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# Assessment of Hydrogen Peroxide Potential in Mitigating Salinity Stress on Growth and Yield of *Zea mays* (L.) - Maize

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**Abstract** Salt stress is one of the major limitations of seed germination, plant growth, productivity and nutritional composition. Hydrogen peroxide ($H_2O_2$) functions as a signalling molecule that modulates physiological and biochemical processes under abiotic stress. Therefore, this research was conducted to assess the potential of $H_2O_2$ in mitigating adverse effects of salinity stress on the growth and yield of *Zea mays* (L.). The experiment was conducted in a screenhouse using 96 pots each filled with 14 kg topsoil and arranged in a completely randomized design with eight replicates per treatment. Maize seedlings raised were grouped into two: Each pot in Group A was irrigated with sodium chloride (NaCl) solution and supplemented with 50 ml of 3% $H_2O_2$ (882 mM) which was applied to the soil, while each pot in Group B received NaCl solution without $H_2O_2$. Salinity treatments were applied at 0 (control), 50, 100, 150, 200, and 250 mM NaCl three times per week and flushed once per week to prevent salt accumulation. Growth, yield, biomass, leaf chlorophyll as well as grain nutritional composition were assessed following standard procedures, and data were analysed using One Way Analysis of Variance at $p \leq 0.05$. Plant height declined the most from 160.76 cm in control to 112.19 cm at 250 mM NaCl without $H_2O_2$, while $H_2O_2$ treated plants at the same salinity decreased to only 123.52 cm. However, other growth parameters were not significantly enhanced by $H_2O_2$. The effect of salinity on number of grains per plant was positively influenced by $H_2O_2$ as salinity decreased it from 226.25 to 84.50 without $H_2O_2$, but $H_2O_2$-treated plants maintained up to 88.12 per plant at 250 mM. Salinity treatments devoid of $H_2O_2$ had protein reduced from 15.14% to 13.44%, fat from 1.88% to 1.74%, and crude fibre from 3.40% to 2.74%. However, salinity with $H_2O_2$ treatment sustained higher values (14.31%, 2.41%, and 2.80%, respectively). This study demonstrates that hydrogen peroxide can mitigate salinity-induced stress on growth and productivity in maize, supporting its potential role as a stress modulator in crop production under saline conditions.

**Keywords** Salt stress; Hydrogen peroxide; Salinity tolerance; *Zea mays*

## 1 Introduction

Maize (*Zea mays* L.) is a major cereal crop globally, serving as a staple food for millions and a vital component of the agricultural economy (Yadesa and Diro, 2023). Its significance stems from high yield potential, economic value, and broad adaptability. The global annual production of maize exceeds 1 billion metric tons, with leading producers including the United States of America, China, Brazil, and various African countries (Galani et al., 2022). In Nigeria, maize plays a critical role in food security and rural livelihoods, being widely cultivated across subsistence and commercial farming systems (Ogunniyi et al., 2021). Maize is rich in carbohydrates, providing essential energy, and contains key micronutrients such as vitamin A, iron, and zinc, essential for human nutrition (Galani et al., 2022; Kihara et al., 2024). Its industrial importance is underscored by its use in livestock feed and as raw material for bioethanol, starch, and biodegradable plastics (Maitra and Singh, 2021).

Despite this importance, maize productivity faces considerable challenges from abiotic stresses like soil salinity, which severely limit plant growth, yield, and nutritional quality (Syed et al., 2021; Islam et al., 2024). Soil salinity, typically resulting from excessive sodium chloride accumulation, disrupts water uptake, ionic balance, and induces oxidative stress through reactive oxygen species (ROS), including hydrogen peroxide ($H_2O_2$) (Al Otaibi et al., 2024). These biochemical imbalances cause reductions in photosynthesis, biomass, and ultimately grain yield (Zhu et al., 2023).

Several mitigation strategies have been explored to combat salinity stress, including breeding salt-tolerant genotypes, soil amendments, and exogenous application of biostimulants (Haque et al., 2021; Irin and Hasanuzzaman, 2024). Among these, hydrogen peroxide has gained attention as a signaling molecule modulating physiological responses under abiotic stress through activation of antioxidant defenses and osmotic adjustment mechanisms (Kesawat et al., 2023). Exogenous $H_2O_2$ application at low concentrations promotes antioxidant enzyme activities such as superoxide dismutase, catalase, and peroxidase, thereby reducing oxidative damage and improving salinity tolerance (Chattha et al., 2022). Moreover, $H_2O_2$ enhances nutrient uptake and water use efficiency in salt-stressed plants (Iqbal et al., 2023).

However, while $H_2O_2$'s role in mitigating salinity effects has been studied in several crops, its influence on maize performance under saline conditions remains underexplored. Given maize's critical role in food security and its vulnerability to salt stress, there is a pressing need to evaluate the potential of hydrogen peroxide as a sustainable management option for salinity mitigation in maize cultivation. This study, therefore, aims to assess the effect of $H_2O_2$ application on growth, yield, and grain nutritional composition of maize subjected to varying levels of salinity stress.

## 2 Materials and Methods

### 2.1 Location of the experiment

This experiment was carried out at the screen house of the Department of Plant Science & Biotechnology (PSB), Adekunle Ajasin University, Akungba-Akoko (AAUA), Ondo State, Nigeria (latitude 7.2 $^0$N, longitude 5.44 $^0$E).

### 2.2 Sources of materials for the experiment

Seeds of *Zea mays* (maize) were obtained from the Federal College of Agriculture, Akure, Ondo State (FECA), Nigeria. The salt (NaCl) and Hydrogen peroxide ($H_2O_2$) were obtained from the laboratory, and the soil used for planting was collected from the experimental plots of PSB Department, AAUA. The soil was analyzed for physical and chemical properties using the standard methods of AOAC (1985). It was shade-dried and passed through a 2-mm sieve. Total N was analyzed using the macro Kjeldahl procedure; organic carbon by Walkley and Black procedure with percentage derived by multiplying organic carbon content by 1.72; and pH using soil: water ratio of 1:2 with a pH meter. Available phosphorus was got through the Bray 1 method; exchangeable acidity by titration method; exchangeable K, Na, Ca, Al and Mg by extraction with 1 M ammonium acetate at pH 7.0; and the amount of K and Na was measured using a Corning Flame Photometer with appropriate filter, while Ca, Al and Mg were determined using a Perkin-Elmer Atomic Absorption Spectrophotometer (AAS). The electrical conductivity was read with a conductivity meter.

### 2.3 Soil collection and preparation

Topsoil (0~15 cm depth) was collected from an arable farmland within the premises of Adekunle Ajasin University, Akungba-Akoko, Ondo State. The soil was sieved to remove debris and thoroughly mixed to obtain a homogeneous medium. Approximately 14 kg of prepared soil was placed into each perforated polythene pot. Maize was grown in perforated polythene pots filled with 14 kg of the prepared topsoil. Three maize seeds were sown per pot, and seedlings were allowed to establish before thinning to one seedling per pot prior to the commencement of treatments.

### 2.4 Experimental setup

A total of 96 pots were grouped into two (Groups A and B), each consisting of 48 pots. The potted soils on which the maize seedlings were grown were irrigated three weeks after planting with sodium chloride (NaCl) solution at concentrations of 0 (control), 50, 100, 150, 200, and 250 mM three times in the week of planting. Each potted soil in Group A received 50 ml of 3% hydrogen peroxide ($H_2O_2$) solution the following week equivalent to 882 mM, while pots in Group B received no $H_2O_2$ treatment. All pots were watered to saturation and allowed to drain once per week to prevent salt accumulation beyond intended concentrations. Pots were arranged in a completely randomized design with eight replicates per treatment in the screenhouse.

### 2.5 Data collection
Plant height was measured from the surface of the soil to the plant apical bud using a meter rule. Stem girth was measured at the 2 cm point from the base of the plants using a digital vernier caliper. Leaf length and breadth were measured using a meter rule, and leaf area was calculated. The number of leaves and ears were counted manually on each plant. Ear length and diameter were measured using a meter rule, and a vernier caliper respectively. Root growth was determined by measuring the root length using a meter rule after uprooting, and the number of roots was counted manually. Fresh and dry mass of plant parts were assessed using an electronic weighing balance.

### 2.6 Laboratory analysis of maize grains
Dried maize grains were ground into fine powder for analysis. Fiber content was determined by boiling the sample in 1.25% $H_2SO_4$ and 1.25% NaOH, followed by washing and drying. Other parameters of proximate composition were analyzed using the standard methods of AOAC (1985) in which the mixture was boiled until a clear solution was obtained and allowed to cool at room temperature. The resulting solution was quantitatively transferred into a calibrated flask and completed to 25 mL with distilled water. Moisture, crude protein, crude fat, carbohydrate and ash contents were calculated using relevant formulas. N was analyzed using the macro Kjeldahl method, while P was determined using ammonium-vanadomolybdate reagent and a calibration curve. Potassium contents were assayed through flame emission photometry, and calcium contents by Ethylenediaminetetraacetic acid (EDTA) titration.

### 2.7 Statistical analysis
All data collected were subjected to One-Way Analysis of Variance (ANOVA) using the Statistical Package for Social Sciences (SPSS), version 27.0. Where significant differences were observed among treatment means, Tukey's Honest Significant Difference (HSD) test was used at a 95% confidence level to perform post-hoc comparisons, and values presented as mean ± standard error (SE).

## 3 Results
### 3.1 Soil used for planting
The soil used for planting was a sandy clay loam adequate for maize cultivation with physico-chemical characteristics shown in Table 1.

Table 1 Physico-chemical parameters of soil used for planting

| Parameter | Value |
|---|---|
| Sand (%) | 57.50 |
| Clay (%) | 29.37 |
| Silt (%) | 13.13 |
| Soil textural class | Sandy clay loam |
| Soil pH | 6.53 |
| Electrical conductivity EC (%) | 0.39 |
| Organic matter (%) | 1.56 |
| Available N (mg/kg) | 0.17 |
| Available P (mg/) kg | 20.11 |
| Available K (cmol/kg) | 0.22 |
| Available Na (cmol/kg) | 0.37 |
| Available Ca (cmol/kg) | 5.78 |
| Available Al (cmol/kg) | 20.58 |
| Available Mg (cmol/kg) | 2.23 |

### 3.2 Plant survival and growth
Table 2 shows the influence of hydrogen peroxide ($H_2O_2$) on the plant height, stem girth, number of leaves, leaf length, leaf breadth, leaf area, number of roots, root length and the number of tassels of *Zea mays* under salt stress. While all plants survived, salinity reduced plant height in both hydrogen peroxide treated and untreated plants (Figure 1). However, no significant difference was observed between the control and the salinity treated plants with hydrogen peroxide application at lower levels, though at 250 mM NaCl, $H_2O_2$ treated plants maintained

123.52 cm compared to 112.19 cm without $H_2O_2$. In contrast, plants exposed to salt stress without hydrogen peroxide were generally shorter than the control, with significant reductions occurring at higher NaCl concentrations (200~250 mM).

Table 2 Growth parameters of *Zea mays* under salinity treatments with and without Hydrogen peroxide ($H_2O_2$) application

| Parameters | With and without HP | Salinity treatment (mM NaCl) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 50 | 100 | 150 | 200 | 250 |
| Survival (%) | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| Plant height (cm) | WHP | 160.76±2.69$^{c}$ | 119.69±0.29$^{b}$ | 119.40±0.30$^{b}$ | 114.69±0.87$^{ab}$ | 113.99±0.50$^{ab}$ | 112.19±0.29$^{ab}$ |
| | PHP | 173.08±1.26$^{c}$ | 150.12±0.47$^{b}$ | 123.76±0.28$^{ab}$ | 118.52±0.26$^{a}$ | 120.62±0.25$^{a}$ | 123.52±0.27$^{a}$ |
| Stem girth (cm) | WHP | 27.23±0.08$^{a}$ | 22.83±0.22$^{a}$ | 21.13±0.21$^{a}$ | 19.76±0.27$^{ab}$ | 18.49±0.06$^{ab}$ | 18.11±0.13$^{ab}$ |
| | PHP | 25.30±0.06$^{a}$ | 22.95±0.08$^{a}$ | 22.12±0.08$^{a}$ | 18.52±0.05$^{a}$ | 17.57±0.04$^{a}$ | 17.55±0.03$^{a}$ |
| Number of leaves | WHP | 13.00±0.00$^{a}$ | 12.75±0.16$^{a}$ | 12.63±0.18$^{a}$ | 12.00±0.19$^{a}$ | 11.25±0.16$^{a}$ | 10.87±0.13$^{a}$ |
| | PHP | 13.00±0.00$^{a}$ | 14.00±0.00$^{a}$ | 12.75±0.16$^{a}$ | 12.00±0.00$^{a}$ | 12.00±0.00$^{a}$ | 12.00±0.00$^{a}$ |
| Leaf length (cm) | WHP | 25.35±0.04$^{a}$ | 21.43±0.13$^{a}$ | 20.35±0.05$^{a}$ | 19.79±0.23$^{a}$ | 19.49±0.15$^{a}$ | 20.71±1.28$^{a}$ |
| | PHP | 23.53±0.18$^{a}$ | 20.05±0.06$^{ab}$ | 19.52±0.05$^{ab}$ | 19.70±0.00$^{ab}$ | 19.78±0.23$^{ab}$ | 19.46±0.05$^{ab}$ |
| Leaf breadth (cm) | WHP | 9.80±0.05$^{a}$ | 7.98±0.04$^{a}$ | 7.6±0.03$^{a}$ | 7.25±0.02$^{a}$ | 7.20±0.04$^{a}$ | 7.07±0.03$^{a}$ |
| | PHP | 9.58±0.05$^{a}$ | 9.13±0.04$^{a}$ | 7.93±0.0.3$^{a}$ | 7.46±0.42$^{a}$ | 7.31±0.03$^{a}$ | 7.36±0.04$^{a}$ |
| Leaf area ($cm^2$) | WHP | 133.02±0.67$^{a}$ | 124.15±0.39$^{ab}$ | 114.74±0.25$^{b}$ | 107.82±0.78$^{b}$ | 109.10±0.31$^{b}$ | 105.25±0.16$^{b}$ |
| | PHP | 127.51±0.74$^{a}$ | 124.48±0.39$^{a}$ | 114.28±0.32$^{ab}$ | 107.00±0.11$^{b}$ | 104.230.16$^{b}$ | 103.99±0.08$^{b}$ |
| Number of roots | WHP | 32.25±0.59$^{a}$ | 31.88±0.30$^{a}$ | 26.25±0.45$^{ab}$ | 19.87±0.44$^{ab}$ | 23.50±0.65$^{ab}$ | 22.88±0.67$^{ab}$ |
| | PHP | 32.25±0.49$^{a}$ | 28.62±1.49$^{b}$ | 23.25±0.37$^{bc}$ | 20.37±0.50$^{bc}$ | 22.75±0.31$^{bc}$ | 22.50±0.27$^{bc}$ |
| Root length (cm) | WHP | 64.66±2.87$^{a}$ | 44.17±0.56$^{b}$ | 42.03±0.79$^{b}$ | 40.87±2.63$^{b}$ | 33.53±0.46$^{c}$ | 37.73±4.39$^{c}$ |
| | PHP | 66.76±2.04$^{a}$ | 55.48±0.63$^{b}$ | 54.68±1.84$^{b}$ | 43.30±0.10$^{bc}$ | 36.40±1.27$^{bc}$ | 45.88±0.69$^{bc}$ |
| Number of tassels | WHP | 11.38±0.26$^{a}$ | 11.50±0.19$^{a}$ | 11.37±0.18$^{a}$ | 11.25±0.16$^{a}$ | 11.12±0.23$^{a}$ | 12.38±0.18$^{a}$ |
| | PHP | 11.63±0.26$^{a}$ | 11.37±0.18$^{a}$ | 11.25±0.16$^{a}$ | 11.50±0.19$^{a}$ | 11.62±0.26$^{a}$ | 11.75±0.25$^{a}$ |

Note: Values are mean ± standard error of 8 replicates (Tukey HSD test at $p \leq 0.05$). Mean with the same alphabet(s) along the row are not significantly different from each other. PHP: plus hydrogen peroxide ($H_2O_2$); WHP: without hydrogen peroxide ($H_2O_2$)


Figure 1 Effect of salinity stress with hydrogen peroxide (A) and without hydrogen peroxide (B) on *Zea mays* growth

Stem girth was influenced by salinity, with hydrogen peroxide treated plants showing minor improvements at 50~150 mM NaCl compared to the control. However, at 200~250 mM NaCl, stem girth declined, though the reduction was less than without hydrogen peroxide. Without hydrogen peroxide, stem girth generally decreased under salinity, with significant reductions observed at higher NaCl levels.

Leaf production was also affected by salinity. At lower concentrations (50~100 mM NaCl), plants produced similar or slightly fewer leaves than the control, though the change was not significant. However, at higher concentrations (150~250 mM NaCl), leaf production declined, though the reduction was not significantly different from the control in many cases. Similarly, in plants grown without hydrogen peroxide, the number of leaves decreased under salinity, with more pronounced reductions at 200~250 mM NaCl compared to the control. Leaf length, breadth, and area followed similar trends, with hydrogen peroxide providing partial mitigation, resulting in less severe declines than without it, likely due to improved osmotic regulation. The number of tassels remained relatively stable under salinity, with hydrogen peroxide having a negligible effect, indicating reproductive initiation was less impacted than vegetative growth.

At the end of the experiment, root growth parameters (number and length) varied depending on hydrogen peroxide treatment and salt concentration. At 50~150 mM NaCl, plants treated with hydrogen peroxide ($H_2O_2$) had better root development compared to those without. However, at 200~250 mM NaCl, root parameters declined more sharply without hydrogen peroxide($H_2O_2$).

### 3.3 Plant biomass

Salinity stress significantly reduced the vegetative biomass (fresh and dry weights of roots, stems, and leaves) of Zea mays in both hydrogen peroxide ($H_2O_2$) treated (PHP) and without hydrogen peroxide ($H_2O_2$) (WHP) plants, with reductions intensifying at higher NaCl concentrations (200~250 mM) as shown in Table 3. Without hydrogen peroxide, fresh and dry weights of roots, stems, and leaves decreased markedly, reflecting impaired cell division and photosynthetic efficiency due to osmotic stress and ion toxicity. For instance, at 250 mM NaCl, root dry weight was significantly lower compared to the control.

