solute accumulation processes (Zhang et al., 2025). Water stress can activate galactose and sucrose metabolic pathways and increase the activities of sucrose synthase and sucrose phosphate synthase, thereby promoting the conversion of starch into soluble sugars. Organic acid responses generally show similar patterns. He et al. (2024) reported that deficit irrigation increased organic acid accumulation in greenhouse tomato fruits. Moderate water deficit promoted the accumulation of tartaric acid, malic acid, shikimic acid, α-ketoglutaric acid, and succinic acid, while reducing oxalic acid and citric acid contents. The decrease in fruit pH under limited irrigation conditions also indicates enhanced fruit acidity, which may contribute to improved flavor characteristics (Habibi et al., 2025).

However, the response of sugar and organic acid metabolism to water regulation is not always consistent and is influenced by growth stage, harvest maturity, genotype, and irrigation method. For example, Poomkokrak et al. (2024) found that glucose content in cherry tomato fruits did not differ significantly among different irrigation regimes. Therefore, although moderate water deficit generally favors the accumulation of sugars and flavor-related compounds, its effects should be evaluated according to specific production conditions.

5.2 Effects of irrigation on nutritional quality

Vitamin C is one of the most consistent nutritional quality indicators responding to moderate water deficit in tomato fruits. Compared with full irrigation, regulated deficit irrigation generally increases vitamin C content. In a limited irrigation study, Habibi et al. (2025) reported that vitamin C concentration increased from 49 to 64 mg/100 g fresh weight, while electrolyte leakage decreased, indicating that water regulation not only enhanced antioxidant capacity but also improved cell membrane integrity. In greenhouse drip fertigation systems, Zhang et al. (2025) found that both reduced irrigation amount and shorter irrigation intervals increased vitamin C content, which may be associated with improved fruit light exposure due to a smaller canopy structure and enhanced ascorbic acid synthesis.

In addition to vitamin C, deficit irrigation can enhance the overall antioxidant system of tomato fruits, including soluble proteins, proline, total phenolics, total flavonoids, and comprehensive antioxidant activity (Jin et al., 2022). In processing tomatoes, regulated deficit irrigation increased total phenolic content by 20.58% (Burato et al., 2024). Other greenhouse studies have also shown that deficit irrigation improves antioxidant capacity and increases flavonoid and phenolic compound contents, although the magnitude of these responses varies among product types and cultivars (Bogale et al., 2016; Liava et al., 2023).

Lycopene and related carotenoids generally increase under moderate water stress, although their responses show stronger genotype dependence compared with vitamin C. He et al. (2024) reported that moderate deficit irrigation during fruit ripening increased lycopene, lutein, α-carotene, and β-carotene contents by 11.85%, 12.28%, 20.87%, and 63.89%, respectively. In black cherry tomatoes, deficit irrigation increased carotenoid levels while maintaining fruit size and weight (Coyago-Cruz et al., 2022). Salinity-related water stress has also been shown to enhance lycopene, β-carotene, total phenolics, soluble solids, firmness, and vitamin C contents at harvest or during storage. However, tomato cultivars do not always exhibit consistent responses to water regulation. Bogale et al. (2016) found that deficit irrigation increased lycopene and vitamin C contents in the ‘Matina’ cultivar but reduced these quality parameters in ‘Cochoro’. Early-stage water management may also have long-lasting effects on subsequent fruit nutritional quality. Tömösközi-Farkas et al. (2024) demonstrated that plants cultivated under 50% irrigation combined with water-retaining agents produced fruits with the highest lycopene, vitamin C, antioxidant capacity, and total phenolic content during later production stages.

5.3 Effects of water management on fruit appearance quality

Water management has substantial effects on tomato fruit size, firmness, and cracking incidence, although different quality traits do not always respond to water changes in the same manner. Studies have shown that deficit irrigation reduces fruit size and weight, whereas restricted irrigation improves fruit firmness but is often accompanied by smaller fruits (Habibi et al., 2025). However, moderate water regulation can maintain or optimize fruit size. Poomkokrak et al. (2024) reported that in cherry tomato production, irrigation once every three days