

can increase yield per tree and improve fruit size, soluble solids content, color, and phenolic composition. However, excessive phosphorus application may be unfavorable for sugar accumulation (Maatallah et al., 2024). Excessive fertilization also increases production costs and the risk of environmental pollution. Therefore, optimizing fertilization rate, application timing, and internal nutrient balance of trees has become an important direction in peach orchard management (Casamali et al., 2021a; Nava et al., 2022; Mosie et al., 2025).

Irrigation management also determines peach yield and quality, especially in semi-arid and arid regions and areas with limited water resources (Pascual et al., 2016; Toumi et al., 2022). Supplemental irrigation can promote canopy growth, trunk thickening, photosynthesis, and early yield formation, with more pronounced effects in dry years (Fisk et al., 2015; Casamali et al., 2021a). However, severe water stress during the later stage of fruit development can reduce fruit size, quality, and economic returns (Fisk et al., 2015). Zhou et al. (2017) showed that moderate deficit irrigation can maintain yield while improving individual fruit weight, soluble solids content, vitamin C content, firmness, sugar-acid ratio, and water use efficiency. In arid regions of Tunisia, sustained deficit irrigation and partial root-zone drying treatments also improved fruit dry matter, sugars, phenolics, and mineral element contents (Toumi et al., 2022). A meta-analysis further indicated that regulated deficit irrigation generally helps improve water use efficiency in peach trees, while yield losses are usually within a controllable range (Ali et al., 2024).

With the development of high-density cultivation, dwarf tree forms, mechanized management, and increasing water constraints under climate change, traditional fertilization and irrigation practices can no longer fully meet the needs of modern peach orchards for high yield and high quality (Anthony and Minas, 2021; Iglesias and Echeverría, 2022). Integrated water and fertilizer management combines water supply and fertilizer application through drip irrigation, micro-sprinkler irrigation, and other approaches. It enables synchronized, small-dose, repeated, and precise water and nutrient supply during key growth stages, helping improve water and nutrient use efficiency while reducing input waste and environmental risks.

This study focuses on water management, nitrogen, phosphorus, and potassium nutrient supply, and the coordinated regulation of deficit irrigation and fertilization in peach trees. It aims to provide technical references for stable yield, high productivity, superior quality, and sustainable management of peach orchards.

2 Physiological Basis of Peach Yield Formation

2.1 Flowering, fruit set, and fruit development

High yields and good fruit size are associated with balanced NPK supply, with peak N demand around flowering and fruit set (Figure 1). In commercial orchards, NPK supply regimes that emphasized relatively high N during S2 (flowering/fruit set) produced the highest yields (50-68 kg/tree) and supported later fruit size and quality (Maatallah et al., 2024). N is a key macronutrient for leaf development, photosynthetic capacity, and sugar formation, and peak N demand in stone fruits occurs at bud break, flowering, and fruit set (Chawla and Sharma, 2025). Inadequate N reduces flower bud quality and effective fruiting, and also impairs root growth and water and nutrient uptake (Nava et al., 2022).

Peach fruit development proceeds through four stages (S1-S4), with rapid cell division and growth in S1, pit hardening in S2, a second exponential growth phase in S3, and final ripening in S4 (Zhang et al., 2022). N supply during pit hardening and fruit expansion directly affects yield, fruit quality, and metabolite composition, particularly carbon and amino acid metabolism (Zhang et al., 2022). Excessive P supply, in contrast, can be negatively correlated with total sugar content in the fruit (Maatallah et al., 2024).

During the rapid fruit expansion stage (S3/fruit expansion), water demand is high because fruit size increases quickly and large amounts of carbohydrates are required (Zhang et al., 2022). Studies in semi-arid conditions show that water deficit from mid-pit hardening to harvest significantly reduces shoot and fruit growth, with growth more sensitive to water shortage than photosynthesis (Rahmati et al., 2015). As tree water status declines