In contrast, $H_2O_2$ treated plants exhibited less severe biomass reductions across all salinity levels. At 50~150 mM NaCl, hydrogen peroxide ($H_2O_2$) treated (PHP) sustained higher fresh and dry weights for roots, stems, and leaves compared to without hydrogen peroxide ($H_2O_2$) (WHP) plants, indicating improved water retention and metabolic activity. At 250 mM NaCl, hydrogen peroxide ($H_2O_2$) treated (PHP) plants still showed higher biomass than without hydrogen peroxide ($H_2O_2$) (WHP), though not fully restored to control levels. This suggests hydrogen peroxide mitigated salinity induced stress by enhancing antioxidant defenses and osmotic adjustment, partially preserving biomass accumulation as shown in Table 3.

Table 3 Vegetative biomass of *Zea mays* under salinity treatments with and without Hydrogen peroxide ($H_2O_2$) application

| Growth parameters (g) | With and without HP | Salinity treatment (mM NaCl) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 50 | 100 | 150 | 200 | 250 |
| Leaf fresh weight | WHP | 64.91±1.05$^{a}$ | 47.60±0.81$^{b}$ | 46.85±0.58$^{b}$ | 39.28±1.00$^{bc}$ | 39.65±0.29$^{bc}$ | 30.90±5.35$^{c}$ |
| | PHP | 61.90±3.09$^{a}$ | 47.56±1.48$^{b}$ | 37.50±1.59$^{bc}$ | 46.96±1.07$^{bc}$ | 41.13±0.78$^{bc}$ | 44.32±0.35$^{b}$ |
| Stem fresh weight | WHP | 142.63±1.30$^{a}$ | 105.31±0.81$^{b}$ | 103.30±1.45$^{b}$ | 54.22±0.22$^{c}$ | 38.05±1.03$^{c}$ | 35.15±0.57$^{c}$ |
| | PHP | 149.90±0.39$^{a}$ | 113.56±0.82$^{b}$ | 102.98±0.13$^{b}$ | 61.92±0.41$^{c}$ | 41.58±0.36$^{d}$ | 35.03±0.38$^{d}$ |
| Root fresh weight | WHP | 52.84±0.15$^{a}$ | 37.94±1.50$^{b}$ | 33.45±0.41$^{b}$ | 24.45±0.58$^{c}$ | 28.26±0.94$^{c}$ | 28.13±0.43$^{c}$ |
| | PHP | 55.13±0.57$^{a}$ | 42.77±0.62$^{b}$ | 43.05±0.81$^{b}$ | 34.20±0.71$^{c}$ | 32.62±0.81$^{c}$ | 35.28±0.59$^{c}$ |
| Leaf dry weight | WHP | 39.98±2.10$^{a}$ | 32.87±1.93$^{a}$ | 28.12±1.56$^{bc}$ | 21.11±0.78$^{bc}$ | 17.78±0.17$^{c}$ | 15.41±0.16$^{c}$ |
| | PHP | 30.16±0.49$^{a}$ | 30.66±0.23$^{a}$ | 29.72±0.17$^{a}$ | 23.00±0.19$^{b}$ | 15.92±0.11$^{bc}$ | 15.07±0.17$^{bc}$ |
| Stem dry weight | WHP | 72.20±0.44$^{a}$ | 65.62±0.85$^{b}$ | 52.10±0.53$^{b}$ | 35.26±0.69$^{c}$ | 31.21±1.55$^{c}$ | 22.36±0.46$^{d}$ |
| | PHP | 69.12±0.52$^{a}$ | 68.03±0.50$^{a}$ | 64.25±0.32$^{a}$ | 57.47±1.31$^{b}$ | 27.80±0.53$^{c}$ | 27.75±0.21$^{c}$ |
| Root dry weight | WHP | 33.47±0.38$^{a}$ | 29.36±0.66$^{b}$ | 22.27±0.18$^{b}$ | 20.19±0.32$^{b}$ | 24.61±0.84$^{b}$ | 25.11±0.59$^{b}$ |
| | PHP | 34.15±0.55$^{a}$ | 23.25±0.41$^{b}$ | 23.66±0.83$^{b}$ | 25.10±1.31$^{b}$ | 24.66±0.65$^{b}$ | 23.23±0.42$^{b}$ |
| Total biomass | WHP | 145.24±2.21$^{a}$ | 128.58±2.0$^{b}$ | 102.80±1.52$^{c}$ | 76.63±1.16$^{d}$ | 73.71±1.69$^{d}$ | 62.90±0.71$^{d}$ |
| | PHP | 133.43±0.72$^{a}$ | 121.92±0.77$^{ab}$ | 117.65±0.88$^{ab}$ | 105.57±0.97$^{ab}$ | 68.38±0.93$^{c}$ | 65.71±0.47$^{c}$ |

Note: Values are mean ± standard error of 8 replicates (Tukey HSD test at $p \leq 0.05$). Mean with the same alphabet(s) along the row are not significantly different from each other. PHP: plus hydrogen peroxide ($H_2O_2$); WHP: without hydrogen peroxide ($H_2O_2$)

### 3.4 Yield parameter

Salinity significantly reduced yield components, including ear number, ear length, grain number, and grain weight per plant (Table 4), with the most pronounced effects at 250 mM NaCl. Without hydrogen peroxide ($H_2O_2$) (WHP), the number of grains per plant dropped from 226.25 in the control to 84.50 at 250 mM, reflecting disrupted assimilate allocation and kernel development due to salinity stress.

Hydrogen peroxide ($H_2O_2$) treated (PHP) plants showed improved yield parameters across all salinity levels. At 250 mM NaCl, PHP maintained grain numbers at 88.12 per plant, a slight but notable improvement over without hydrogen peroxide ($H_2O_2$) (WHP). Ear number and weight were also less reduced in Hydrogen peroxide ($H_2O_2$) treated (PHP) plants, particularly at moderate salinities (50~150 mM), suggesting hydrogen peroxide supported reproductive development by reducing oxidative damage and improving nutrient mobilization. However, at higher salinities, the mitigation was partial, indicating limits to $H_2O_2$ protective capacity under severe stress.

Table 4 Yield parameters of *Zea mays* under salinity treatments with and without Hydrogen peroxide ($H_2O_2$) application

| Parameters | With and without HP | Salinity treatment (mM NaCl) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 50 | 100 | 150 | 200 | 250 |
| Number of ears | WHP | 2.38±0.18[a] | 2.38±0.18[a] | 2.13±0.23[a] | 1.50±0.19[b] | 1.38±0.18[b] | 1.38±0.18[a] |
| | PHP | 2.50±0.18[a] | 2.38±0.18[a] | 2.37±0.18[a] | 2.12±0.13[a] | 1.50±0.18[ab] | 1.50±0.18[ab] |
| Ear length (cm) | WHP | 19.63±1.01[a] | 18.21±0.65[a] | 14.75±0.80[b] | 13.62±0.42[b] | 13.25±0.59[b] | 12.12±0.30[b] |
| | PHP | 17.87±0.52[a] | 17.37±0.46[a] | 15.62±0.18[a] | 16.00±0.33[a] | 12.25±0.36[ab] | 11.00±0.27[ab] |
| Ear diameter (cm) | WHP | 13.50±0.13[a] | 14.23±0.08[a] | 14.61±0.22[a] | 13.02±0.60[a] | 12.15±0.94[a] | 14.08±0.19[a] |
| | PHP | 29.43±15.36[a] | 13.02±0.24[b] | 11.86±0.87[b] | 13.21±0.59[b] | 12.61±0.47[b] | 11.98±0.97[b] |
| Ear fresh weight (g) | WHP | 307.62±159.77[a] | 93.57±2.30[b] | 85.62±0.65[c] | 75.73±0.76[b] | 72.41±1.41[b] | 73.41±1.29[b] |
| | PHP | 146.57±1.12[a] | 120.91±1.59[b] | 119.75±11.22[b] | 108.08±1.36[c] | 93.58±0.78[c] | 94.58±0.84[c] |
| Ear dry weight (g) | WHP | 106.91±1.53[a] | 86.83±0.79[b] | 75.17±0.83[b] | 69.61±1.39[b] | 65.88±1.41[b] | 43.60±0.27[c] |
| | PHP | 107.56±0.39[a] | 82.96±0.32[b] | 81.68±0.39[b] | 68.12±0.33[bc] | 70.01±0.30[bc] | 50.05±1.67[c] |
| Number of grains | WHP | 226.25±13.13[a] | 217.38±2.71[a] | 212.13±1.42[a] | 175.50±0.82[ab] | 146.00±11.72[ab] | 84.50±3.85[b] |
| | PHP | 262.75±13.23[a] | 217.62±12.11[ab] | 169.87±14.84[b] | 177.75±17.14[b] | 111.37±1.50[bc] | 88.12±5.05[c] |
| Grain fresh weight (g) | WHP | 139.41±1.04[a] | 124.63±0.86[a] | 133.10±1.83[a] | 91.76±0.40[ab] | 92.67±5.56[ab] | 75.65±0.87[ab] |
| | PHP | 139.73±0.75[a] | 134.12±0.63[a] | 133.70±1.15[a] | 130.07±0.31[a] | 92.11±2.15[b] | 85.57±2.24[b] |
| Grain dry weight (g) | WHP | 55.78±0.68[a] | 52.87±0.52[a] | 54.26±0.75[a] | 54.01±1.28[a] | 49.36±0.27[a] | 38.89±5.30[ab] |
| | PHP | 55.60±0.50[a] | 53.71±0.23[a] | 52.83±0.39[a] | 53.58±0.44[a] | 54.90±0.24[a] | 51.83±0.32[a] |
| 1000 grain weight (g) | WHP | 30.88±0.64[a] | 25.25±1.03[ab] | 20.13±0.48[ab] | 22.13±0.52[ab] | 22.75±1.16[ab] | 23.88±1.62[ab] |
| | PHP | 31.25±0.70[a] | 27.25±1.58[ab] | 23.63±1.45[ab] | 21.12±1.30[ab] | 20.50±0.85[ab] | 18.25±1.15[c] |

Note: Values are mean ± standard error of 8 replicates (Tukey HSD test at $p \leq 0.05$). Mean with the same alphabet(s) along the row are not significantly different from each other. PHP: plus hydrogen peroxide (H2O2); WHP: without hydrogen peroxide ($H_2O_2$).

### 3.5 Nutritional and proximate composition

Table 5 shows that salinity stress without hydrogen peroxide ($H_2O_2$) (WHP) led to significant reductions in grain proximate components. Protein content decreased from 15.14% in the control to 13.44% at 250 mM NaCl, fat from 1.88% to 1.74%, and crude fiber from 3.40% to 2.74%. Concurrently, moisture and ash contents increased, likely due to disrupted metabolic processes and ion accumulation.

Hydrogen peroxide ($H_2O_2$) treated (PHP) plants maintained higher proximate values under salinity stress. At 250 mM NaCl, protein was sustained at 14.31%, fat at 2.41%, and crude fiber at 2.80%, closer to control levels. This indicates hydrogen peroxide helped stabilize metabolic pathways, reducing the impact of salinity on nutrient synthesis and storage.

### 3.6 Grain nutritional composition

Salinity without hydrogen peroxide plants increased $Na^+$ and $Cl^-$ accumulation in grains while reducing key nutrients like potassium, phosphorus, and magnesium, reflecting ion imbalances and impaired nutrient uptake. Hydrogen peroxide ($H_2O_2$) treated (PHP) mitigated these effects, with lower $Na^+$ and $Cl^-$ accumulation and better retention of essential nutrients as shown in (Table 5) (e.g., higher potassium levels at all salinities). This suggests hydrogen peroxide improved ion homeostasis, likely through enhanced antioxidant enzyme activity.

### 3.7 Leaf total chlorophyll content

Table 6 shows that the chlorophyll content declined significantly under salinity stress without hydrogen peroxide, with the lowest levels at 250 mM NaCl due to pigment degradation and chloroplast damage. Hydrogen peroxide treated plants preserved higher chlorophyll content across all salinity levels, supporting sustained photosynthetic capacity and contributing to better grain quality.

Table 5 Grain nutritional and proximate compositions of *Zea mays* under salinity treatments with and without hydrogen peroxide ($H_2O_2$) application

| Proximate (%) and nutritional (mg/kg) composition | With and without HP | Salinity treatment (mM NaCl) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 50 | 100 | 150 | 200 | 250 |
| Moisture | WHP | 7.11±0.11$^{a}$ | 7.82±0.22$^{a}$ | 8.14±0.11$^{a}$ | 8.83±0.28$^{a}$ | 8.03±0.55$^{a}$ | 8.74±0.27$^{a}$ |
| | PHP | 7.10±0.10$^{a}$ | 8.87±0.34$^{a}$ | 8.01±0.18$^{a}$ | 8.82±0.18$^{a}$ | 9.39±0.02$^{a}$ | 9.84±0.28$^{a}$ |
| Fat | WHP | 1.88±0.13$^{a}$ | 1.83±0.03$^{a}$ | 2.04±0.08$^{a}$ | 2.02±0.02$^{a}$ | 1.82±0.06$^{a}$ | 1.74±0.05$^{a}$ |
| | PHP | 1.78±0.11$^{a}$ | 1.75±0.06$^{a}$ | 1.58±0.02$^{a}$ | 1.83±0.19$^{a}$ | 1.89±0.02$^{a}$ | 2.41±0.11$^{b}$ |
| Ash | WHP | 3.22±0.22$^{a}$ | 4.94±0.07$^{a}$ | 2.79±1.59$^{a}$ | 4.20±0.21$^{a}$ | 3.76±0.18$^{a}$ | 4.06±0.05$^{a}$ |
| | PHP | 3.22±0.27$^{a}$ | 3.91±0.11$^{a}$ | 3.77±0.17$^{a}$ | 4.14±0.12$^{a}$ | 3.73±0.13$^{a}$ | 3.89±0.21$^{a}$ |
| Crude fibre | WHP | 3.40±0.01$^{b}$ | 2.48±0.23$^{a}$ | 2.92±0.09$^{ab}$ | 2.55±0.26$^{ab}$ | 3.08±0.07$^{ab}$ | 2.74±0.09$^{ab}$ |
| | PHP | 2.99±0.02$^{a}$ | 2.83±0.08$^{a}$ | 2.97±0.04$^{a}$ | 2.21±0.23$^{a}$ | 2.67±0.08$^{a}$ | 2.80±0.23$^{a}$ |
| Crude protein | WHP | 15.14±0.58$^{b}$ | 11.21±0.23$^{ab}$ | 11.50±0.51$^{ab}$ | 10.36±0.38$^{ab}$ | 12.48±0.31$^{ab}$ | 13.44±0.57$^{ab}$ |
| | PHP | 15.17±0.58$^{a}$ | 12.24±0.24$^{b}$ | 13.50±0.51$^{b}$ | 10.96±0.01$^{b}$ | 14.50±0.63$^{b}$ | 14.31±0.34$^{b}$ |
| Carbohydrate | WHP | 69.26±0.81$^{a}$ | 71.72±0.12$^{a}$ | 72.61±0.97$^{a}$ | 72.03±0.55$^{a}$ | 70.83±1.03$^{a}$ | 69.28±0.65$^{a}$ |
| | PHP | 69.29±0.83$^{a}$ | 70.40±0.56$^{a}$ | 70.17±0.14$^{a}$ | 72.03±0.26$^{a}$ | 67.82±0.79$^{a}$ | 66.76±0.07$^{a}$ |
| Nitrogen (N) | WHP | 5.07±0.01$^{a}$ | 3.80±0.15$^{b}$ | 3.90±0.20$^{b}$ | 3.52±0.00$^{b}$ | 4.25±0.02$^{ab}$ | 4.28±0.10$^{ab}$ |
| | PHP | 5.10±0.00$^{a}$ | 4.15±0.00$^{a}$ | 4.58±0.01$^{a}$ | 3.72±0.02$^{a}$ | 4.92±0.02$^{a}$ | 4.85±0.02$^{a}$ |
| Potassium (k) | WHP | 329.80±0.30$^{a}$ | 331.50±0.60$^{a}$ | 328.15±0.2$^{5a}$ | 329.80±0.30$^{a}$ | 331.50±0.60$^{a}$ | 328.15±0.25$^{a}$ |
| | PHP | 329.80±0.30$^{a}$ | 335.05±0.45$^{a}$ | 336.50±0.30$^{a}$ | 339.95±0.35$^{a}$ | 342.80±0.30$^{a}$ | 333.50±0.20$^{a}$ |
| Calcium (Ca) | WHP | 10.45±0.25$^{a}$ | 11.05±0.65$^{a}$ | 11.00±0.10$^{a}$ | 11.45±0.25$^{a}$ | 12.05±0.35$^{a}$ | 12.50±0.40$^{a}$ |
| | PHP | 10.47±0.25$^{a}$ | 5.50±0.30$^{ab}$ | 7.80±0.30$^{ab}$ | 10.30±0.10$^{a}$ | 11.15±0.75$^{a}$ | 12.70±0.20$^{a}$ |
| Phosphorus (P) | WHP | 318.45±0.05$^{a}$ | 320.45±0.05$^{a}$ | 317.15±0.25$^{a}$ | 318.45±0.05$^{a}$ | 320.45±0.05$^{a}$ | 317.15±0.25$^{a}$ |
| | PHP | 316.55±0.05$^{a}$ | 318.15±0.05$^{a}$ | 316.15±0.2$^{5a}$ | 322.80±0.30$^{a}$ | 320.85±0.25$^{a}$ | 318.75±0.15$^{a}$ |

Note: Values are mean ± standard error of 8 replicates (Tukey HSD test at $p \leq 0.05$). Mean with the same alphabet(s) along the column are not significantly different from each other. PHP: plus hydrogen peroxide ($H_2O_2$); WHP: without hydrogen peroxide ($H_2O_2$)

Overall, hydrogen peroxide application consistently reduced the adverse effects of salinity on *Zea mays* by approximately 10%~20% across biomass, yield, and nutritional/proximate composition metrics, particularly at moderate salinity levels. However, under severe stress (250 mM NaCl), mitigation was partial, indicating that while hydrogen peroxide enhances resilience, it does not fully counteract extreme salinity effects.

## 4 Discussion

The results of this study clearly show that hydrogen peroxide ($H_2O_2$) serves as an effective agent in reducing the harmful impacts of salinity stress on *Zea mays* (maize). This aligns well with the established understanding that HP functions as a key signaling molecule in plants' responses to various abiotic stresses. At low concentrations, HP acts not as a damaging oxidant but as a regulator that triggers protective mechanisms, such as activating antioxidant systems, modulating gene expression, and facilitating cellular acclimation to adverse conditions like high salt levels.

