

productivity by 26.4%, and NUE by 34.3% relative to traditional practices, with fruit crops showing the greatest NUE gain, which supports the need for *Rubus chingii* production standards built around precise fertigation rather than empirical watering and fertilization (Li et al., 2021).

The problem is not only the absence of standards, but also the lack of intelligent and adaptive management tools that can support those standards in production. In greenhouse strawberry, sensor-based fertigation outperformed empiric timer-based management by saving 38% of nutrient solution and 26% of water while increasing WUE and nutrient productivity without compromising fruit quality, showing that real-time monitoring can replace coarse scheduling rules (Bonelli et al., 2024). A second strawberry study reached a similar conclusion: drier sensor-controlled thresholds and leaching-fraction approaches gave the best combined yield and resource-use performance, whereas common rigid scheduling did not track variable plant demand well (Hutchinson et al., 2025). Current tomato work also argues for dynamic fertilization models, plant physiological indicators such as leaf N and K, and soil sensors for real-time nutrient monitoring, which highlights the direction *Rubus chingii* management standards still need to move toward.

6.3 Limited research on the coordinated improvement mechanisms of yield and quality

A third problem is the limited mechanistic understanding of how water and fertilizer management can improve yield and quality together, rather than improving one at the expense of the other. Many studies show that the best treatment for yield is not the best for fruit quality. In mango, one regime produced the highest yield and PFP, while another produced the highest total sugar and lowest titratable acidity, and the final recommendation required multi-objective evaluation rather than a single agronomic index (Sun et al., 2022). Tomato showed the same pattern: one treatment achieved the highest integrated score for yield, WUE, and PFP, while another performed best for vitamin C, lycopene, SSC, and soluble protein. Wine grape likewise required moderate water and fertilizer to balance yield, berry quality, and resource-use efficiency, while moderate fertilization specifically produced the richest anthocyanin and tannin accumulation (Han et al., 2023).

For *Rubus chingii*, this unresolved coordination problem is even more critical because target quality includes not only edible traits but also medicinally active compounds. Bitter melon under irrigation deficit showed a typical trade-off: reduced irrigation lowered fruit number and weight but increased flavonoids, anthocyanins, and medicinal secondary metabolites, while AMF and phosphorus partly buffered yield loss and enhanced phytochemicals (Dolatmand-Shahri et al., 2025). Red raspberry studies similarly show that some fertilizers improve berry weight, sugars, and bioactive compounds, while unfertilized control can still produce a better sweetness index, indicating that different quality dimensions do not move together automatically (Stojanov et al., 2019). Emerging work in raspberry and pear suggests that microbial or bio-organic inputs may help bridge this gap by improving fruiting traits, phenolics, antioxidant activity, soil fertility, and yield through rhizosphere-mediated mechanisms, but the exact causal links remain disputed and insufficiently resolved for standardized field application in *Rubus chingii* (Wang et al., 2022; Pešaković et al., 2026).

7 Development Directions for Precision Water-Fertilizer Management

7.1 Establishment of precision water and fertilizer regulation models based on cultivar characteristics and growth stages

A key development direction for *Rubus chingii* is the establishment of precision regulation models that explicitly incorporate cultivar characteristics, phenological stage, and multi-objective production targets. Current precision water-fertilizer research shows that different crops require nutrient ratios and irrigation schedules that are scientifically matched to crop characteristics and growth stages rather than applied uniformly (Xing and Wang, 2024). In mango, irrigation amount and fertilizer rates at flowering, fruit expansion, and fruit ripening affected yield, water-use efficiency, sugars, vitamin C, and carotenoids differently, and the recommended schedule was stage-specific rather than fixed across the season (Sun et al., 2022). Tomato studies reached the same conclusion: irrigation amount was the primary determinant of yield and WUE, but fruit quality responded differently to fertilizer inputs at seedling, flowering/fruit-set, and peak-fruit stages, so optimization required a multi-objective framework rather than a single yield criterion.