Machine learning-assisted decision-making systems further improve smart irrigation by integrating sensor data with predictive models to dynamically optimize irrigation strategies. In tomato production, machine learning-guided irrigation systems achieved water productivity comparable to full irrigation under regulated deficit irrigation or moderate deficit conditions, saved approximately 33% of water during high-temperature seasons, and improved fruit quality (Martelli et al., 2025). However, the sensitivity of these models to high-temperature environments and crop stress conditions still requires further improvement.

6.3 Integration of irrigation and fertilization management

Water and nutrient management require coordinated regulation because tomato growth, yield, and quality are jointly determined by water and nutrient availability rather than irrigation level alone. Drip fertigation improves the synchronization of water and nutrient supply in the root zone, reduces nutrient leaching associated with conventional irrigation methods, and is particularly important for indeterminate greenhouse tomatoes, where vegetative and reproductive growth stages overlap for an extended period (Singh et al., 2023). A greenhouse experiment by Lyu et al. (2025) showed that combining suitable or mild deficit irrigation with integrated fertilization management improved yield, water-use efficiency, nitrogen uptake capacity, and root-shoot coordination. For example, maintaining soil moisture at 72%-80% of field capacity combined with soluble organic fertilizer and chemical fertilizer application achieved high yield while improving water-use efficiency and nitrogen uptake compared with higher or lower irrigation treatments. A stage-specific coupling study under substrate cultivation also demonstrated that irrigation amount was the primary factor affecting yield and water-use efficiency, whereas fertilizer supply during flowering and fruit-setting stages played an important role in final production efficiency, highlighting the need to match water and nutrient supply with tomato growth requirements (Song et al., 2025).

Strategies for improving water and fertilizer use efficiency are gradually shifting from fixed management regimes toward integrated optimization models. For example, a decision-making model based on dynamic plant morphological feedback adjusted irrigation and fertilization schemes according to changes in plant height and stem diameter. Compared with fixed management practices, this approach increased fruit yield by 6.9%-14.7% and improved water-use efficiency by 6.93%-43.17%, demonstrating the potential of real-time regulation based on crop growth information (Zuo et al., 2025). The integration of water, fertilizer, and oxygen management provides further opportunities for optimization. Lei et al. (2023) reported that oxygen-enriched subsurface drip irrigation increased yield by 4.25% compared with fixed water management and by 26.13% compared with non-aerated irrigation. The optimized combination included an irrigation amount of 420 mm, dissolved oxygen concentration of approximately 24.55 mg/L, and nitrogen input of 281.43 kg N/ha.

7 Comprehensive Effects and Production Applications of Irrigation Regulation

7.1 Balance between yield and quality under different irrigation regimes

Higher irrigation levels generally promote vegetative growth and increase total tomato yield, but they may also dilute quality-related components, including soluble solids, sugars, vitamin C, and organic acids, thereby reducing fruit quality (Wu et al., 2021). Full irrigation can achieve higher absolute yield; however, it is often accompanied by greater water consumption and lower water-use efficiency. In contrast, severe water deficit generally improves nutritional composition and flavor-related traits but restricts plant growth, reduces fruit size, and may decrease fruit number (Alshami et al., 2023).

Studies have shown that moderate deficit irrigation can achieve a more favorable balance between yield and quality. A four-season greenhouse experiment demonstrated that 75% ETc irrigation reduced the proportion of non-marketable fruits, improved fruit size distribution, and increased marketable yield water-use efficiency, providing better overall benefits than full irrigation. Lyu et al. (2025) also found that mild deficit irrigation maintained relatively high yield while improving root-to-shoot ratio, nitrogen uptake capacity, and water-use efficiency, with stronger effects when combined with appropriate fertilization. Similar results were observed in growth stage-based deficit irrigation studies, where fruit quality showed greater sensitivity to water supply