One prominent benefit observed from this experiment was $H_2O_2$ capacity to lessen the salinity induced decline in plant height. Specifically, plants treated with HP reached an average height of 123.52 cm under 250 mM NaCl stress, in contrast to only 112.19 cm in untreated stressed plants. This improvement reflects $H_2O_2$ contributions to processes like osmotic adjustment where plants accumulate compatible solutes to maintain cell turgor and enhanced scavenging of reactive oxygen species (ROS), which otherwise accumulate excessively under salt stress and cause cellular damage. Such effects are supported by prior research demonstrating $H_2O_2$ involvement in these protective pathways in plants facing osmotic challenges (Qureshi et al., 2022; Zulfiqar et al., 2022).

However, the benefits were not uniform across all growth metrics. While plant height showed clear gains, other parameters like leaf number and stem girth exhibited only limited or no significant enhancement from $H_2O_2$ treatment. This pattern points to species-specific sensitivities in maize or concentration dependent responses of $H_2O_2$, where the applied dose or timing may optimally influence certain traits but not others. Comparable variability has been documented in different crops exposed to salinity or related stresses, highlighting that $H_2O_2$ efficacy can vary based on plant type, stress severity, and application details (Roque et al., 2024; Thomas et al., 2025).

Table 6 Leaf chlorophyll contents of *Zea mays* under salinity treatments with and without hydrogen peroxide ($H_2O_2$) application

| Salinity treatment (mM NaCl) | With or without HP | Chlorophyll (mg/L) | | Total chlorophyll (mg/L) |
|---|---|---|---|---|
| | | A | b | |
| 0 | WHP | 22.25 | 48.00 | 70.24 |
| 50 | | 10.16 | 22.04 | 32.20 |
| 100 | | 10.14 | 22.53 | 32.67 |
| 150 | | 10.77 | 25.42 | 36.18 |
| 200 | | 11.08 | 26.76 | 37.85 |
| 250 | | 10.07 | 22.16 | 32.23 |
| 0 | PHP | 24.62 | 47.81 | 72.43 |
| 50 | | 21.83 | 25.69 | 47.54 |
| 100 | | 18.33 | 24.91 | 43.24 |
| 150 | | 13.13 | 27.00 | 40.13 |
| 200 | | 12.35 | 18.64 | 30.98 |
| 250 | | 15.11 | 19.58 | 34.69 |

Note: PHP: plus hydrogen peroxide ($H_2O_2$); WHP: without hydrogen peroxide ($H_2O_2$)

Positive effects extended to vegetative biomass and root development, where $H_2O_2$ application led to noticeable improvements. These outcomes likely stem from better nutrient uptake and water retention capabilities under saline conditions, as salt stress typically disrupts ion balance and water availability, impairing root function and overall growth. Similar enhancements in biomass and root systems have been reported in other species like Mungbean and Tomato when $H_2O_2$ mitigates salt stress (Nehela et al., 2021). At moderate salinity levels (50~150 mM NaCl), $H_2O_2$ treated maize plants displayed approximately 10%~15% higher biomass than untreated counterparts. This advantage is attributable to strengthened antioxidant defenses which neutralize excess ROS and improved osmotic regulation, allowing plants to maintain physiological balance more effectively. These mechanisms tie directly into $H_2O_2$ broader role in orchestrating physiological adjustments during abiotic challenges (Ranjan et al., 2023; Saidi et al., 2024).

In terms of yield components, $H_2O_2$ positively affected key reproductive traits, most notably grain number per plant. Under severe stress at 250 mM NaCl, treated plants retained 88.12 grains per plant, compared to 84.50 in untreated plants. This indicates that $H_2O_2$ helps sustain reproductive development by minimizing oxidative damage to floral tissues and improving the allocation of assimilates (photosynthates) toward grain formation. Such protective influences on yield have been noted in maize and related crops under salinity (Rehan et al., 2025; Zhao et al., 2025). Nevertheless, the mitigation was only partial at higher salinity levels (200~250 mM NaCl), suggesting that HP protective effects have boundaries under extreme conditions. Severe stress can generate overwhelming ROS levels or cause profound ion toxicity (e.g., excessive $Na^+$ accumulation), which may exceed $H_2O_2$ capacity to fully counteract (Sachdev et al., 2021).

Beyond growth and yield, $H_2O_2$ helped preserve grain quality attributes. Proximate composition, such as protein content, remained more stable in treated plants (14.31% with $H_2O_2$ versus 13.44% without at 250 mM NaCl). Nutritional elements, including better potassium retention, were also maintained. These outcomes reflect $H_2O_2$ influence on metabolic stability, enabling continued synthesis of essential compounds and better ion homeostasis despite saline disruption. Related observations in other studies emphasize $H_2O_2$ contribution to nutrient metabolism and balanced ion regulation under stress (Saritha et al., 2020; Yadesa and Diro, 2023).

Additionally, $H_2O_2$ treated plants showed superior chlorophyll retention, which supports greater photosynthetic efficiency. Salinity often degrades chlorophyll and impairs light-harvesting complexes, reducing carbon fixation and energy production. By preserving chlorophyll, $H_2O_2$ indirectly bolsters carbohydrate synthesis and translocation, ultimately contributing to improved grain quality. This pattern mirrors findings in maize and pea subjected to salt stress, where maintained photosynthetic pigments enhance overall plant performance (Zahra et al., 2022; Stefanov et al., 2024).

Overall, this investigation addresses an important knowledge gap regarding maize specific applications of $H_2O_2$ under salinity, drawing parallels to how other modulators like salicylic acid have been used successfully in different crops (Elsisi et al., 2024). The findings position $H_2O_2$ as a promising, sustainable tool for boosting maize resilience in saline prone agricultural areas, where soil salinization is increasingly driven by climate change, poor irrigation practices, and other factors (Singh, 2022). That said, the incomplete protection at very high salinity levels underscores the need for additional studies to fine tune $H_2O_2$ concentrations, application timing (e.g., priming versus foliar sprays), and methods to achieve optimal results under severe conditions. Such optimization could further enhance its practical utility in saline agriculture.

## 5 Conclusion and Recommendations

In conclusion, these screenhouse-based results indicate that hydrogen peroxide shows promise as a signaling molecule capable of partially alleviating salinity stress effects on maize, potentially contributing to improved resilience in saline environments and supporting food security in affected areas (as highlighted in global assessments of salt-affected soils). However, the evidence remains preliminary and context-specific to controlled conditions.

The study demonstrates that salinity stress markedly impairs *Zea mays* (maize) growth, yield, grain nutritional quality, and leaf chlorophyll content, with the strongest negative impacts observed at 250 mM NaCl. Key parameters such as plant height, leaf production, stem girth, root development, biomass accumulation, grain number (declining from 226.25 to 84.50 per plant at 250 mM NaCl without mitigation), and grain proximate composition (e.g., protein decreasing from 15.14% to 13.44%, fat from 1.88% to 1.74%, crude fiber from 3.40% to 2.74%) were progressively reduced, consistent with effects of osmotic stress and ion toxicity. Chlorophyll content also declined, likely due to chloroplast damage affecting photosynthetic capacity.

Based on this research the application of hydrogen peroxide ($H_2O_2$) consistently alleviated these adverse effects across the tested salinity levels (50~250 mM NaCl). Treated plants showed improvements, including greater plant height (123.52 cm vs. 112.19 cm at 250 mM NaCl), higher biomass (approximately 10%~15% increase), increased grain number (88.12 vs. 84.50 per plant), enhanced grain quality (e.g., protein at 14.31%, fat at 2.41%, crude fiber at 2.80%), and better maintenance of chlorophyll content, which may support improved photosynthetic efficiency. These observations align with prior research indicating that exogenous $H_2O_2$, often applied as a priming or foliar treatment, can enhance antioxidant defenses, protect chloroplast ultrastructure, modulate metabolites, and improve physiological performance under salt stress in maize. Nonetheless, $H_2O_2$ mitigation did not completely restore parameters to non-stressed control levels, especially under severe salinity (250 mM NaCl), suggesting inherent limitations in extreme conditions.

Field validation under natural saline soils, along with further exploration of optimal application methods, concentrations, physiological/biochemical mechanisms (e.g., antioxidant enzyme responses, ionic homeostasis), and possible integration with other amendments or interventions, would be essential to strengthen any practical recommendations for maize production in salt-affected regions.

### Author's contribution

O. Kekere was the experimental designer, and J. K. Afolabi was executor of the study; J. K. Afolabi completed data analysis and wrote the first draft of the paper; J. K. Afolabi participated in the experimental design and analysis of experimental results; O. Kekere was the project conceptualizer and leader, guiding experimental design, data analysis, paper writing and revision. The paper was read and received the approval of both authors for publication in the journal.

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# Effects of Water Deficit Irrigation on Quality of Pear

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**Abstract** This study focuses on the effects of moderate deficit irrigation on pear fruit quality and provides a systematic analysis. Based on a review of global pear orchard irrigation patterns and technological developments, it summarizes the implementation methods and outcomes of deficit irrigation under different climatic conditions, cultivar types, and cultivation management practices. Applying moderate water deficit at appropriate growth stages of fruit trees can not only effectively save water resources, but also improve, to some extent, the soluble solid content, sugar–acid ratio, and flavor quality of the fruit, while enhancing storage performance. Deficit irrigation regulates fruit physical traits, chemical composition, and aroma compound formation, and its effects are jointly influenced by multiple factors such as cultivar, rootstock, soil type, and climate conditions. The study proposes suitable irrigation regulation strategies and simple, farmer-friendly technical approaches, emphasizing the importance of coordinated water–fertilizer management and low-cost monitoring methods. Moderate deficit irrigation is a practical technique that balances water saving and quality improvement, and it is of great significance for enhancing resource use efficiency and promoting sustainable development in the pear industry.
**Keywords** Pear (*Pyrus* spp.); Deficit irrigation; Fruit quality; Water use efficiency; Sustainable agriculture

## 1 Introduction

Pear (*Pyrus* spp.) is one of the most widely cultivated temperate fruit trees in the world, playing an important role in horticultural production and rural economies in regions such as Europe, China, and South America. As consumers increasingly demand better sensory and nutritional quality, pear growers are not only under pressure to maintain stable yields, but also to improve fruit appearance, texture, flavor, and storage performance. Climate change, more frequent droughts, and competition for limited freshwater resources are making traditional irrigation methods harder to sustain. Agriculture accounts for about 70% of global freshwater withdrawals, and fruit trees are usually irrigated to avoid water stress, especially in semi-arid and arid regions where rainfall is insufficient or unstable (Vélez-Sánchez et al., 2023).

In many major pear-producing areas, current irrigation management mainly relies on supplying all or nearly all crop evapotranspiration (ETc) through surface or subsurface drip irrigation, micro-sprinkler irrigation, furrow irrigation, or flood irrigation. Full irrigation at 100% ETc or maintaining relatively high soil moisture thresholds (such as 80% of field capacity) is commonly used as a reference or “safe” strategy when comparing deficit irrigation treatments (Zhang et al., 2022). The rapid development of pressurized irrigation systems, especially drip irrigation, has greatly improved the precision of water supply. However, in practice, it often leads to “insurance irrigation,” where excessive water is applied to avoid potential yield loss (Vandermaesen et al., 2021). Under conventional management, irrigation amounts are often close to or even exceed ETc in order to maintain vigorous vegetative growth and larger fruit size.

Deficit irrigation refers to the intentional application of water below crop water requirements without causing unacceptable reductions in yield or quality. Regulated deficit irrigation (RDI) is one of the most commonly used approaches in fruit trees. It applies moderate water deficit during phenological stages that are less sensitive to water stress, while maintaining near-full irrigation during critical periods such as rapid fruit enlargement. In pear production, moderate deficit irrigation is usually implemented as applying 50%-80% ETc at specific growth stages, or maintaining soil moisture at about 60%~70% of field capacity, rather than applying it throughout the entire growing season. In some cases, reduced irrigation can even increase soluble solids content and improve storage performance, although fruit size may decrease slightly.

This study reviews the effects of deficit irrigation on pear fruit quality, summarizes global trends in pear cultivation and irrigation practices, and compiles results from different deficit irrigation strategies (including RDI and partial root-zone drying) under various climates, rootstocks, and cultivars. It focuses on how the intensity, timing, and duration of water deficit affect yield components, fruit size distribution, internal quality traits, and postharvest physiological behavior. Based on this, it proposes design principles for deficit irrigation under different production regions and resource conditions, providing a scientific basis for using deficit irrigation as a practical tool to improve sustainability and fruit quality in modern pear production.

## 2 Implementation of Moderate Deficit Irrigation in Pear Orchards

### 2.1 Irrigation control methods: soil moisture and irrigation interval

In soil moisture-based regulation, irrigation is triggered when soil water content drops below a preset proportion of field capacity (FC). In subsurface drip irrigation studies on Xinjiang fragrant pear, adjustments to total seasonal irrigation (3 750~6 750 $m^3$/ha) and emitter burial depth showed that deeper pipe placement combined with a reasonable irrigation amount can reduce excessive wetting of surface soil and better match the wetted zone with the active root layer (Wang et al., 2024).

In ET- or Ep-based regulation, irrigation is calculated as a proportion of ETc or Ep, and deficit irrigation is achieved by reducing this proportion or extending irrigation intervals. Young pear trees were irrigated at 70% (T70), 100% (control), and 130% (T130) of the FAO water budget. The T70 treatment reduced water use by 30% while promoting trunk growth and increasing fruit number, indicating that “full irrigation” may actually be excessive (Marsal et al., 2002). Later, the control treatment was reduced to 82% of the original irrigation level during mid-growth (Control-82%), and regulated deficit irrigation was applied at about half of this level during specific fruit development stages.

In regulated deficit irrigation experiments with the “Triunfo de Viena” cultivar, irrigation was reduced to 67% and 55% ETc only during the rapid fruit growth period (about two months), while 100% ETc was maintained at other times. This approach saved 33%~45% water without significant changes in yield or fruit quality (Molina-Ochoa et al., 2016). Under desert climate conditions, both RDI and PRD treatments used the same water amount (50% Ep during slow growth and 80% Ep during rapid expansion), and results showed that plant responses were mainly controlled by irrigation volume rather than irrigation method (Wu et al., 2020).

### 2.2 Key application periods of moderate deficit irrigation

Pear fruit growth is usually divided into the cell division stage (Stage I), slow growth stage (Stage II), and rapid enlargement or maturation stage (Stage III/IV). Moderate deficit irrigation can be applied at all stages, but the purpose differs.

In Bartlett pear, irrigation was stopped in spring to dry the root zone, followed by regulated deficit irrigation at 23%-46% of evaporation. This significantly reduced vegetative growth (about 52%) without affecting fruit growth. When irrigation was restored to 120% Eps during the rapid growth stage, fruit growth was promoted and yield increased by about 20% (Chalmers et al., 1986). Applying RDI in Stage I can increase flowering and fruit set, while applying it in Stage II can control fruit size. Adjusting irrigation to an intermediate level (Control-82%) helps balance yield and fruit size. In widely spaced mature pear trees, water deficit during Stage II (slow growth stage) has little effect on yield, indicating strong tolerance to moderate stress and making this stage suitable for deficit irrigation.

In studies on pear jujube and other woody fruit trees, the period from bud break to leaf expansion (Stage I) and the fruit maturation stage (Stage IV) are considered key regulation windows. Applying moderate or severe deficit during these stages can increase yield by 9%~32%, reduce water use by up to 17.5%, improve water use efficiency by up to 41%, and enhance fruit firmness, soluble solids, sugar-acid ratio, vitamin C content, and storage performance (Cui et al., 2008; 2009; Guo and Gao, 2023).

### 2.3 Common irrigation patterns in pear production

Common irrigation patterns in pear orchards mainly include the following. The most widely used is regulated deficit irrigation (RDI), which applies full irrigation during sensitive stages and reduces irrigation to a certain proportion of ETc or Ep during non-sensitive stages. Typical schemes include: 40%-60% Ep in early stages and 80% Ep later; 50% adjusted ETc in Stage I or II for young trees; 60%~80% ETc at specific stages and 100% ETc at other times; or 67%~55% ETc only during the rapid growth stage. Another method is partial root-zone drying (PRD), where irrigation alternates between the two sides of the root system.

At the orchard scale, irrigation patterns are also influenced by irrigation systems and soil moisture thresholds. In northern China, drip irrigation (surface, ring, subsurface, single-line or double-line) is commonly combined with a lower limit of 60%-80% FC, and subsurface double-line drip at 60% FC performs best (Wang et al., 2021). In Xinjiang fragrant pear, 30 cm subsurface drip irrigation with a moderate irrigation amount shows the best performance in yield, water use efficiency, and economic return, while traditional flood irrigation uses more water but has low efficiency (Wang et al., 2024).

In semi-arid regions of Brazil, drip and micro-sprinkler irrigation were tested at 60%~120% ETc, and the highest yield was achieved at about 92% ETc. Both excessive and insufficient water reduced gas exchange and affected carbohydrate metabolism (Gomes et al., 2023). In Kosovo, 50% ETc reduced yield per plant but increased the proportion of high-quality fruit and saved half of the irrigation water (Lepaja et al., 2024).

### 2.4 Indicators for monitoring water deficit

For soil monitoring, gravimetric methods, capacitance sensors, or tensiometers are commonly used, with indicators including volumetric water content, percentage of FC, or soil water potential. In the “Triunfo de Viena” study, combining ETc with soil moisture monitoring achieved water savings of up to 73% while avoiding severe drought (Vélez-Sánchez et al., 2023).

In plants, leaf and stem water potential ($\Psi$leaf, $\Psi$stem) are widely used indicators, usually measured in the early morning or at midday with a pressure chamber. In the Abbé Fetèl cultivar, the 60% ETc treatment significantly reduced water potential and gas exchange, but fruit size was maintained and postharvest soluble solids increased on BA29 rootstock, indicating that moderate decreases in water potential are acceptable (Venturi et al., 2021). Under tropical high-altitude conditions, $\Psi$pdl, $\Psi$stem, $\Psi$pdf, and $\Psi$f showed no significant differences among different RDI treatments (-0.25 to -1.03 MPa) (Vélez-Sánchez et al., 2022). Other indicators include maximum daily trunk shrinkage (MDS) and pressure–volume curve parameters.

## 3 Effects on Fruit Physical Quality

### 3.1 Fruit size and single fruit weight

In the cultivar Abbé Fetèl, trees grafted onto the more dwarfing quince rootstock (SYDO) produced significantly smaller fruits under 60% ETc compared to 110% ETc. In contrast, on the more vigorous BA29 rootstock, final fruit size remained essentially unchanged among 110%, 80%, and 60% ETc treatments (Venturi et al., 2021). On both rootstocks, moderate irrigation reduction increased fruit dry matter content, indicating that water inflow through the xylem (and also the phloem under stronger deficit) was reduced, leading to lower fruit water content, while carbohydrate supply did not decrease proportionally.

