sugar-acid balance and vitamin C content, and at the same time reduce overall fertilizer input (Nakro et al., 2023). However, excessively high nutrient concentrations or long-term use of a "single formula" often lead to nutrient imbalance and salt accumulation. Moderately reducing concentration (e.g., to 65% of the standard level) may maintain yield in short-cycle production, but in long-cycle cultivation from autumn to spring, it may reduce yield.

Irrigation scheduling has a strong influence on nutrient supply and leaching losses. Timer-based fertigation or high leaching fractions (20%~40% of applied water) are common, but they often result in over-irrigation (Savvas et al., 2024). Sensor-based strategies, such as using substrate volumetric water content (VWC) or combined VWC-EC thresholds, allow fertigation only when needed. This approach can reduce water use by 26%~38% and nutrient solution consumption by up to 38%, while increasing marketable yield and improving water and nutrient use efficiency by 46%~74%, clearly outperforming timer-based control (Hutchinson et al., 2025a).

Experiments with different irrigation frequencies show that dividing fertigation into multiple daily applications (e.g., four times per day), compared with low-frequency irrigation, significantly promotes vegetative growth, increases early yield, improves fruit quality, and enhances leaf and root biomass (Malekzadeh et al., 2024). In addition, partial deficit irrigation strategies (such as alternating wet and dry conditions in half of the root zone volume) can save up to 50% of water and fertilizer inputs without reducing yield, while improving fruit quality by limiting excessive vegetative growth (Alavi et al., 2025).

5.2 Controlled-release fertilizers

Controlled-release and slow-release fertilizers (CRFs/SRFs) release nutrients gradually, better matching crop demand. Compared with conventional quick-release fertilizers, they can significantly reduce nutrient losses caused by leaching, volatilization, and denitrification (Jariwala et al., 2022; Duan et al., 2023). In greenhouse strawberry production, the use of controlled-release fertilizers can increase plant height, stem diameter, leaf area, photosynthetic rate, chlorophyll content, root activity, and fresh fruit yield by more than 10%, while maintaining high agronomic efficiency of nitrogen, phosphorus, and potassium.

Compared with conventional fertilizers, controlled-release fertilizers are more effective in maintaining fruit quality, such as vitamin C content and flavor. In contrast, traditional fertilizers often have higher initial salt concentrations, which may reduce sensory quality. Long-term soil experiments have shown that the use of controlled-release compound fertilizers in strawberry cultivation increases plant nitrogen and phosphorus content and forms a nutrient release pattern that matches the needs of different growth stages. Soil available nutrients increase first and then decrease, avoiding excessive accumulation.

5.3 Recirculating vs. non-recirculating systems

Nutrient solution management can be divided into open (free drainage) and closed (recirculating) systems. Open systems usually operate with high leaching fractions. They are simple to manage but have low nutrient use efficiency (NUE) and can easily cause nitrate and phosphate pollution.

Closed recirculating systems collect and reuse drainage solution, which can reduce water consumption by about 20%~40% and fertilizer use by 40%~50%, while almost eliminating nutrient discharge (Savvas et al., 2024). In greenhouse strawberry production, a well-managed closed hydroponic system, combined with nutrient correction every 2~4 weeks based on drainage ion analysis, can maintain yields comparable to open systems. At the same time, nutrient use efficiency can increase by 32%~36% compared with uncorrected systems and by up to 94% compared with open systems (Lim et al., 2024).

If the recirculation process is controlled only by drainage EC, salt accumulation and ion imbalance may occur over time, reducing yield and requiring periodic discharge. Therefore, ion monitoring and precise regulation are essential. In addition, when strawberry drainage is reused for other crops (such as maize), improper evaluation of its fertilizer value and application rate may lead to soil salinization, reflecting environmental risks associated with unregulated discharge (Kopeć et al., 2020).

Life cycle assessment studies also show that in hydroponic vegetable systems, closed-loop recirculation can reduce eutrophication impacts by 35%~54%. Although additional infrastructure may slightly increase energy use and carbon emissions, this can be offset by higher yields and long-term system use (Rufí-Salís et al., 2020).