4.3 Characteristics of nutrient allocation and assimilate accumulation during fruit development

Fruit development in greenhouse-grown tomatoes is essentially a continuous process of assimilate translocation and accumulation toward the fruit as the primary sink. During the late growth stage, fruits become the dominant site of dry matter accumulation, accounting for up to 73% of aboveground dry biomass under organic cultivation conditions, indicating a clear shift to fruit-centered resource allocation. Nitrogen and potassium are key macronutrients for maintaining sink activity, particularly under continuous fruiting. Nutrient demand varies across developmental stages: early fruit development is characterized by cell division and sink establishment, regulated by assimilate supply and hormonal signals, whereas the rapid expansion stage depends on sustained inputs of sugars and mineral nutrients to determine fruit weight and quality. Appropriate supplemental lighting and nutrient supply can enhance both yield and quality, while excessive electrical conductivity (EC) may improve quality concentration but inhibit growth, reflecting a trade-off between biomass production and quality (Xie et al., 2024).

At the single-fruit level, assimilate accumulation involves not only sugars and dry matter but also dynamic changes in mineral nutrients and secondary metabolites. Increasing the proportion of blue light can enhance soluble sugars, lycopene, and β-carotene contents while maintaining fruit fresh weight, indicating that carbon allocation affects both fruit size and composition. Mineral elements continue to change during fruit development and postharvest ripening, suggesting that fruit maturation is a dynamic process involving both import and internal redistribution. Thus, fruit quality formation results from the coordinated interaction of carbon assimilation, mineral transport, and metabolic regulation. Environmental and nutrient management further shape these processes by regulating source strength and assimilate transport. Moderate deficit irrigation may reduce yield but improve quality attributes, whereas supplemental lighting and CO_2 enrichment enhance carbon supply, increasing fruit weight and overall yield. The research conducted by Su et al. (2025) demonstrated that appropriate Cl^- supply can improve photosynthetic performance and sucrose metabolism, promoting sugar transport to fruits and increasing soluble sugar content (Su et al., 2025). Overall, the coordinated improvement of yield and quality depends not only on total assimilate production but also on their allocation patterns within the fruit.

5 Root Traits and Nutrient Uptake Capacity in Protected Tomato Production

5.1 Effects of root activity and root distribution on water and fertilizer uptake efficiency

Root activity is one of the key factors determining water and nutrient uptake efficiency in protected tomato production. Highly active root systems usually exhibit a higher root tip growth rate, a more developed fine-root system, a larger absorptive surface area, and higher root metabolic activity. As a result, they can respond more rapidly to changes in root-zone water and nutrient availability and convert these resources into the supply needed for plant growth and fruit development. In intensive protected cultivation systems, roots are not merely passive absorbing organs, but the core interface linking irrigation, fertilization, and yield formation. Under drip fertigation, increases in root length, root surface area, and root volume in different soil layers are significantly positively correlated with tomato fruit yield and water-use efficiency. Under appropriate water-nitrogen management conditions (100% ETc + 250 kg $N \cdot ha^{-1}$), compared with the no-nitrogen treatment, root length, root surface area, and root volume increased by about 40%-150%, while yield increased by 31.6% and water-use efficiency by 34.4% (Figure 4) (Feng et al., 2024). This indicates that improved root activity is not simply reflected in having more roots, but rather in more efficient resource capture and utilization.

The fine-root system is especially important in this process. Active fine roots with smaller diameters usually account for the main absorptive function of the root system, and their length, surface area, and branching degree directly determine the intensity of contact between roots and the root-zone solution. Studies on aerated irrigation further show that increasing dissolved oxygen levels in the root zone can significantly increase the length and surface area of fine roots (≤2 mm), and these fine-root traits are significantly positively correlated with aboveground biomass, fruit yield, nitrogen-use efficiency, and irrigation water-use efficiency (Zhang et al., 2023). Therefore, the high and stable yields of protected tomatoes do not depend simply on a large root mass, but on an efficient root system characterized by abundant fine roots, active absorption, and strong renewal capacity.