Under field conditions, in ‘Conference’, complete irrigation was stopped for 3 weeks at the beginning of the second growth stage, followed by deficit irrigation at only 20% ETc during the remaining period. This reduced fruit size at harvest but improved internal quality. Thinning under deficit conditions partially restored fruit size and fresh-market yield (López et al., 2011). In postharvest deficit irrigation (DI) studies of ‘Conference’, stopping irrigation after harvest for 3~4 consecutive seasons did not cause a sustained reduction in fruit size in subsequent years. In some years, a “carry-over effect” was observed, where fruit number decreased but individual fruit size increased. This reflects changes in crop load rather than a direct limitation of fruit growth by water stress (Marsal et al., 2011).

In ‘Triunfo de Viena’ grown in high-altitude tropical regions, even when irrigation was greatly reduced to 25% ETc or completely stopped during the rapid fruit growth stage, fresh weight and diameter at harvest did not significantly decrease compared to 100% ETc (Bayona-Penagos et al., 2017).

### 3.2 Fruit firmness and texture characteristics

In Abbé Fetèl, deficit irrigation at 60% ETc significantly reduced shoot and leaf water potential as well as gas exchange, but did not consistently reduce firmness at harvest. Storage performance depended on rootstock type: on the more dwarfing SYDO, firmness was more affected by irrigation, while on BA29, reduced irrigation mainly increased soluble solids after 6 months of storage at 1 °C, with only slight fruit size reduction (Venturi et al., 2021).

At a more microscopic level, the effect of RDI on stone cells (a key factor determining the gritty texture of pear flesh) has also been studied. In potted ‘Williams’ (‘Bartlett’), RDI at about 15% of the control applied from 32 to 60 days after flowering (late stage I) showed, through microscopic image analysis, no significant differences in stone cell area, size, or spatial distribution between RDI and full irrigation at the end of stage I or at harvest (Peco et al., 2023) (Figure 1).

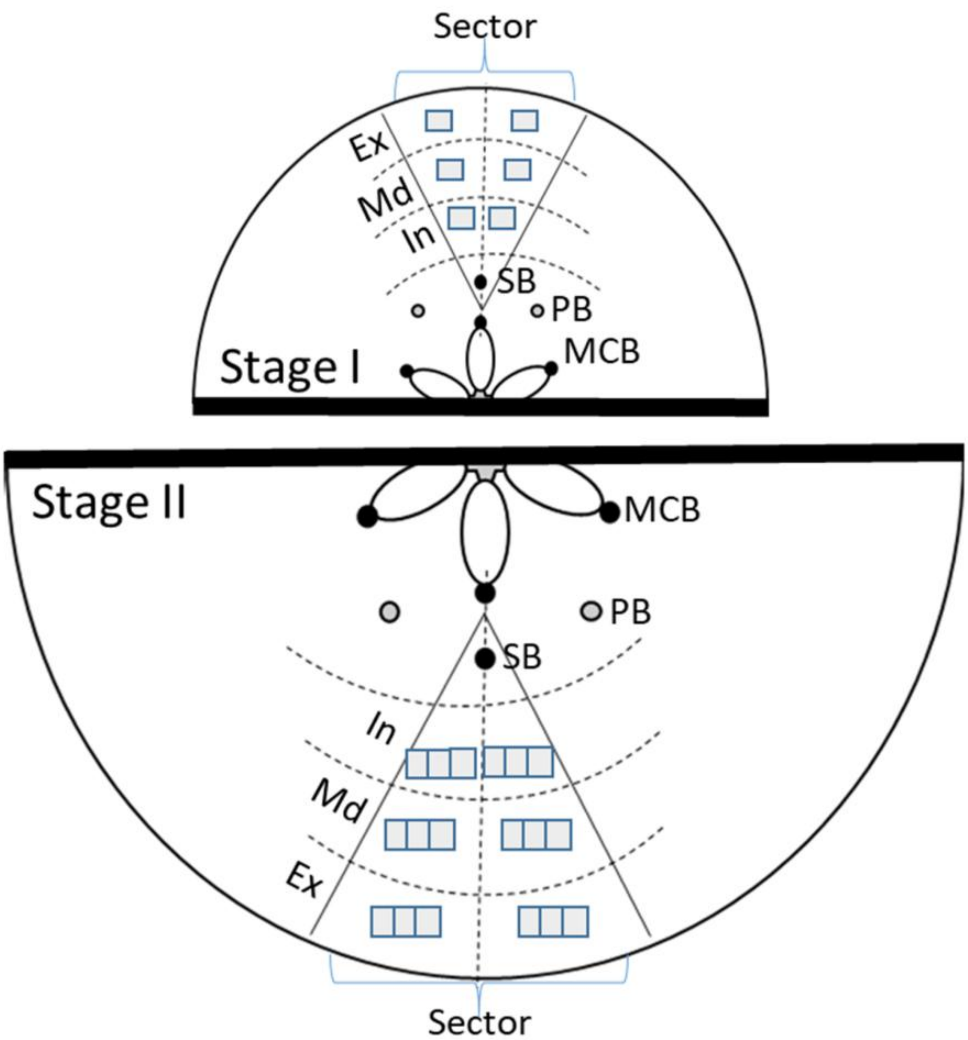


Figure 1 Scheme for the analysis of pear fruit cells in sections of Stages I (upper) and II (lower). Wedge-shaped sectors were cut from central transverse fruit slices, each extending from a sepal bundle (SB) to the fruit exterior, and processed for histological study. For measurements, the sector was visually divided into two halves and three concentrically oriented zones: Ex (Exterior), Md (Middle), and In (Interior). The squares within each zone represent the number of microscope image areas (0.06 cm2) captured and analyzed (two images per zone for Stage I; six per zone for Stage II). SB: sepal bundle, PB: petal bundle, and MCB: median carpelary bundle (Adopted from Peco et al., 2023)

### 3.3 Peel coloration and external appearance

In 'Triunfo de Viena', applying 74%~60% and 48%~27% ETc during the rapid fruit growth stage resulted in no significant differences at harvest in peel chlorophyll, carotenoid content, or overall color index compared with 100% ETc (Vélez-Sánchez et al., 2021).

By regulating vegetative growth, deficit irrigation can indirectly improve external appearance. For example, in 'Bartlett' under the Tatura system, applying RDI at 46% Eps during vigorous vegetative growth reduced shoot and structural growth without affecting fruit growth. This may improve light distribution within the canopy, thereby enhancing color uniformity and reducing russeting, although color parameters were not directly measured in that study (Mitchell et al., 1984).

### 3.4 Effects on fruit uniformity and commercial grading

In high-altitude tropical 'Triunfo de Viena', under postharvest deficit treatments of 25% and 0% ETc, the largest diameter and volume were observed in the fully irrigated treatment 2 days after harvest. However, subsequent evaluations did not show a decline of fruit below market standards, and all quality parameters remained within commercially acceptable ranges (Bayona-Penagos et al., 2017).

In contrast, when continuous deficit was applied throughout the entire growing season, some trade-offs occurred. In field trials in Kosovo, compared with 100% ETc drip irrigation, a simplified 50% ETc treatment reduced yield per tree by about 38%, but improved fruit grading quality: 92.30% of fruits reached the extra class under 50% ETc, compared to 85.41% under full irrigation (Lepaja et al., 2024). Average fruit diameter and length did not differ significantly between treatments, indicating that the higher proportion of top-grade fruit was mainly due to improved uniformity, shape, or peel quality rather than larger fruit size.

## 4 Effects on Fruit Chemical Quality

### 4.1 Soluble solids content (ssc) and sugar accumulation

In pears and other woody fruit trees, mild to moderate deficit irrigation generally increases SSC and enhances sugar concentration. This may result from reduced fruit water content leading to solute concentration, or from restricted water inflow while maintaining or even increasing carbohydrate supply, or a combination of both.

In sparsely planted mature pear orchards in Xinjiang, regulated deficit irrigation (RDI) at 40%~60% of pan evaporation (Ep) applied during the cell division stage or slow fruit expansion stage significantly increased total soluble sugar content compared with full-season irrigation at 80% Ep. Meanwhile, fruit growth and yield were maintained or even improved under some treatments (Wu et al., 2013). In 'Conference' pear, applying deficit irrigation (0% followed by 20% ETc) during stage II increased SSC at harvest and after storage, and combining deficit irrigation with fruit thinning further enhanced SSC (López et al., 2011).

The mechanisms may include increased dry matter content under stress, osmotic adjustment promoting sugar accumulation, and reduced energy consumption for fruit growth, which lowers sugar use in glycolysis (Bai et al., 2022; Toumi et al., 2022). These findings are consistent with observations in Abbé Fetèl and mature pears, indicating that moderate water deficit generally increases sugar concentration and potential sweetness, especially after storage in climacteric cultivars.

### 4.2 Organic acids and sugar-acid balance

Direct measurements in 'Williams' pear showed that irrigation (adequate water supply) reduced malic acid, citric acid, fumaric acid, and shikimic acid contents, and also decreased SSC. In contrast, non-irrigated fruits had higher sugar and acid contents, indicating that water limitation concentrates primary metabolites, including organic acids (Hudina and Stampar, 2005).

In 'Conference' pear, moderate preharvest deficit irrigation during stage II increased titratable acidity at harvest and maintained higher levels during storage. Together with higher SSC, this resulted in a richer and more complex flavor (López et al., 2011). Postharvest deficit (irrigation stopped while maintaining stem water potential above about -1.5 MPa) generally had little effect on acidity, although in one season SSC slightly increased while acidity remained unchanged (Marsal et al., 2011).

In pear-jujube, regulated deficit irrigation applied during the germination stage and fruit maturation stage increased SSC, vitamin C, and the sugar-acid ratio, while only slightly reducing fruit water content (Cui et al., 2008).

### 4.3 Changes in flavor and texture quality

In 'Conference' pear, preharvest stage II deficit treatment (no irrigation followed by 20% ETc) increased firmness, SSC, and acidity at harvest. This higher SSC/TA combination corresponds to a more complex and pronounced flavor. These advantages were maintained during storage, and fruit thinning under deficit conditions further increased SSC and promoted ripening, allowing earlier harvest of high-flavor fruit (López et al., 2011).

In 'Williams' pear, continuous irrigation increased fruit size but reduced SSC, monosaccharides, and organic acids. In contrast, non-irrigated fruits were smaller but had stronger flavor and higher sweetness (Hudina and Stampar, 2005).

### 4.4 Effects on aroma-related compounds

In 'Triunfo de Viena', the effects of irrigation levels at 100%, 74%, and 48% ETc during the rapid fruit expansion stage (with full irrigation at other stages) on aroma were evaluated. Moderate RDI had no significant effect on firmness, SSC, acidity, pigments, or phenolic compounds at harvest, and yield was similar to the control, but it altered the temporal dynamics of volatile compound release during ripening (Vélez et al., 2019).

Esters are the main components of pear aroma and showed a continuous increase during the climacteric stage under all treatments. Under moderate water limitation, RDI maintained or slightly increased ester formation without causing off-flavors, provided that the deficit occurred at less water-sensitive growth stages and did not exceed the stress threshold.

## 5 Yield–Quality Relationship under Moderate Deficit Conditions

### 5.1 Changes in total yield and yield stability

In 'Yali' pear, both early and late RDI significantly suppressed vegetative growth and reduced irrigation water use. However, over two consecutive growing seasons, there were no significant differences in fruit yield at harvest or average single fruit weight compared with the control. This indicates that yield remains stable when stress is applied from bud break to 25 days after full bloom (pullulation-25 DAFB) or during the last month before harvest (Cheng et al., 2012).

Responses of roots and canopy also support yield stability. In mature 'Sinkiang' pear, moderate RDI (60% Ep) during the early fruit development stage had no effect on final yield compared with full irrigation. Although more severe or longer deficits altered fine root distribution, they did not produce clear positive or negative effects on yield (Wu et al., 2021).

In pear–jujube systems, applying light to moderate water deficit at the bud stage or maturity stage increased yield by 13%~32% or kept it similar to full irrigation, while reducing irrigation water use by up to 18% (Cui et al., 2008; 2009).

### 5.2 Balance between yield reduction and quality improvement

In 'Yali' pear, late-season RDI improved SSC, sugar content, and dry matter without reducing yield (Cheng et al., 2012).

For 'Triunfo de Viena', applying RDI during the rapid fruit growth stage maintained yield and standard quality traits, with the main effect being water saving. Even under stronger deficits at this stage (25% ETc or no irrigation), yield still did not decrease (Moreno-Hernández et al., 2017).

### 5.3 Suitable deficit thresholds in production practice

Appropriate deficit thresholds for pear come from pear trials and broader studies on woody fruit trees. For 'Triunfo de Viena', applying RDI at 60%~74% ETc (and even 48% ETc in wet years) during the rapid fruit growth stage can achieve 26%~73% seasonal water savings without affecting yield or quality (Moreno-Hernández et al., 2017).

Results from ‘Yali’ pear show that under deep soil conditions, completely stopping irrigation (close to 0% ETc) from bud break to 25 days after flowering or during the last month before harvest is feasible, as long as the stress period is limited and followed by sufficient rewatering. These strategies improved WUE and late-stage quality without reducing yield (Cheng et al., 2012).

From a broader perspective, a meta-analysis of woody fruit trees (including pear) shows that mild deficit irrigation at 80%~100% of full irrigation maximizes yield and water productivity (WP). It is best applied during the first and second growth stages (bud break to leaf expansion, and flowering to fruit set), which can increase WP by about 2%~9% while reducing yield risk (Wen et al., 2023). More severe seasonal deficits (below 60% of full irrigation) increase the risk of yield reduction, but may still be reasonable when water resources are extremely limited or when fruit quality has a high price premium.

## 6 Differences in Cultivars and Growth Conditions

### 6.1 Differences in responses among common pear cultars

The European pear cultivar “Triunfo de Viena,” grown in high-altitude tropical regions of Colombia, shows strong tolerance to regulated deficit irrigation (RDI) during the rapid fruit growth stage. Across different years, reducing irrigation to 74%~60% or even 48%~27% of ETc did not significantly affect fruit number, average weight, size distribution, yield, or key quality traits (firmness, sugars, organic acids, pigments, and phenolic compounds), while saving up to about 73% of water (Vélez-Sánchez et al., 2021). Even under more severe conditions (such as 25% ETc or no irrigation during rapid fruit growth), no significant differences in yield and quality were observed for this cultivar.

In contrast, the late-maturing European pear cultivar “Abbé Fetél” under Mediterranean climate conditions is more sensitive to seasonal water deficit. After storage, fruits on BA29 rootstock showed higher soluble solids at 60% ETc, while fruit firmness on SYDO rootstock was more sensitive to irrigation level. This indicates that tree vigor and scion–rootstock combinations play an important role in regulating stress resistance and fruit quality (Venturi et al., 2021).

Asian pear types show different response patterns. For white pear (*Pyrus* bretschneideri ‘Sinkiangensis’), applying moderate deficit irrigation at 60% of pan evaporation (Ep) during the early cell division stage (Stage 1) or Stage 1+2 reduces fine root length density, but has no significant effect on final yield compared with full irrigation. This suggests that the whole plant still has strong recovery ability even when roots are temporarily restricted. More severe early stress (40% Ep) causes clear changes in root distribution and can even increase final yield when applied only in Stage 1, indicating a specific compensation mechanism when early vegetative growth is controlled (Wu et al., 2021) (Table 1).

Studies on other pear cultivars further show differences in water use and stress sensitivity. In South African orchards, seasonal transpiration of “Packham’s Triumph” and “Forelle” was 539 mm and 733 mm, respectively. This is related to the higher leaf area index and longer growth period of “Forelle,” reflecting differences in water demand among genotypes (Dzikiti et al., 2024).

### 6.2 Effects of soil conditions and climate

Soil profile and climate conditions largely determine the safe range of deficit irrigation. Water limitation is more obvious in semi-arid and arid climates, and plant responses are stronger. In the semi-arid middle São Francisco River region of Brazil, pear trees under both drip and microsprinkler irrigation were negatively affected by either insufficient or excessive water. This was shown by reduced gas exchange and abnormal synthesis and accumulation of carbohydrates, amino acids, and proteins in leaves. Yield reached its maximum at 91.8% ETc, indicating that under high evaporative demand and shallow or moderately deep soils, the room for deficit regulation is limited (Gomes et al., 2023).

Soil texture and water-holding capacity interact with climate to influence deficit irrigation effects. In coarse-textured or salinity-prone soils in desert or continental regions, deficit irrigation may lead to salt accumulation due to reduced leaching. In peach studies, saline water under deficit irrigation increased soil salinity along the drip line, but rainfall and sandy soils helped stabilize salinity at the end of the season (Toumi et al., 2024). Similar processes may limit long-term deficit irrigation in pear orchards, requiring monitoring of soil electrical conductivity and periodic leaching.

Table 1 Yield, fruit quality, and shoot length of each treatment (Adopted from Wu et al., 2021)

| Year | Treatment | Yield (t/ha) | Total Soluble Solid Content (%) | Soluble Sugar Content (%) | Fruit Volume (cm3) | Final Shoot Length (cm) | Shoot Length in Late May (cm) |
|---|---|---|---|---|---|---|---|
| 2009 | MRDI-1 | 18.9 ab | 12.3 b | 8.14 c | 94 a | 27.5 b | 25.6 b |
| | SRDI-1 | 21.5 a | 12.5 ab | 8.82 a | 100 a | 25.9 bc | 23.6 bc |
| | MRDI-1+2 | 18.1 bc | 12.0 bc | 7.97 c | 103 a | 26.0 b | 24.9 bc |
| | SRDI-1+2 | 15.8 c | 13.1 a | 8.61 b | 96 a | 24.0 c | 22.3 c |
| | Control | 18.6 b | 11.5 c | 6.93 d | 98 a | 32.4 a | 30.2 a |
| 2010 | MRDI-1 | 21.2 ab | 12.8 b | 8.08 a | 116 a | 25.4 b | 23.1 b |
| | SRDI-1 | 23.6 a | 13.8 a | 8.05 a | 123 a | 23.9 c | 21.9 b |
| | MRDI-1+2 | 20.6 b | 13.6 a | 7.71 bc | 113 a | 24.3 bc | 22.6 b |
| | SRDI-1+2 | 17.2 c | 13.9 a | 7.99 ab | 122 a | 22.5 c | 21.0 b |
| | Control | 19.8 b | 13.6 a | 7.63 c | 114 a | 31.3 a | 29.1 a |

Note: Different letters within the same column indicate significant differences at the $p < 0.05$ level. MRDI-1 and SRDI-1 were applied with moderate and severe water stress, respectively, during Stage 1 (0~30 DAB), and fully irrigated during other stages; MRDI-1+2 and SRDI-1+2 were applied with moderate and severe water stress, respectively, during Stage 1+2 (0-86 DAB), and fully irrigated during other stages. The shoot lengths in late May were measured on 20 and 21 May in 2009 and 2010, respectively; the final shoot lengths were measured on 4 September and 29 August in 2009 and 2010, respectively (Adopted from Wu et al., 2021)

In the Bukhara region of Uzbekistan, dwarf high-density orchards of "Williams," "Abbot," and "Carmen" under drip irrigation reduced water use by half while increasing yield per tree to 1.6 kg. This shows that proper planting density and canopy management can help reduce climate and soil limitations (Yunusov et al., 2023). In the Dukagjini Plain of Kosovo, irrigation at 100% and 50% ETc resulted in yields of 8.33 kg and 5.10 kg per tree, respectively, but the 50% ETc treatment produced a higher proportion of high-quality fruits. This indicates that climate-soil-water interactions significantly affect both yield and fruit grading (Lepaja et al., 2024).

