

conversion and export (Zahoor et al., 2017). In tomato, fruit fresh weight, dry weight, and carbon allocation were highly sensitive to irrigation amount under potassium supply, and the activities of sucrose synthase, sucrose phosphate synthase, acid invertase, and AGPase responded strongly to water regime, showing that water-potassium interactions directly shape fruit carbon metabolism (Wu et al., 2023). In red raspberry, moderate irrigation at 75% ETc produced the highest yield, implying that carbon gain and reproductive allocation are optimized under moderate rather than excessive irrigation. For *R. chingii*, these findings support a mechanism in which suitable water-fertilizer management enhances photosynthetic carbon assimilation, stabilizes sucrose metabolism, and improves the transfer of assimilates from leaves to developing fruits.

5.2 Regulatory mechanisms of water and fertilizer supply on nutrient uptake, transport, and allocation

Water and fertilizer management also regulates yield and quality through its effects on nutrient release in soil, root absorption, xylem-phloem transport, and allocation among leaves, stems, roots, and fruits. Water availability strongly governs nutrient mobility in soil and transpiration-driven mass flow, so drought often creates simultaneous water and nitrogen limitation and restricts nutrient entry into the vascular system (Plett et al., 2020). In alpine plants, drought restricted rhizospheric nitrogen release, limited root growth, reduced root surface area, root length, and root volume, and decreased both aboveground and belowground fertilizer utilization rates. Soybean showed the same overall pattern: water deficit and no nitrogen fertilization reduced the accumulation and partitioning of N, P, K, Ca, Mg, S, and micronutrients, and water limitation impaired biomass and nutrient accumulation even when nitrogen was supplied (Setubal et al., 2023). These mechanisms are highly relevant to *R. chingii* because stable fruiting requires continuous nutrient supply to both vegetative tissues and reproductive sinks, and any reduction in root uptake or long-distance transport can weaken fruit set, fruit growth, and quality formation.

The effect of fertilizer depends on both dose and coordination with water supply. In substrate-grown tomato, an appropriate potassium level promoted coordinated uptake of K, N, P, Ca, and Mg during the reproductive stage, while insufficient potassium restricted root-mediated water and nutrient flux and excessive potassium reduced physiological efficiency because of luxury consumption and salt stress. In winter wheat, NPK uptake in aboveground biomass decreased as water stress intensified, but mild deficit did not differ significantly from full irrigation, and moderate fertigation promoted nutrient transfer to grains without significantly reducing yield or protein (Yan et al., 2022). In greenhouse grape, bacterial fertilizer under mild water stress increased available phosphorus, dissolved organic carbon, microbial biomass carbon and nitrogen, and soil enzyme activities, indicating that rhizosphere biological processes can improve nutrient availability and production efficiency under constrained water supply (Gao et al., 2025). Together, these studies indicate that *R. chingii* likely responds best to moderate, coordinated water-fertilizer supply that sustains root activity, preserves ionic balance, and directs more nutrients toward fruit-bearing organs rather than inefficient vegetative accumulation.

5.3 Effects of water and fertilizer conditions on secondary metabolite biosynthesis and accumulation

Water and fertilizer conditions affect fruit quality further by regulating the biosynthesis and accumulation of secondary metabolites, which are central to the medicinal and nutritional value of *R. chingii*. *Rubus chingii* fruit contains abundant flavonoids, phenolic compounds, terpenoids, phenolic acids, organic acids, and related metabolites, and ellagic acid and kaempferol-3-O-rutinoside are currently used as representative quality markers (He et al., 2023). In fruit crops more broadly, secondary metabolism is highly sensitive to abiotic cues, and these compounds influence pigmentation, flavor, antioxidant capacity, and economic value (Savoi et al., 2016). Grape studies show that water deficit directly modulates the flavonoid pathway: early or moderate deficit can increase anthocyanin accumulation by upregulating *PAL*, *C4H*, *4CL*, *CHS*, *F3H*, *F3'5'H*, *UFGT*, *GST*, and related transcriptional regulators, whereas severe or poorly timed deficit can downregulate pathway genes or shift composition in less favorable directions (Palai et al., 2022). Water deficit can also accelerate sugar accumulation and ripening, thereby interacting with developmental signals that promote anthocyanin synthesis.