

3.3 Effects of water-fertilizer coupling management on yield performance and production efficiency

Water-fertilizer coupling management affects not only total yield but also yield performance and production efficiency because synchronized resource supply better matches crop demand across reproductive stages. In pear, appropriate coupling treatments promoted root and leaf growth and produced the highest yield, single-fruit weight, and primary fruit rate, showing that coordinated water, nitrogen, and phosphorus inputs improve the structural basis for stable fruit production (Li et al., 2024). In capsicum, moderate irrigation and nitrogen supply produced the highest fruit weight and fruit number per plant, and the I2N2 combination also maximized irrigation water productivity and fertilizer nitrogen use efficiency (Sharma et al., 2025). In jujube, increasing irrigation and nitrogen significantly increased fruit yield, and integrated water-fertilizer regulation improved economic efficiency by reducing mismatches between water and nutrient supply (Zhang et al., 2024).

Meta-analyses show that these responses are general rather than crop-specific. Across China, drip fertigation increased yield by 12.0%, water productivity by 26.4%, and nitrogen use efficiency by 34.3% compared with traditional irrigation and broadcast fertilization, with fruit crops showing especially large gains in nitrogen use efficiency (Li et al., 2021). A second meta-analysis found that water-fertilizer integration with drip irrigation improved yield by 12.5%, NUE by 31.3%, and WUE by 34.5%, and recommended lower-flow drip systems with nitrogen rates reduced by 10~25% from traditional practice. Stage-specific coupling studies in mango and watermelon add an important nuance: the treatment with the highest yield is not always the one with the highest comprehensive efficiency score, because moderate water deficit can reduce input costs and improve WUE while maintaining strong production (Sun et al., 2022; Wu et al., 2026). For *R. chingii*, the practical implication is that water-fertilizer coupling should aim at coordinated and stage-adapted input management to secure stable fruit yield, higher resource-use efficiency, and lower production risk rather than simply maximizing irrigation or fertilizer application.

4 Fruit Quality Formation in *Rubus chingii*

4.1 Effects of water and fertilizer conditions on fruit appearance quality and commercial value

Fruit appearance quality is a core component of the commercial value of *Rubus chingii* because size, firmness, color, and uniformity directly affect market acceptance for both fresh fruit and processed raw material, and these traits are highly responsive to preharvest water and fertilizer management (Jezek et al., 2018; He et al., 2023). Across fruit crops, suitable water and fertilizer supply improves fruit growth and marketable appearance, whereas insufficient or excessive inputs reduce quality by disturbing assimilate allocation and fruit development (Yang et al., 2023). In pear, water and fertilizer control within an appropriate range improved fruit growth and quality, and the best coupling treatment produced the highest fruit shape index, indicating a direct effect on appearance traits linked to commodity value (Li et al., 2024). In blackberry, nitrogen form strongly altered appearance quality, and $\text{NH}_4^+\text{-N}$ improved fruit size, firmness, and color more than other treatments, showing that not only fertilizer amount but also nutrient form can shape the external quality of berry fruit (Duan et al., 2023).

Water regulation also changes visible fruit traits in ways that can either improve appearance or sacrifice yield-related attributes, depending on stress intensity and timing. In table grape, a deficit irrigation program reduced water input by 30% without reducing total yield and promoted berry growth, higher maturity index, and earlier harvest, while biostimulation further increased berry size, berry weight, and the proportion of commercially colored berries (Zapata-García et al., 2025). In Crimson Seedless grape, reducing irrigation from 100% ETc to 40% ETc enhanced berry color, but the highest berry diameter and firmness occurred under full irrigation, and 60% ETc was judged the best compromise for pigmentation and quality with only slight yield penalties. Strawberry studies likewise show that fertilizer regime significantly changes color parameters and firmness, with organic fertilization producing more intensely colored fruit and higher soluble solids but lower firmness than conventional fertilizer (Kılıç et al., 2021). For *R. chingii*, these findings support the expectation that moderate water supply and balanced nutrient management will improve fruit size, color development, and marketability, whereas severe water deficit or unbalanced fertilization will tend to create trade-offs between appearance quality and production stability (Yu et al., 2019; He et al., 2023; Wu et al., 2024).