**6.3 Adaptability of moderate deficit irrigation in different regions**

Evidence from pear experiments and global meta-analyses of woody fruit trees shows that moderate deficit irrigation has wide adaptability, but optimal thresholds and strategies vary by region and cultivar. For woody fruit trees (including pear), mild deficit irrigation at 80%~100% irrigation level can slightly increase yield (+0.87%) and improve water productivity (+9.77%). Stronger seasonal deficits may reduce yield by about 14%, but still improve water productivity. Deficit irrigation is suitable for regions with annual precipitation over 400 mm and mean annual temperature ≥10 °C, and should be applied mainly during early growth stages to reduce yield risk (Wen et al., 2023).

In high-rainfall or high-altitude tropical regions (such as Sesquilé, Colombia), RDI can be applied at relatively high intensity (even down to 27% ETc or with no irrigation during certain stages) without affecting yield and quality of "Triunfo de Viena." This is because rainfall and deep soils buffer water fluctuations, and the main advantage is significant water saving.

In arid and semi-arid inland regions (such as Xinjiang in China, semi-arid Brazil, and northern desert regions of China), deficit irrigation needs to be more conservative and combined with efficient irrigation methods. In fragrant pear production, subsurface drip irrigation at 30 cm depth combined with a higher irrigation amount (6 750 $m^3$/ha) can optimize yield, quality, water use efficiency, and economic returns. Subsurface drip irrigation can increase yield by 13%~17% and water productivity by 45%-137%, showing that improving irrigation methods can sometimes be more effective than simply reducing water amount. In semi-arid Brazil, optimal yield is close to full irrigation level (about 92% ETc), indicating limited room for deficit irrigation under high evaporation and shallow soil conditions (Gomes et al., 2023).

## 7 Conclusion

Moderate deficit irrigation, achieved through fine control of soil moisture at specific phenological stages, can improve multiple quality indicators, including soluble solids content, flavor, nutritional composition, and storage performance, while having limited or acceptable effects on yield. Compared with conventional full irrigation, deficit irrigation helps achieve the dual goals of producing high-quality fruit and improving water use efficiency, which is particularly important in regions facing increasing water scarcity and more frequent droughts due to climate change.

Moderate deficit irrigation generally increases soluble solids content and sugar concentration, improves the sugar–acid ratio, and enhances flavor and aroma. Fruits under deficit treatment often show higher firmness and better texture, lower incidence of physiological disorders, and in many cases higher levels of vitamin C, phenolic compounds, and antioxidant capacity. Although fruit size and total yield may decrease slightly, these losses are usually compensated by better appearance quality, more uniform fruit within the marketable size range, and improved storage and transport tolerance.

Moderate deficit irrigation is a practical water-saving technique that can be integrated into existing orchard management systems with relatively low additional cost. By adjusting irrigation schedules based on soil moisture conditions, evapotranspiration, or plant water status indicators, growers can reduce irrigation water use without reducing, and sometimes even improving, fruit quality. Deficit irrigation can also be combined with optimized fertilization, canopy management, and pruning practices to improve light distribution and source-sink relationships. At the regional scale, promoting deficit irrigation in pear orchards can contribute to sustainable water use, reduce energy consumption for pumping, and lessen environmental impacts caused by over-irrigation and nutrient leaching.

To promote wider application, several recommendations are proposed. First, the level and timing of deficit irrigation should be scientifically determined based on cultivar characteristics, local climate, soil water-holding capacity, and orchard structure, and severe water stress should be avoided during highly sensitive stages such as early fruit development and cell division. Moderate deficit is generally recommended during the middle to late stages of fruit enlargement and, in some cases, the pre-harvest maturation stage, with quantitative thresholds set using soil moisture, stem water potential, or other reliable indicators. Second, simple and low-cost monitoring tools and decision-making methods should be promoted so that deficit irrigation can be applied by both smallholders and large-scale growers. Third, more demonstration orchards and field trials should be established to validate and optimize deficit irrigation strategies under different production conditions, forming region-specific technical guidelines and training materials. Finally, future research should focus on the long-term effects of continuous deficit irrigation on tree vigor, alternate bearing, root development, and soil health, and explore its integration with precision agriculture technologies, so as to fully realize the water-saving and quality-improving potential of moderate deficit irrigation in pear production and support its wider adoption.

### Author Contributions

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### Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Substrate Selection and Nutrient Supply for Greenhouse Strawberry Yield Optimization

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**Abstract** This study focuses on the combined effects of substrate selection and nutrient supply in greenhouse strawberry production, and provides a systematic analysis. It mainly discusses how different substrate types and nutrient management strategies influence plant growth, yield formation, and fruit quality. An ideal substrate should maintain a balance in physical structure, chemical buffering capacity, and biological activity, so as to ensure root aeration, water supply, and stable nutrient release. Coconut coir, peat, and their mixed substrates with perlite, vermiculite, and vermicompost show clear advantages in improving the rhizosphere environment, enhancing nutrient use efficiency, and optimizing fruit quality. Integrated water and fertilizer management based on dynamic regulation at different growth stages is a key measure to achieve high yield and good quality. By reasonably adjusting the proportions of elements such as N, K, and Ca, yield can be increased significantly, and the sugar-acid ratio and vitamin content can be improved. Sensor-based precise water and fertilizer management, together with recycling systems, can greatly improve water and nutrient use efficiency while reducing environmental pressure, without reducing yield. Substrate and nutrient supply should be optimized together, and combined with regional resource conditions and sustainability requirements, to build an efficient, stable, and environmentally friendly greenhouse strawberry production system.
**Keywords** Greenhouse strawberry; Soilless cultivation; Substrate optimization; Nutrient management; Water-fertilizer integration

## 1 Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is one of the most economically valuable soft fruits in modern horticulture, combining high economic returns with excellent nutritional and sensory quality. Strawberries are rich in vitamin C, polyphenols, and antioxidant compounds, making them an important part of a healthy diet and increasingly promoted as a functional food. Over the past two decades, global strawberry cultivation area and production have increased rapidly, and in many countries it has become one of the most profitable horticultural industries (Rahim Doust et al., 2023). Protected cultivation systems, including greenhouses, high tunnels, and other controlled environments, have played a key role in this expansion. These systems provide frost protection, extend the harvest period, stabilize yields, and improve control over major diseases and abiotic stresses, thus supporting industry growth (Samtani et al., 2019). Within these systems, the development of advanced cultivation techniques—especially soilless culture—has turned strawberry into a representative crop for intensive and urban horticulture, enabling high-density planting, off-season production, and more efficient use of resources (Nichols, 2021; Kouloumprouka Zacharaki et al., 2024).

Consumers now expect strawberries to be available year-round, with not only good appearance—uniform size, consistent color, and attractive shape—but also high sensory quality such as sweetness, aroma, and firmness, along with strong nutritional and functional value (Hernández-Martínez et al., 2023; Cardarelli et al., 2024). This shift in market demand has pushed breeding and production systems to focus more on varieties and cultivation practices that combine high yield with high internal quality. Key targets include improving soluble solids, organic acids, polyphenol content, and antioxidant capacity (Sturzeanu et al., 2025). By optimizing fertilization and water management, it is possible to enhance soluble solids, organic acid levels, color, and bioactive compounds while maintaining yield (Raffaelli et al., 2025).

Soil-borne diseases such as Verticillium wilt, Phytophthora crown rot, root rot, and complex root disease syndromes can seriously reduce plant vigor and yield. At the same time, control methods like soil fumigation face economic, regulatory, and environmental constraints (Rathod et al., 2021). Soil heterogeneity, salt accumulation, and poor drainage and aeration can also disrupt the uniform distribution of water and nutrients, leading to uneven plant growth and unstable fruit quality. Soilless cultivation systems—including solid substrates (such as peat, coco peat, coconut fiber, perlite, and rockwool) and hydroponic systems—provide a more controlled root environment and can effectively address these problems. They allow production in areas where soil is unsuitable, contaminated, or unavailable, and enable precise control of water supply, nutrient delivery, root aeration, and electrical conductivity (Wanas and Khamis, 2022).

This study evaluates different combinations of soilless substrates and nutrient supply strategies to optimize yield and fruit quality in greenhouse strawberry production, with a focus on resource use efficiency and practical applicability. Specifically, the study aims to: (i) compare different substrate types or their mixtures with conventional soil cultivation in terms of plant growth, yield, and fruit quality; (ii) assess the effects of different nutrient solution management strategies on productivity and key quality traits; and (iii) identify substrate–nutrient combinations that improve water and nutrient use efficiency while maintaining or enhancing fruit quality. By clarifying these relationships, this study provides both scientific support and practical guidance for substrate selection and nutrient management in greenhouse strawberry production.

## 2 Characteristics of Ideal Substrates for Strawberry Cultivation

### 2.1 Physical properties

From a physical perspective, an ideal substrate should have a balanced pore structure, good aeration, sufficient water-holding capacity, and stable root-zone temperature. Organic substrates such as coir, peat-based mixes, bark, sawdust mixtures, and polyester fiber generally hold more water than mineral soils under saturated conditions and after free drainage. With proper irrigation management, this feature is usually associated with larger canopy size, higher biomass, and increased marketable yield (Zahid et al., 2021).

However, if the proportion of fine particles is too high, or the substrate becomes compacted over time, leading to increased bulk density and electrical conductivity (EC), it will result in poor aeration, salt accumulation, and reduced yield. For example, this occurs in organic substrates where the proportion of particles smaller than 0.25 mm is high and the EC exceeds 2.0 $mS \cdot cm^{-1}$ (Guerrero-Guerrero et al., 2021).

Substrates with moderate bulk density and good water retention can buffer day–night temperature fluctuations. Together with ambient and substrate temperatures, they affect fruit firmness, acidity, vitamin C content, and volatile flavor composition. Compared with soil cultivation, substrate-based systems generally improve fruit quality (Buragienė et al., 2024; Xu et al., 2025).

### 2.2 Chemical properties

From a chemical perspective, an ideal substrate should maintain a slightly acidic pH, moderate EC, and relatively high cation exchange capacity (CEC), so that it has good nutrient buffering capacity under intensive water and fertilizer management. Studies on potting soils and soilless substrates show that slightly acidic conditions, high CEC, and low background salinity are favorable for strawberry growth. In contrast, too low EC limits plant vigor, while EC above about 2.0 $mS \cdot cm^{-1}$ can cause salt stress and substrate compaction (Guerrero-Guerrero et al., 2021).

In practical greenhouse production, nutrient solutions and substrates are usually controlled within pH 5.5~6.5 and EC below about 1.5~1.8 $mS \cdot cm^{-1}$. This range is associated with better vegetative growth, yield, and fruit quality in coir-perlite-vermicompost mixtures, peat-based substrates, coir, and bark–sawdust formulations (Schafer and Lerner, 2022).

Substrates with higher CEC, especially those rich in organic matter (such as coir, peat, vermicompost, or livestock manure-based substrates), can adsorb and slowly release $K^+$, $Ca^{2+}$, and $Mg^{2+}$. This helps buffer rapid changes in nutrient solution composition and reduces nutrient leaching (Tang et al., 2024). However, strong microbial immobilization or adsorption may temporarily reduce the availability of N, P, and S. In peat-sawdust substrates, it has been observed that initial fertilization is needed to alleviate nutrient immobilization (Depardieu et al., 2016).

### 2.3 Biological properties

From a biological perspective, the substrate is not only a habitat for microbial communities but also an important factor in regulating nutrient cycling, promoting plant growth, and suppressing diseases. Substrates amended with organic materials (such as livestock manure, vermicompost, mushroom residues, or organic fertilizers) usually contain higher populations of bacteria and fungi, are enriched with phosphate-solubilizing and nitrogen-fixing bacteria (e.g., Azotobacter), and show higher enzyme activities related to carbon and nitrogen cycling (Hindersah et al., 2023).

Amendments such as vermicompost and livestock manure can improve substrate fertility, increase microbial abundance and enzyme activity, and reduce the accumulation of phenolic acids. As a result, they significantly promote plant height, leaf area, root length, and fruit yield and quality, especially in continuous cropping systems (Bai et al., 2025). Sheep manure organic fertilizer can significantly improve soil pH, nutrient availability, and the activity of enzymes such as sucrase, protease, and urease, while also increasing bacterial and fungal diversity, thereby promoting strawberry growth and nutrient supply (Zha et al., 2024).

An ideal substrate should also have some disease-suppressive ability. This mainly comes from good aeration and drainage conditions (which are unfavorable for many root pathogens) and microbial communities that can compete with or antagonize pathogens. Compared with greenhouse soil, artificial substrates can change the composition and functional pathways of rhizosphere bacterial communities in strawberry, showing enrichment in plant growth-related metabolic pathways (such as flavonoid biosynthesis) and changes in antimicrobial compound synthesis pathways (Zhang et al., 2023).

Substrates with good physical and chemical conditions (such as coir-perlite-vermicompost mixtures, peat combined with rice husk or perlite, and optimized vermicompost-coir/biochar formulations) can promote dense root branching and high survival rates. This increases the surface area for beneficial microbial colonization, further improving nutrient uptake efficiency, yield, and system stability (Yafuso and Boldt, 2024; Selivanova et al., 2025).

## 3 Common Substrate Types and Their Performance

### 3.1 Organic substrates

Among organic substrates, coir, peat, compost, and vermicompost-based media are the most widely used. Pure coir or coir-based mixtures have high water-holding capacity, good aeration, and low bulk density, which support strong vegetative growth and canopy development. In both open-field and greenhouse trials, 100% coir or peat-perlite mixtures produced yields comparable to soil cultivation, while also forming larger canopies and higher biomass (Wang et al., 2016).

Peat remains an important reference substrate due to its favorable structural properties and high cation exchange capacity (CEC). Commercial peat-based mixtures (such as peat combined with coir, perlite, vermiculite, or zeolite) often support strong root growth and high long-term productivity in both pot and hydroponic systems (Lee et al., 2023) (Figure 1). Compost- and vermicompost-based substrates can increase organic matter content, improve nutrient supply, and stimulate microbial activity. In particular, mixtures of vermicompost-coir and vermicompost-biochar at about a 0.5:0.1 ratio significantly improved water retention, nitrogen use efficiency, enzyme activity, nutrient uptake, as well as fruit yield and quality (Tang et al., 2024).

However, organic substrates may also have some drawbacks, such as compaction, high electrical conductivity (EC), and nutrient immobilization. For example, peat mixed with sawdust or bark often requires additional fertilization at the early stage to overcome the immobilization of nitrogen, phosphorus, and sulfur. Pure coir may also become compacted under certain conditions, and compared with treatments containing mineral amendments, it may result in fewer fruits (García-López and Cruz-Ortega, 2023).

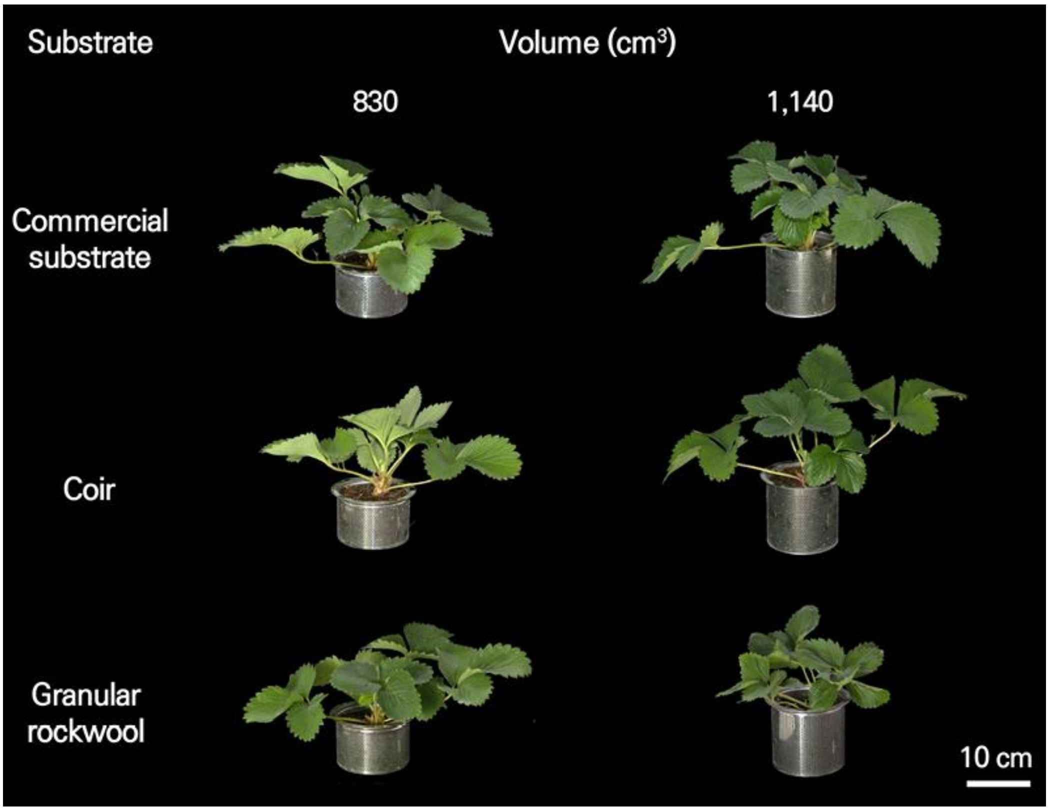


Figure 1 Plants grown with two different pot volumes (830 and 1 140 $cm^3$) with three different substrate types (commercial substrate, coir, and granular rockwool) treatment 63 days after transplant (Adopted from Lee et al., 2023)

### 3.2 Inorganic substrates

Common inorganic substrates include perlite, vermiculite, and rockwool, as well as other mineral materials such as tuff and volcanic rock. Perlite is highly porous and has very low bulk density, which helps improve drainage and aeration. When mixed with peat, vermicompost, or plant compost (e.g., perlite:peat = 1:1, perlite:vermicompost = 3:2, perlite:compost = 4:1), it can significantly enhance vegetative growth, leaf area, nutrient accumulation, yield, and fruit quality compared to substrates with poor aeration (El-Sayed et al., 2016).

