamin C content, while maintaining stable substrate pH (Shirko et al., 2018).

Substrate properties further affect nutrient availability. pH determines the solubility of micronutrients and the risk of deficiency or toxicity, while EC, cation exchange capacity (CEC), and organic matter content regulate the fixation and release of N, P, S, K, and Mg. Organic amendments (such as vermicompost and mushroom waste) can increase total and available N, P, and K in soil, enhance microbial and enzyme activity, and alleviate continuous cropping obstacles, thereby promoting nutrient uptake and improving yield and fruit quality (Allayorov et al., 2023). In contrast, peat-based substrates with low fertility may lead to deficiencies of N, P, and K if fertilization is not properly managed, further indicating that substrate selection and nutrient solution design must be optimized together to meet nutrient uptake dynamics at different growth stages.

5 Nutrient Supply Strategies in Soilless Cultivation

5.1 Fertigation management

The composition and concentration of nutrient solutions must be adjusted according to crop growth stage and cultivar. In practice, the ratios of N:K and K:Ca are usually modified during the vegetative stage, flowering stage, and fruit expansion stage. This helps improve photosynthetic efficiency, promote rapid fruit ripening, enhance