variation than to nitrogen supply. Moderate deficit irrigation applied during both early and late fruit ripening stages resulted in improved overall performance (Wang et al., 2015).

However, yield and quality responses do not always change simultaneously. Under reduced irrigation conditions, some treatments primarily affect fruit development timing or fruit number distribution rather than total yield across the entire production cycle. This indicates a partial decoupling between quality improvement and production capacity under water regulation (Tringovska et al., 2026). In practical production, irrigation management should be adjusted according to market requirements and production objectives, with a comprehensive balance among yield stability, fruit quality, and resource-use efficiency rather than focusing on a single target.

7.2 Environmental factors affecting irrigation performance

The effectiveness of irrigation is influenced by greenhouse environmental conditions, including temperature, humidity, light intensity, and ventilation. Light intensity and fruit temperature are considered important environmental factors affecting tomato quality formation and shelf life, whereas relative humidity and irrigation regimes mainly regulate fruit firmness, water loss, and the occurrence of physiological disorders (Fanourakis et al., 2025). Ge et al. (2022) reported that greenhouse tomato evapotranspiration is closely associated with microclimatic conditions. Net solar radiation, average temperature, and maximum temperature increase evapotranspiration, while higher relative humidity reduces evapotranspiration. Therefore, irrigation strategies should be dynamically adjusted according to greenhouse environmental changes and actual atmospheric evaporative demand.

Ventilation generally has a stronger regulatory effect on greenhouse temperature and humidity conditions than irrigation management alone, particularly during flowering, fruit development, and harvesting stages. Xue et al. (2023) found that ventilation treatments had limited effects on yield but significantly influenced vitamin C content and sugar-acid ratio. Among different management combinations, the T2W2 treatment provided a favorable balance between yield and fruit quality. During high-temperature periods, irrigation strategies require further optimization. The combination of micro-sprinkler irrigation and drip irrigation can reduce air and leaf temperatures, increase relative humidity, improve photosynthesis and stomatal conductance, and increase tomato yield by 40.4%. This improvement was mainly attributed to reduced flower damage and increased fruit number.

Irrigation methods should also be coordinated with greenhouse production systems. Under mulching conditions, micro-sprinkler irrigation increased tomato yield compared with drip irrigation or non-mulched treatments. However, the response of yield to irrigation amount followed a quadratic relationship, with 1.0 Epan providing a more suitable irrigation target than the highest irrigation level (Zhang et al., 2022). These results indicate that irrigation optimization depends not only on water supply amount but also requires integrated consideration of greenhouse structure, mulching practices, and environmental regulation measures.

7.3 Application prospects in sustainable greenhouse tomato production

An important future direction for sustainable greenhouse tomato production is the development of efficient water-saving systems integrating moderate deficit irrigation, drip irrigation, fertigation, and real-time monitoring and control technologies. Sensor-based smart irrigation can maintain stable root-zone moisture conditions and significantly improve plant growth and yield performance compared with management strategies involving prolonged water fluctuations (Dirlik et al., 2025). Meanwhile, advances in modeling approaches and machine learning technologies further enhance precision irrigation capacity by predicting greenhouse evapotranspiration and crop yield responses, enabling dynamic irrigation scheduling under complex climatic conditions (Ge et al., 2022; Locatelli et al., 2024).

Sustainable protected agriculture requires not only optimization of field-scale irrigation management but also improved water recycling and resource utilization. For example, a recycled water and nutrient system in rooftop greenhouses maintained tomato yield while reducing water consumption per unit tomato mass from 75.2 L to 48.7