Vermiculite has higher water-holding capacity and CEC than perlite. Coir-vermiculite and coir-vermiculite-perlite mixtures, compared with sand culture, can increase petiole length, canopy size, root biomass, and total soluble solids (TSS), indicating that vermiculite improves water and nutrient retention without seriously reducing aeration when used in proper proportions.

Rockwool is a uniform and inert substrate with excellent control over root-zone moisture. In greenhouse soilless systems, rockwool can promote earlier transition to reproductive growth in strawberry and produce more fruits and higher total yield than coir. In contrast, coir is more favorable for vegetative growth, and there is little difference between the two in terms of sugar content and fruit firmness. Granular rockwool has very high water retention, and improper irrigation management may lead to water stress and restricted root growth.

Volcanic rock (tezontle), used alone or mixed with coir at a 1:1 ratio, produced more fruits per plant as well as larger berries and higher individual fruit weight than soil cultivation. This suggests that properly graded mineral substrates, when combined with precise water and nutrient management, can match or even exceed organic substrates in yield performance (Lekavičienė et al., 2025).

### 3.3 Mixed substrate systems

Mixed substrates combine organic components that supply water, nutrients, and biological activity with inorganic components that provide structural stability and improved aeration, creating a synergistic effect. Coir-perlite (4:1) and peat-perlite (4:1) mixtures performed better than pure tuff or tuff-organic mixtures in terms of photosynthesis, transpiration, free radical scavenging activity, fruit firmness, and yield. This indicates that adding 20% perlite can significantly improve the physical properties of coir or peat (Alsmairat et al., 2018).

Perlite-vermiculite-coir (50:25:25) and coir-vermiculite (25:75) substrates resulted in higher plant height, longer roots, larger canopy size, bigger fruits, and higher TSS compared with sand culture or single-component treatments (Raja et al., 2018). Perlite-vermiculite (3:2) and perlite-peat (1:1) mixtures, used in greenhouse and closed hydroponic systems, supported better vegetative growth, higher fruit number, earlier and higher total yield, and improved leaf nutrient status compared to other mineral-organic combinations (El-Sayed et al., 2016; Ahmed and Gad, 2022).

### 3.4 Comparative analysis of substrate performance

Substrate composition has a significant impact on strawberry growth, flowering, fruit set, yield, and fruit quality. In terrace cultivation and greenhouse systems, a mixture of soil, vermicompost or farmyard manure, and coir at a 1:1:1 ratio resulted in higher plant height, leaf number, runner length, fruit number, and yield per plant than soil alone, highlighting the advantage of coir-rich organic substrates (Kumar et al., 2022).

Soilless substrates composed of coir, perlite, and vermicompost improved leaf area, chlorophyll index, root biomass, and overall vegetative growth compared with soil. Among these, the coir-perlite-vermicompost ratio of 4:1:2 achieved the highest TSS/acid ratio, total sugar, and reducing sugar content, indicating improved fruit flavor quality (Sharma and Godara, 2017; Sharma et al., 2025).

Peat-vermiculite-perlite (1:1:1) and other ternary mixtures (peat:vermiculite, peat:perlite, vermiculite:perlite) outperformed single mineral substrates or pure peat in terms of fruit size, fruit number per plant, early yield, and total yield (Hassan et al., 2021). Rockwool promoted earlier reproductive development and produced more fruits and higher total yield than coir, although coir supported stronger vegetative growth. Quality traits such as sugar content and fruit firmness showed no significant differences between the two substrates (An et al., 2025).

In open-field trough cultivation systems, coir or peat-perlite substrates produced marketable yields comparable to fumigated soil, while offering better control of root-zone moisture (Wang et al., 2016).

## 4 Nutrient Requirements of Greenhouse Strawberries

### 4.1 Macronutrient requirements

Nitrogen (N), phosphorus (P), and potassium (K) are the main nutrients regulating strawberry growth and yield. Nitrogen is essential for vegetative growth, runner formation, and flower bud differentiation. Insufficient nitrogen reduces aboveground biomass, alters the balance between shoots and roots, and restricts canopy development. In contrast, appropriate nitrogen uptake is closely related to plant height, dry matter accumulation, and fresh fruit yield.

Phosphorus plays an important role in root development, energy transfer, photosynthesis, and the conversion and transport of sugars. Phosphorus deficiency not only inhibits plant growth but also affects the uptake of nitrogen and potassium, and significantly influences fruit quality traits such as total soluble solids (TSS) and sugar content.

Potassium is crucial for cell expansion, osmotic regulation, carbohydrate synthesis, nutrient transport, and fruit coloration. Potassium deficiency leads to poor fruit coloring and affects the formation of high-quality marketable fruits (Jiang et al., 2023).

Seasonal nutrient uptake patterns show that, under fertilization conditions, the total uptake of N, P, and K by plants can reach 78~91, 12~17, and 92~125 $kg \cdot hm^{-2}$, respectively. The highest net uptake occurs from flowering to fruit development, while nutrient absorption is relatively low in autumn and during dormancy (Bayram and Elmacı, 2021).

### 4.2 Importance of micronutrients

Calcium (Ca), magnesium (Mg), iron (Fe), and other micronutrients (such as Zn, Mn, Cu, B, and Mo) play important roles in yield potential and fruit quality. Calcium stabilizes cell walls and membranes, improving fruit firmness, shelf life, and resistance to physiological and abiotic stresses. Most Ca in plants accumulates in vegetative organs, and insufficient Ca supply is common in commercial production systems, often associated with reduced fruit formation and quality decline.

Magnesium is an important component of chlorophyll and also acts as an activator for many enzymes. It is distributed between leaves and fruits, and its uptake is positively correlated with plant height and the number of fruits per plant (Quddus et al., 2025).

Elements such as Fe, Zn, Mn, Cu, and B are essential for photosynthesis, respiration, enzyme activation, and hormone balance. Application of Fe, Zn, and Ca through foliar spray or substrate can improve vegetative growth, flowering, yield, and fruit quality (such as vitamin C content and firmness) (Marchenko et al., 2024; Singh et al., 2024).

Long-term investigations of leaf nutrient status in commercial plantations show that although N, P, K, and Mg are usually sufficient, deficiencies of Ca, S, Zn, and Cu occur in more than half of the samples, which may limit yield and fruit quality under both open-field and protected conditions (Osvalde et al., 2023). Typical deficiency symptoms include chlorosis and poor growth caused by Fe and Mg deficiency, weak pedicels and soft fruits caused by Ca deficiency, and reduced fruit set, smaller fruit size, or lower sugar content due to insufficient Zn, B, and other micronutrients, ultimately reducing marketable yield and economic returns (Sangeeta et al., 2019; Sayğı, 2022).

### 4.3 Nutrient uptake dynamics

Under greenhouse soilless cultivation, nutrient uptake is influenced not only by root physiological characteristics but also by the interaction between substrate and nutrient solution. The uptake of most macronutrients is lowest in the early stage after autumn planting and reaches a peak from flowering to fruit maturity. Among these, K shows the highest uptake rate, followed by N, Ca, Mg, and P. Roots and crowns store nitrogen during autumn and winter, and about 40% of the stored nitrogen is remobilized for new growth during flowering.

Analysis of leaves, crowns, roots, and fruits indicates that during fruit maturation, N, P, and K are mainly transported to fruits, while Ca is largely retained in leaves and roots, and Mg is distributed between vegetative organs and fruits. This suggests that continuous nutrient supply is required during the reproductive growth stage (Ikegaya et al., 2020).

In hydroponic and low-substrate-volume systems, root uptake patterns are strongly affected by the composition of the nutrient solution (such as N/K and K/Ca ratios), electrical conductivity (EC), pH, and cultivar-specific uptake characteristics. Adjusting these ratios at different growth stages can improve photosynthetic efficiency, promote earlier fruit ripening, increase yield by about 20%~26%, and improve the sugar-acid ratio and vitamin C content, while maintaining stable substrate pH (Shirko et al., 2018).

Substrate properties further affect nutrient availability. pH determines the solubility of micronutrients and the risk of deficiency or toxicity, while EC, cation exchange capacity (CEC), and organic matter content regulate the fixation and release of N, P, S, K, and Mg. Organic amendments (such as vermicompost and mushroom waste) can increase total and available N, P, and K in soil, enhance microbial and enzyme activity, and alleviate continuous cropping obstacles, thereby promoting nutrient uptake and improving yield and fruit quality (Allayorov et al., 2023). In contrast, peat-based substrates with low fertility may lead to deficiencies of N, P, and K if fertilization is not properly managed, further indicating that substrate selection and nutrient solution design must be optimized together to meet nutrient uptake dynamics at different growth stages.

## 5 Nutrient Supply Strategies in Soilless Cultivation

### 5.1 Fertigation management

The composition and concentration of nutrient solutions must be adjusted according to crop growth stage and cultivar. In practice, the ratios of N:K and K:Ca are usually modified during the vegetative stage, flowering stage, and fruit expansion stage. This helps improve photosynthetic efficiency, promote rapid fruit ripening, enhance 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).

## 6 Interaction between substrate and nutrient supply

### 6.1 Effects of substrate on nutrient retention and release

Different organic and inorganic components show clear differences in nutrient adsorption, fixation, and slow release. In soilless strawberry cultivation, low-peat substrates containing wood fiber and compost can retain a relatively large proportion of Ca (76%~88%), Mg (70%~85%), and N (61%~81%) after use, while K is mainly removed through aboveground biomass. This indicates that different elements have specific retention patterns, which should be considered when designing fertigation strategies (Vandecasteele et al., 2023a).

Substrates amended with compost can supply large amounts of P and K, reducing fertigation input by 10%-50% and lowering nutrient losses in drainage. However, during long spring cultivation cycles, when compost mineralization slows down, additional N input is required (Vandecasteele et al., 2018). Similarly, biochar or lignocellulosic materials can act as nutrient adsorbents, recovering nitrate, phosphate, Ca, and sulfate, and stabilizing the chemical properties of nutrient solutions. At the same time, they may increase pH and change K dynamics, thereby affecting nutrient availability (Haraz et al., 2020).

The addition of organic amendments can increase cation exchange capacity (CEC), pH buffering capacity, and the storage of $NH_4^+$ and K, while reducing P fixation, thus improving fertilizer use efficiency. This effect is especially obvious in sand–coco coir mixed substrates. The buffering effect of different substrates is closely related to pH regulation and ion balance. Substrates rich in coco coir have strong pH buffering capacity and nutrient storage ability, which can promote vigorous plant growth. However, if fertilization does not match crop demand, it may lead to excessive nutrient accumulation (Xu et al., 2021). Compost and spent mushroom substrate often contain high nutrient levels at the early stage, promoting root and shoot growth and increasing marketable yield. However, their mineralization rate changes over time, so nutrient supply should be adjusted in stages to avoid excess in the early stage and deficiency later.

In contrast, substrates with low CEC, such as sand or mixtures with a high proportion of wood fiber, have weaker buffering capacity, and nutrient concentrations in the root zone are more directly affected by fertigation management. Although this allows for rapid adjustment, improper fertilization can more easily lead to osmotic stress or nutrient deficiency.

### 6.2 Regulation of the rhizosphere environment

Besides chemical properties, substrates also influence nutrient uptake efficiency by regulating the physical environment of the rhizosphere, especially aeration, water distribution, and temperature. Studies in soilless cultivation show that root function depends on sufficient oxygen supply. When aeration is poor or waterlogging occurs in the root zone, nutrient uptake and plant growth are inhibited even if nutrient solution concentration is high (Balliu et al., 2021).

Studies in both hydroponic and soil systems indicate that moderate increases in rhizosphere oxygen can improve root length, root volume, root activity, and P uptake capacity, thereby increasing yield and quality. However, both excessive and insufficient oxygen can inhibit growth (Wang et al., 2022; Nitu et al., 2024). Under waterlogged or low-oxygen conditions, even with adequate nutrient supply, the uptake of K, Mg, and Ca decreases, and shoot growth is also restricted. This shows that good aeration is a prerequisite for efficient fertilizer use.

Substrate structure, such as pore distribution, water-holding capacity, and bulk density, determines the balance between water and oxygen. Mixed substrates of peat, coco coir, and compost or organic composites, combined with inorganic nutrient supply, can improve both aeration and water retention, thus promoting root development and increasing strawberry yield (Prasad et al., 2022). Materials such as wood fiber can increase porosity and moisture, but they immobilize nitrogen during decomposition, so additional N fertilization is needed to maintain nutrient balance.

In addition, substrate pH regulation is critical for nutrient availability. Most macronutrients are most easily absorbed at pH 6~6.5, while higher pH reduces the solubility of micronutrients and disrupts nutrient balance. This has been confirmed in container experiments with peat substrates (Ferrarezi et al., 2022).

### 6.3 Optimization model of substrate-nutrient combinations

Building an efficient production system requires coordinated design of substrate characteristics and nutrient management strategies, rather than considering them separately. Long-term strawberry experiments show that in substrates with added compost or reduced peat content, fertigation strategies must be recalibrated to account for nutrients supplied and retained by the substrate itself. When compost mineralization is high in autumn, inputs of N, P, and K should be reduced. In extended spring cultivation, when the internal nutrient supply capacity of the substrate declines, inputs should be increased.

Current optimization approaches increasingly rely on quantitative models that link substrate physicochemical properties with plant performance. For example, structural equation modeling has been used to analyze how vermicompost indirectly promotes plant growth, fruit morphology, and yield by altering substrate nutrients, microbial activity, and enzyme activity (Bai et al., 2025).

## 7 Case Studies and Practical Applications

### 7.1 Regulation model based on vermicompost

Under continuous greenhouse cultivation, substrate degradation and continuous cropping obstacles are key factors limiting the stability of strawberry yield and quality. Bai et al. (2025) conducted a study under greenhouse conditions in Hebei, China, using a randomized block design with the strawberry cultivar "Xiangye." They compared the effects of different substrate types and vermicompost application methods on plant growth, yield, and quality. The experiment included two background conditions: new substrate (0 years) and substrate continuously cultivated for 2 years. On this basis, three treatments were set: no vermicompost (CK), cattle manure-derived vermicompost, and sludge-derived vermicompost. The experiment covered a full strawberry growing season. Plant growth parameters (plant height, leaf area, root length), substrate physicochemical properties (nutrient content, microbial quantity, enzyme activity), yield, and fruit quality indicators (soluble sugars, vitamin C, and amino acids) were systematically measured.

The addition of vermicompost significantly improved the substrate environment. Compared with the control, nutrient content in the substrate increased by about 12.04%~42.54%. At the same time, microbial populations and related enzyme activities were clearly enhanced, while the content of phenolic autotoxins decreased significantly. This effect was more obvious in continuously cropped substrates, indicating that vermicompost plays an important role in alleviating continuous cropping obstacles. The improved substrate environment further promoted plant growth. In the treatment groups, plant height, leaf area, and root length increased by about 15.01%~32.77% and 23.75%~32.78%, showing that root vitality and nutrient uptake capacity were enhanced.

Under new substrate conditions, yield increased by about 18.29%, while in continuously cropped substrate the increase reached 19.64%. Fruit quality was also improved. During the peak fruiting stage, soluble sugar content increased by about 9.62%~42.62%, and both vitamin C and free amino acid contents increased significantly, indicating improvements in both flavor and nutritional value (Figure 2).

### 7.2 Substrate cultivation combined with integrated water-fertilizer management

In greenhouse soilless cultivation systems, the traditional practice of using a fixed nutrient solution throughout the whole growth period often cannot meet the different nutrient requirements of strawberries at different growth stages. Yu et al. (2023) conducted a greenhouse experiment in the Xiaotangshan Modern Agricultural Demonstration Park in Beijing, China, based on dynamic adjustment of nutrient solution according to growth stages. The study used an elevated substrate cultivation system with strawberry 'Ssanta' as the test material. Under volcanic rock substrate, horticultural substrate, and commercial substrate conditions, they compared the traditional Yamazaki standard nutrient solution (control) with an optimized nutrient solution adjusted according to growth stages. The treatment increased nitrogen supply during the vegetative stage, gradually increased potassium supply and adjusted the K/Ca ratio during flowering and fruit expansion stages, and optimized the ratio of $NO_3^-$-N to $NH_4^+$-N.

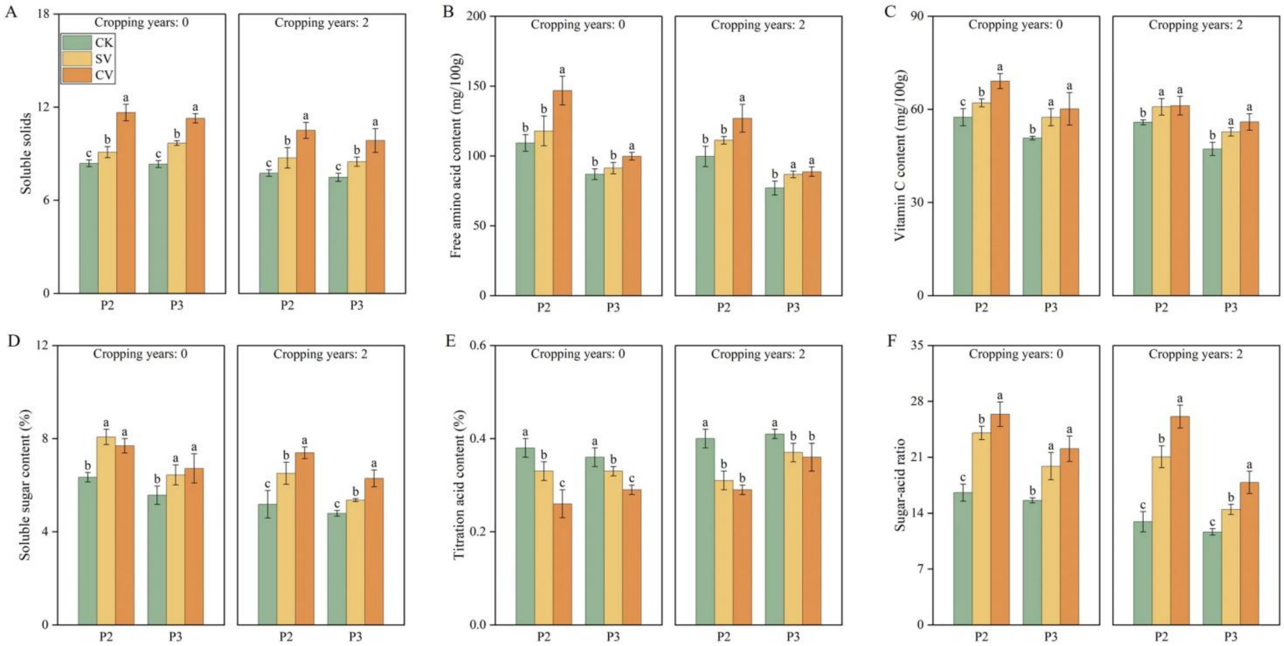


Figure 2 Effects of vermicompost on soluble solids (A), free amino acid content (B), vitamin c content (C), soluble sugar content (D), titration acid content (E) and sugar-acid ratio (F) in different periods. Letters indicate significant differences in the effects of different vermicompost treatments on this indicator at different time periods, with a significance level of $p < 0.05$. P2 and P3 represent peak fruiting period and the senescence phase respectively. Abbreviations for treatment: Control (CK), sludge vermicompost (SV) and cattle manure vermicompost (CV) (Adopted from Bai et al., 2025)

Compared with the traditional fixed formula, the nutrient management model based on growth stage regulation significantly improved strawberry production performance. In terms of yield, total yield per plant increased by about 20%, with the highest increase reaching 26% under horticultural substrate conditions. The peak fruiting stage was advanced by about one week. In terms of physiological performance, the optimized treatment significantly improved photosynthetic capacity during both vegetative growth and flowering stages. Regarding fruit quality, the sugar-acid ratio increased by about 41%, and vitamin C content increased by about 34%, reaching up to 74.1 mg/100 g.

## 8 Challenges and Future Prospects

### 8.1 Limitations of current substrate technologies

Although substrate cultivation technology has become relatively mature, its long-term sustainability and system resilience are still constrained by multiple factors. Peat remains the dominant material in commercial strawberry substrates, but peatlands are non-renewable on a practical timescale, and their extraction leads to serious problems such as increased carbon emissions and habitat destruction. Even in regions where peat resources are relatively abundant, it is widely recognized that peat cannot be rapidly regenerated. Therefore, efforts are being made to reduce its carbon footprint through practices such as artificial cultivation of sphagnum moss and partial substitution with local materials like sawdust, bark, and compost.

The reuse of peat, coir, and wood fiber has, to some extent, reduced pressure on resource extraction and waste disposal. Under properly adjusted fertigation management, these substrates can be reused for up to three cycles without significant reductions in yield or physical properties (Vandecasteele et al., 2024; Woznicki et al., 2024). However, reuse also introduces new issues, including nutrient accumulation (especially increases in nitrogen and calcium and depletion of potassium), changes in cellulose content, and the buildup of pathogenic fungi. Therefore, disinfection (such as steam treatment) and nutrient rebalancing are necessary to maintain system stability (Hu et al., 2025).

The disposal and end-use of spent substrates remain major challenges. Rockwool, widely used in greenhouse horticulture, has low organic carbon content and limited value as a soil amendment. It also tends to accumulate large amounts of phosphorus, potassium, magnesium, and calcium and is difficult to recycle (Vandecasteele et al., 2023b). In contrast, organic spent substrates (such as reduced-peat mixtures, compost-based substrates, and biochar composites) contain higher levels of carbon and nutrients and can be reused as carbon-rich soil amendments. However, this requires well-developed systems for collection, blending, and safe utilization, including pathogen control and salinity management.

### 8.2 Precision nutrient management

Precision water and nutrient management is a key direction for future optimization, as substrate cultivation systems are highly sensitive to water and nutrient conditions. Currently, both wireless and wired sensor systems are capable of real-time monitoring of substrate moisture content and electrical conductivity, achieving promising results.

In intensive production systems in Western Europe, automation and data-driven control have become standard. Computer-controlled fertigation systems can precisely formulate nutrient solutions based on water quality, cultivar requirements, and the EU "zero discharge" policy. Drainage water is collected, filtered, disinfected (e.g., ultraviolet treatment, slow sand filtration), and reused (Lieten, 2013).

A frontier direction is the integration of sensor networks, modeling, and artificial intelligence. The SmartBerry project is a typical example: by building a greenhouse image dataset covering seven growth stages of strawberry and training deep learning models, the EfficientNetB7 model achieved an accuracy of 0.837 in growth stage recognition. This provides a foundation for stage-specific nutrient management based on automated phenotyping (Darlan et al., 2025). If such AI-based growth stage recognition is integrated with fertigation systems and substrate sensors, it could enable closed-loop control systems, allowing dynamic adjustment of nitrogen, potassium, calcium, and irrigation levels according to crop growth stage, substrate type, and environmental conditions.

Future research should focus on improving system stability under commercial production conditions, compatibility with existing greenhouse control systems, and transparency of decision-making rules, in order to enhance grower acceptance.

### 8.3 Development of environmentally friendly substrates

The development and promotion of bio-based and recyclable environmentally friendly substrates is one of the key directions for future research, aiming to reduce dependence on peat and rockwool in strawberry production. With proper fertigation management, materials such as wood fiber, green waste compost, bark, vermicompost, spent mushroom substrate, carbonized rice husk, and phytoremediated marine sediments can partially or completely replace peat or coir while maintaining high yields (Martínez-Nicolás et al., 2020).

Wood fiber-based substrates, when mixed with compost or peat, can achieve yields comparable to coir. However, high proportions of wood fiber may require additional nitrogen supplementation to avoid nitrogen immobilization (Aurdal et al., 2022). Substrates composed of wood fiber mixed with biochar, green compost, bark, or mineral residues can also achieve marketable yields comparable to coir and peat over two production cycles, although they may affect fruit size and tissue phosphorus and calcium content. This indicates that nutrient management must be optimized according to substrate type (Tumbure et al., 2025).

Substrates derived from organic waste have clear advantages in circular use. Compost-amended substrates not only improve physical structure but also supply abundant nitrogen, phosphorus, and potassium, reducing mineral fertilizer use by 10%-50% and lowering nutrient losses in drainage and spent substrates. Vermicompost produced from cattle manure or sludge can significantly enhance substrate fertility, microbial activity, and enzyme activity, alleviate continuous cropping problems, and increase yield and fruit quality by 18%-20%, while also improving sugar, vitamin C, and amino acid contents (Yeganeh et al., 2024).

Spent mushroom substrate can replace 15%~25% of peat and increase yield and biomass with little impact on photosynthesis, thus enabling resource recycling of waste (Prasad et al., 2021). End-use assessments show that organic substrates with reduced peat and added biochar have high carbon sequestration potential and can be reused as soil amendments. Biochar increases carbon content and cation exchange capacity, enabling a cascade use model—first as a cultivation substrate, then as a soil amendment (Vandecasteele et al., 2023b).

Looking ahead, the development of environmentally friendly substrates should be based on local resources (such as wood, crop residues, livestock manure, and sediments), combined with pretreatment and precise nutrient management. Attention should also be given to microbial community changes and pathogen risks during reuse. Achieving coordinated optimization in terms of physical structure, nutrient buffering capacity, and compatibility with precision fertigation systems will be essential for building efficient and low-environmental-impact greenhouse strawberry production systems.

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# Influence of Planting Density on Citrus Yield and Tree Vigor

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**Abstract** This study analyzes the mechanisms by which different planting densities affect citrus yield and tree vigor, and compares low-, medium-, and high-density cultivation systems in terms of yield formation, tree structure, and resource use efficiency. Increasing planting density can significantly improve early yield per unit area and accelerate canopy closure and light interception efficiency. However, it also reduces yield per tree and intensifies competition for light, water, and nutrients, which may lead to excessive canopy shading, increased pests and diseases, and a decline in long-term productivity. In long-term production, medium-density systems often perform better in terms of yield stability and economic returns. Rootstock type and cultivar characteristics play a decisive role in adaptability to dense planting. Dwarfing or semi-dwarfing rootstocks can effectively control tree vigor and improve fruiting efficiency, serving as an important foundation for high-density cultivation. Proper pruning, water and fertilizer management, and mechanization support can help mitigate the negative effects of high-density planting. In the future, combining precision agriculture technologies with breeding innovations will enable dynamic optimization of planting density and sustainable orchard design.
**Keywords** Planting density; Citrus; Yield formation; Tree vigor regulation; High-density cultivation

## 1 Introduction

Citrus is one of the most economically important and widely grown fruit crops in the world. It includes sweet orange, mandarin, grapefruit, lemon, and lime. Citrus fruits are also an important part of the human diet, as they are rich in vitamin C, dietary fiber, and various phytochemicals.

Traditional citrus orchards usually use low planting density and wide spacing. This allows trees to develop large canopies and makes mechanized operations easier. However, it also leads to slow canopy closure and low land and resource use efficiency during the early fruiting stage (Wheaton et al., 1995). In contrast, high-density planting systems aim to speed up canopy development, improve light interception, and increase yield per unit area in the early growth and early bearing stages. At the same time, high density can increase competition for light, water, and nutrients, raise the risk of pests and diseases, and make management practices such as pruning, spraying, and harvesting more complex. It may even shorten orchard lifespan or reduce long-term economic returns (Vidalakis et al., 2011).

In low-density systems, the number of trees per hectare is small and spacing is large. This usually supports vigorous growth, larger canopy size, and easy machine movement, but it may delay canopy closure and the achievement of maximum yield. Medium-density systems try to balance faster canopy formation with higher early yield, while controlling tree vigor, reducing shading, and lowering management costs. High-density and super-high-density systems can reach or exceed 1 000~2 000 trees per hectare. In some citrus studies, these systems have shown clear advantages in improving early yield and land use efficiency, especially when combined with dwarfing or semi-dwarfing rootstocks (Haque and Sakimin, 2022). In citrus production, the development of semi-dwarfing and dwarfing rootstocks, dwarfing viroids, precision irrigation and fertilization, and improved pruning and training practices has further supported the use of high-density planting systems (Azevedo et al., 2020).

This study aims to systematically evaluate how different planting densities affect citrus yield and vegetative growth. It compares low-, medium-, and high-density systems in terms of canopy development, tree size, and vigor. It also quantifies yield per tree, yield per unit area, and their components under different density levels. In addition, the study explores the relationship between tree vigor and yield efficiency under different planting densities. The results are expected to provide a theoretical basis for selecting an optimal planting density that balances land use efficiency and tree performance, and to offer practical guidance for orchard design and management under different production conditions.

## 2 Theoretical Basis of Planting Density Effects

### 2.1 Light interception and canopy structure

Crop yield is closely related to the amount of light intercepted per unit land area. It also depends on how efficiently this light energy is converted into chemical energy and finally into harvestable yield. Canopy structure—defined by tree height, canopy width, leaf area index (LAI), and the spatial distribution of leaves—determines both the amount and vertical distribution of photosynthetically active radiation (PAR) within the canopy (Murchie and Burgess, 2022).

In recent years, studies in citrus orchards have used UAV-based LiDAR and radiation transfer models to analyze the relationship between canopy structure and light interception. By linking canopy geometry, tree spacing, and row orientation with PAR interception, researchers found that both canopy structure and planting density strongly affect the daily and seasonal patterns of light interception. These changes further influence water use and overall productivity (Guillén-Climent et al., 2012; Rojo et al., 2023).

Planting density interacts with these structural factors by altering tree size, canopy overlap, and LAI. High-density planting usually leads to faster canopy closure and higher LAI, which improves light interception at the population level. However, it also increases self-shading within the canopy (Singh et al., 2020; Oliveira et al., 2024).

When LAI becomes too high, further increases in leaf area contribute little to total light interception but significantly increase internal shading. Once light interception exceeds about 50%, the positive relationship between light interception and yield starts to weaken (Dian et al., 2023).

### 2.2 Resource competition mechanisms

Plants compete for resources mainly in two ways. First, individuals can capture resources before their neighbors (pre-emption of resource supply). Second, they can reduce the availability of resources in a shared environment.

As tree density increases, root systems overlap more, which strengthens belowground competition. Under strong resource limitation, this may lead to earlier self-thinning (Huang et al., 2021). In plantations, high density intensifies competition for light, water, and $CO_2$. It also increases shading and limits resource access for smaller individuals. When density exceeds the environmental carrying capacity, mortality risk rises and overall productivity declines.

In semi-arid regions or under irrigation systems, water competition is especially important in citrus production. Different rootstock genotypes vary in their ability to explore soil and tolerate low water potential. Water competition mainly works by reducing soil water availability. As a result, genotypes that can tolerate drought or maintain water uptake under low water conditions gain an advantage (Craine and Dybzinski, 2013).

Under high-density planting, overlapping root zones increase the consumption of soil water and nutrients within tree rows. If irrigation and fertilization are not adjusted to match higher demand, drought stress and nutrient deficiency may become more severe (De Oliveira Sousa et al., 2024; Pokhrel et al., 2025).

When water is limited, belowground competition becomes more important than aboveground competition. This shows that root competition is a major constraint in high-density systems under water stress (Foxx and Fort, 2019). In contrast, when water is sufficient, aboveground competition-mainly for light-becomes the main factor limiting growth.

### 2.3 Physiological responses of citrus trees

At the leaf level, photosynthesis is strongly influenced by the local light environment. In citrus canopies with a clear vertical light gradient, upper leaves are usually close to light saturation, while lower leaves receive less light and therefore have lower net $CO_2$ assimilation rates.

Measurements across canopy layers under different citrus cultivation systems show that in traditional systems and wide-row-narrow-spacing systems, photosynthetic rate, stomatal conductance, and transpiration all decrease from the upper canopy to the lower canopy. In contrast, in systems with more uniform light distribution, such as hedgerow systems, lower leaves can maintain relatively high photosynthetic activity. In these improved canopy structures, higher photosynthetic nitrogen use efficiency (PNUE) indicates better coordination between light capture, nitrogen allocation, and photosynthetic capacity.

Besides photosynthesis, changes in microclimate and resource availability caused by planting density also affect plant hormone balance and growth patterns. Endogenous hormones such as auxin, cytokinin, gibberellin, and abscisic acid play key roles in regulating apical dominance, shoot elongation, branching, and the balance between vegetative and reproductive growth (Dhurve et al., 2025).

In dense canopies, changes in light quality (low red to far-red ratio) and increased shading trigger shade-avoidance responses through phytochrome signaling. This promotes shoot elongation, alters branching patterns, and shifts assimilate allocation toward stems (Jin et al., 2021; Murchie and Burgess, 2022). In contrast, more open canopies and moderate planting densities help maintain a more balanced hormonal environment.

## 3 Effects of Planting Density on Citrus Yield

### 3.1 Relationship between yield per tree and yield per unit area

In tropical fruit crops, including citrus, high-density planting usually leads to lower yield per tree but higher yield per unit area, especially during the early to mid-bearing stages.

In acid lime, ultra-high-density planting (1 600 trees·hm$^{-2}$) showed the lowest yield per tree, but the yield per unit area was more than twice that of conventional density (400 trees·hm$^{-2}$). By the fifth year, the maximum yields reached 35.36 t·hm$^{-2}$ and 11.64 t·hm$^{-2}$, respectively (Ladaniya et al., 2020).

In Nagpur mandarin, a spacing of 2 × 2 m produced much higher yields per unit area during the first three years—26 times, 7.1 times, and 4.6 times higher than conventional planting—although the yield per tree decreased (Ladaniya et al., 2021).

In sweet orange, long-term experiments compared densities ranging from 513 to 1 000 trees·hm$^{-2}$ under different rootstock vigor conditions. Increasing planting density consistently reduced yield per tree, especially with vigorous rootstocks. However, over a 9-year period, the cumulative yield per unit area at 1 000 trees·hm$^{-2}$ increased by about 27%, and this trend was not affected by rootstock type (Girardi et al., 2021).

### 3.2 Fruit quality parameters

In sweet orange, smaller spacing (such as 2.40 × 4.50 m compared with 4.50 × 6.00 m) increased yield per unit area but reduced trunk growth and fruit size. However, total soluble solids (TSS), acidity, and juice content were not significantly affected in some studies (Haque and Sakimin, 2022).

In 'Ray Ruby' grapefruit under HLB conditions, high-density planting (975 trees·hm$^{-2}$) increased fruit acidity by 18%, and soluble solids content was also higher than in low-density planting (300 trees·hm$^{-2}$). This suggests that under disease pressure and intensive nutrient management, high density may even improve some quality traits (Phuyal et al., 2020). Across two growing seasons, fruit acidity and soluble solids content at 975 trees·hm$^{-2}$ were consistently higher than those at 300~440 trees·hm$^{-2}$.

### 3.3 Yield stability and long-term productivity

Experiments conducted in Japan, Florida, and Australia across a wide range of planting densities (e.g., 1 250~10 000 trees·hm$^{-2}$ for Satsuma mandarin and 359~718 trees·hm$^{-2}$ for sweet orange in Florida) showed that the maximum annual yield at maturity was generally similar (about 50~100 t·hm$^{-2}$).

At very high densities, yield tended to decline over time due to increased competition and shading (Wheaton et al., 1995). In long-term comparisons over more than 20 years, moderate density (e.g., 2 500 trees·$hm^{-2}$ in Japan) performed better than extremely high density.

In high-density trials (2 020 trees·$hm^{-2}$) involving ‘Hamlin’, ‘Valencia’, ‘Murcott’, and grapefruit, yields reached 23~75 t·$hm^{-2}$ after 7 years. Under Florida conditions, densities above about 1 000 trees·$hm^{-2}$ did not show clear long-term advantages compared with moderate densities (350~900 trees·$hm^{-2}$) (Wheaton et al., 1991).

## 4 Effects of Planting Density on Tree Vigor

### 4.1 Vegetative growth characteristics

Tree height, canopy volume, and shoot growth show clear responses when plant spacing is reduced. Studies on citrus high-density planting (HDP) indicate that trees in dense orchards are usually taller but have smaller lateral canopy spread. This is mainly because competition for light promotes vertical growth, while limited space restricts horizontal expansion.

For example, in cultivars such as Kinnow mandarin, high-density planting increases tree height. However, under wider spacing, individual trees develop larger canopy volumes, since they can grow with less competition and maintain a more “natural” canopy structure.

In high-density Nagpur mandarin orchards (2 × 2 m), the highest planting density resulted in the tallest trees and the greatest interception of photosynthetically active radiation (PAR). However, the leaf area index (LAI) was the lowest, suggesting that the canopy became narrow and upright rather than well-layered (Ladaniya et al., 2021).

Young sweet orange trees also show faster canopy development under high-density conditions. When planting density increased from 447 trees·$ha^{-1}$ to 897 trees·$ha^{-1}$, the leaf area per tree almost doubled during orchard establishment. Under sufficient irrigation, canopy volume also increased more rapidly in high-density treatments (Hamido and Morgan, 2020).

### 4.2 Root development

Irrigation experiments on citrus trees grown at different densities in sandy soils show that moderate irrigation (about 78%~81% ETc) improves fine root length density (FRLD), root survival, and lifespan. These effects are more obvious under low to medium densities. However, even at higher densities, root development remains good as long as water is not severely limited (Atta et al., 2024).

A study on 16-year-old ‘Pineapple’ sweet orange trees under different spacings (3.0 × 4.6 m, 4.6 × 6.1 m, and 6.1 × 7.6 m) showed that roots can extend to at least 1.9 m depth and are well distributed both within and between rows (Castle, 1980). Root density is highest in the topsoil and decreases with depth. Trees planted at wider spacing have lower root density, while at medium spacing, roots from neighboring trees tend to overlap. Under these soil and water conditions, root competition is not a major limiting factor in high-density citrus orchards.

Studies using minirhizotron techniques also show clear differences in root distribution among rootstocks. These differences are important for high-density systems. For example, trifoliate orange produces finer roots that grow deeper and closer to the trunk, while hybrid rootstocks such as Rusk citrange and sweet orange tend to have shallower or more horizontally spread roots (Zheng et al., 2024).

Fine roots are mainly concentrated in the 0~30 cm or 0~45 cm soil layers, but their vertical and horizontal distribution varies depending on the rootstock. This means that dwarfing or semi-dwarfing rootstocks not only affect shoot growth but also change how roots occupy soil space, which in turn influences root overlap and competition in dense orchards.

### 4.3 Susceptibility to pests and diseases

In high-density and ultra-high-density acid lime orchards, the incidence of leaf miner and bacterial canker is higher compared to traditional spacing (5 × 5 m). However, fruit quality is not significantly affected (Ladaniya et al., 2020).

Dense orchards usually have thicker canopies and higher LAI, which leads to more shading and longer leaf wetness duration. These conditions are closely related to increased disease risk.

Research on Huangguogan orchards shows that reducing planting density from 2 × 3 m to 4 × 5 m significantly changes the microenvironment. Under lower density, photosynthetically active radiation increases by more than 400%, while air and soil temperatures rise slightly, and air humidity and $CO_2$ concentration decrease (Dong et al., 2020).

In contrast, high-density orchards are usually cooler, more humid, and more shaded. These conditions favor the development of fungal and bacterial diseases and also reduce the effectiveness of pesticide penetration and drying.

Although higher root density can improve water and nutrient use efficiency, dense canopies make pest and disease control more difficult. This often requires more frequent or more precise spraying, and sometimes smaller equipment is needed to work in narrow row spacing.

## 5 Interaction Between Cultivar and Rootstock

### 5.1 Differences in cultivar adaptation to high-density planting

Different citrus cultivars vary greatly in growth habit and vigor, which directly affects how well they adapt to high-density systems. In a high-density trial with 2020 trees per hectare, studies on 'Hamlin' sweet orange, 'Valencia' sweet orange, 'Murcott' tangor, and 'Redblush' grapefruit showed that cultivars with moderate vigor, upright growth, and early bearing performed best. In contrast, those with overly strong vigor or excessive dwarfing performed poorly (Wheaton et al., 1991). Among them, 'Murcott' showed good adaptability because of its naturally small size and upright canopy. However, even under high-density conditions, it still showed clear alternate bearing. Grapefruit, which has the strongest vigor, produced relatively high yields under dense planting, but its canopy becomes difficult to manage in the long term.

In experiments with 'Valencia' sweet orange grafted onto 51 hybrid rootstocks, many dwarfing and semi-dwarfing combinations showed high productivity. However, some small-tree combinations were more sensitive to drought and had lower yields under rainfed conditions (Costa et al., 2021). For 'Shamouti' sweet orange, when grafted onto weak rootstocks such as 'Swingle' and 'C-13', the suitable planting density can reach about 337~363 trees $ha^{-1}$. In contrast, when grafted onto vigorous rootstocks like 'Rangpur', 'Sunki', or 'Cleopatra', trees become much larger (>4.2 m), making them suitable only for lower planting densities (Carvalho et al., 2022).

### 5.2 Effects of rootstocks on tree size and vigor

Rootstock selection is a key tool to match tree vigor with planting density. In a 9-year 'Valencia' trial in Brazil, four rootstocks with different vigor levels were tested: super-standard IAC 1710, standard diploid Swingle, semi-dwarf IAC 1697, and dwarf tetraploid Swingle. Even under the same density (513~1 000 trees $ha^{-1}$), there were large differences in tree size and yield (Girardi et al., 2021). Trees grafted onto the most vigorous rootstock produced about 2.5 times more fruit per tree than those grafted onto dwarf tetraploid Swingle. However, regardless of rootstock type, increasing density to 1000 trees $ha^{-1}$ still raised cumulative yield per area by about 27%.

Fruit quality was influenced more by rootstock than by planting density, and dwarfing rootstocks often increased soluble solids content. It is also worth noting that the cumulative incidence of HLB symptoms on the vigorous IAC 1710 rootstock was about twice that on dwarf Swingle 4×. This suggests that smaller trees may be easier to manage under disease pressure. Dwarfing rootstocks such as 'Flying Dragon', 'US-897', 'FA 517', and 'HTR-051' are widely considered key tools for high-density orchards. They can limit tree height to about 2.5 m and reduce canopy volume to 40%~60% (semi-dwarf) or less than 40% (dwarf) of standard trees (Hayat et al., 2022).

A detailed physiological study of 'Shatangju' mandarin grafted onto 11 rootstocks showed that 'Flying Dragon' causes strong dwarfing by reducing node number, shortening internodes, and decreasing trunk diameter. This is also linked to changes in hormones and metabolites, such as lower ABA and GA levels and altered organic acids and flavonoids. Although substandard, semi-dwarf, and dwarf rootstocks reduce yield per tree, they improve yield efficiency (kg fruit $m^{-3}$ canopy) and allow closer spacing. In 'Lane Late' sweet orange, FA13 and FA41 produce smaller trees, and under higher density they show strong yield potential per area. FA13 also improves nutrient use efficiency under low fertilizer input, making it suitable for intensive but sustainable systems (Hervalejo et al., 2021) (Figure 1).

In 'Valencia', several low-vigor trifoliate hybrids (such as IPEACS-239, IPEACS-256, and US-802) showed about 55% higher production efficiency than the vigorous 'Rangpur' lime, making them good candidates for high-density systems (Domingues et al., 2021). In high-density systems, dwarfing citrandarin rootstocks such as IAC 1600, 1697, and 1711 maintained high productivity while improving water use efficiency and reducing HLB susceptibility, performing better than standard Swingle (Devite et al., 2025).

Figure 1 Overview of the experimental plot (Adopted from Hervalejo et al., 2021)

### 5.3 Matching planting density with genetic traits

The optimal planting density in citrus depends on a proper balance among scion vigor, rootstock dwarfing ability, and production goals. For traditional vigorous rootstocks, densities above 1 000 trees $ha^{-1}$ are usually not justified. Once orchards reach full production, yield per year is often no longer strongly affected by density, while excessive density increases competition and management difficulty. When both scion and rootstock are vigorous, a moderate density (about 300~700 trees $ha^{-1}$) is more appropriate. When vigorous scions are grafted onto dwarf or semi-dwarf rootstocks, higher or even super-high densities can be used because tree size is controlled and efficiency is improved. Long-term trials with 'Valencia' grafted onto dwarf TSKC × TRFD citrandarins showed that adjusting spacing based on smaller tree size can increase productivity to about 40 t $ha^{-1}$ $year^{-1}$, nearly doubling yield (Costa et al., 2021).

In Spain, 'Salustiana' grafted onto the dwarf FA517 rootstock performed well under super-high-density planting with mechanical harvesting. Proper rootstock selection can support both high-density systems and mechanization (Hervalejo et al., 2022). For 'Flying Dragon', spacing of 1.5~2.5 m within rows and 4~5 m between rows is recommended to balance early yield and canopy management (Kumar, 2024). Compact or naturally small scions (such as some mandarins and 'Murcott') can be combined with moderately dwarfing rootstocks to create "walkable" orchards, allowing ground-based harvesting and reducing pesticide use.

In 'Shamouti', weaker trifoliate-related rootstocks (such as Swingle and C-13) support higher planting densities than vigorous citrus or Rangpur rootstocks, while still maintaining good fruit quality (Carvalho et al., 2022). On the other hand, under water-limited conditions or high HLB pressure, using high-density systems together with small, efficient rootstocks (such as dwarf citrandarins or some tetraploid rootstocks) can stabilize yield per area, improve water use efficiency, and reduce the risk caused by individual tree loss.

## 6 Agronomic Management Practices Supporting Optimal Planting Density

### 6.1 Pruning and canopy management

In a study on 35-year-old 'Valencia' sweet orange trees, four pruning treatments were applied every year in mid-February, removing 0%, 25%, 50%, and 75% of the main branches. As pruning intensity increased, overall canopy volume decreased, but vegetative growth was stimulated, with longer shoots and larger leaves. At the same time, light penetration inside the canopy improved (Al-Saif et al., 2023). Heavy pruning (75% branch removal) resulted in the highest fruit yield, increasing by nearly 20% compared with the unpruned control. It also significantly improved fruit size, juice content, total soluble solids (TSS), TSS/acid ratio, and vitamin C content. Even in older and larger trees, strong pruning can renew the canopy, restore internal light conditions, and improve both yield and fruit quality.

Mechanical pruning is widely used in high-density orchards to control canopy size and reduce labor costs. It is especially suitable for hedgerow systems combined with topping and side hedging. In 'Finn 95' lemon, a 4-year comparison of five pruning strategies showed that alternating full mechanical pruning (topping, skirting, and double-sided hedging) with manual pruning, or using only mechanical pruning, significantly reduced pruning time and increased net profit compared with continuous manual pruning. These approaches did not show clear long-term yield reduction (Martin-Gorriz et al., 2021). Similarly, in 'Clemenules' mandarin, a 4-year experiment comparing 12 pruning strategies showed that alternating mechanical pruning (topping plus one-sided hedging) with manual pruning maintained stable tree size and canopy vitality. Yield was comparable to fully manual pruning, while costs were lower (Fonte et al., 2022).

In China, new labor-saving cultivation systems further highlight the link between canopy structure and light use. In Hubei, a comparison among traditional planting, wide-row–narrow-spacing planting, and a "fence-type" system showed clear differences in vertical canopy structure measured by UAV LiDAR. The point cloud density above half tree height was 64.85% in the wide-row system and 71.94% in the fence-type system, compared with only 50.02% in the traditional system (Dian et al., 2023). The fence-type system forms a vertical hedgerow canopy using support structures and pruning. This improves light distribution and increases photosynthetic rates in all canopy layers. The average photosynthetic rate of lower canopy leaves in the fence system was 1.74 times that of the traditional system and 1.66 times that of the wide-row system.

### 6.2 Nutrient and water management

Under high planting density, competition for soil resources becomes stronger. Therefore, precise water and nutrient management is essential to maintain tree vigor, yield, and root health. In semi-arid orange orchards, a 5-year study on deficit irrigation showed that compared with full irrigation (100% ETc), sustained subsurface deficit irrigation (SSDI), regulated deficit irrigation (RDI), and partial root-zone drying (PRD) reduced water use by 25%, 33%, and 49%, respectively, without significant yield loss (Stagno et al., 2024). At the same time, water use efficiency increased and some fruit quality traits improved. Vitamin C content was higher under RDI (62.7 vs 58.5 mg 100 $mL^{-1}$). SSDI and PRD increased pulp color index to around 10, compared with 8.44 in the control. Leaf nutrient levels remained generally adequate, although potassium was slightly low, suggesting that K monitoring is important under deficit irrigation.

In high-density young 'Valencia' orchards (955 trees $ha^{-1}$) under Huanglongbing (HLB) conditions in Florida, drip or microsprinkler irrigation combined with fertigation was compared with standard-density orchards (358 trees $ha^{-1}$) using controlled-release fertilizers (Ferrarezi et al., 2020). Nitrogen application followed UF/IFAS recommendations: 0.11-0.34 kg N per tree annually for non-bearing trees, and 224 kg N $ha^{-1}$ annually for bearing trees, adjusted based on leaf analysis. After seven years, leaf nutrient concentrations were generally within or above recommended levels. High-density fertigation treatments produced the highest yield per unit area and total soluble solids. In some years, yields were 86%~300% higher than standard density, even though individual tree canopy volume was smaller (4.3~5.9 $m^3$ vs 6.2~7.2 $m^3$).

In Florida sandy soils, irrigation levels of 50%, 78%, and 100% ETc were compared under different planting densities. The moderate irrigation level (about 78% ETc) improved fine root length density, root survival, and root lifespan compared with both deficit and full irrigation (Atta et al., 2024). At the highest density, trees experienced stronger water stress in spring, indicated by lower stem water potential, showing more intense competition. Moderate irrigation reduced stress and improved stomatal conductance in both low- and medium-density treatments. Compared with traditional irrigation, reducing water by about 20%~30% may improve soil moisture distribution and promote deeper, more resilient root systems. This is especially important in high-density orchards, where shallow roots are more vulnerable to drought and nutrient depletion.

In southern China, a 2-year field experiment combined drip irrigation at 70% field capacity with 2.5 g $L^{-1}$ alginate oligosaccharide (AOS) applied 8–10 times (W70AOS2.5). Compared with no AOS, this treatment increased yield by 11.9%~13.3%, total soluble sugars by 15.2%~17.5%, and sucrose by 18.9%-20.8%. Potassium use efficiency and water use efficiency increased by 51.1%~62.2% and 12.0%~13.3%, respectively (Li et al., 2024). This treatment also increased net photosynthetic rate, total root length, root surface area, and root volume. It improved soil aggregate stability (>0.25 mm), increased available potassium and cation exchange capacity in the topsoil (0-20 cm), and reduced leaching of water and potassium to deeper soil layers.

Monitoring tools such as mobile lysimeters and leaf analysis can further improve fertilization accuracy. In a ‘Nules’ clementine orchard in Morocco, nutrient concentrations in soil solution and leaves showed high variability (about 55% in soil solution and 63% in leaf macronutrients), mainly driven by irrigation, fertilization, and soil conditions (Zayani et al., 2024). Regular monitoring of N, P, K, Mg, and Ca in soil and leaves allows better adjustment of fertilization timing and rates, helping meet crop needs while reducing nutrient loss and production costs.

### 6.3 Mechanization and labor efficiency

High-density planting, combined with controlled tree height and narrow canopy width, makes it easier for tractors to pass and supports mechanical pruning, precision spraying, and even mechanical harvesting in some systems.

Maintaining an appropriate canopy size and avoiding overcrowding not only improves light interception and yield, but also enhances spray coverage and machine efficiency. Large and unmanaged canopies reduce spray penetration inside the canopy and interfere with machine operation. When canopies are too dense and irregular, up to 28% of spray droplets may not reach the tree surface (Verbiest et al., 2020).

In pome fruit systems, semi-autonomous pruning systems have been developed for planar “upright fruiting offshoot” structures. A robotic pruning prototype achieved a cutting success rate of 58% on 10 trees in a planar sweet cherry orchard (You et al., 2023).

## 7 Future Perspectives

### 7.1 Integration with precision agriculture: remote sensing and density optimization

High-density citrus orchards are well suited for integration with precision agriculture. Many key limitations in these systems—such as resource competition, spatial variability, and complex canopy structure—are essentially spatial problems. Multi-scale remote sensing can now quantify canopy nitrogen content (CNC) and link it directly to yield. This makes it possible to manage nutrients under different planting densities. In commercial citrus orchards in Israel, a model combining UAV multispectral indices, Sentinel-2 indices, and UAV structural data derived from SfM achieved good accuracy in estimating CNC ($R^2$ = 0.80), which was better than using a single data source (UAV only: $R^2$ = 0.68; Sentinel-2 only: $R^2$ = 0.48) (Avioz et al., 2025). CNC expressed per tree was also strongly related to yield ($R^2$ = 0.66). This suggests that nitrogen status from remote sensing can be used as an indicator of productivity and may reflect stress levels related to planting density.

Although evergreen and dense canopies, as well as pigment saturation, can make measurements more difficult, remote sensing has shown the ability to estimate leaf area index, chlorophyll, water status, and biochemical traits at leaf, tree, and orchard scales (Ali and Imran, 2021). These traits affect light interception and photosynthesis, and therefore influence the performance of planting density. UAV and satellite-based trait maps can guide variable fertilization and irrigation, and help identify overcrowded areas. These areas may need canopy thinning or local spacing adjustments. More broadly, precision agriculture based on remote sensing—using high-resolution images, vegetation indices, yield mapping, and cloud platforms—has already been widely used in annual crops. It is now providing useful experience for orchard systems (Sishodia et al., 2020).

Small UAVs are increasingly used to measure tree geometry (such as height and canopy size), productivity, and resource use efficiency. In citrus, UAV phenotyping of 4,931 trees across 25 rootstocks achieved 99.9% accuracy in tree detection and counting. The estimated canopy size also showed a strong correlation with field measurements ($R = 0.84$) (Ampatzidis et al., 2019). The cloud-based AI platform Agroview further extended this approach. It analyzed 175 977 citrus trees across 39 blocks under both normal and high-density systems. The mean absolute percentage error was 2.3% for tree detection, 4.5%~12.9% for tree height, and 12.9%~34.6% for canopy area (Ampatzidis et al., 2020). In the future, combining canopy trait maps, soil sensor data, and decision algorithms will support dynamic density management. This means planting, pruning intensity, and input use can be adjusted over time based on spatial performance.

### 7.2 Breeding for varieties suitable for high-density systems

The long-term success of high-density systems depends on whether varieties and rootstocks are biologically suited to crowded conditions. Dwarfing and size-controlling rootstocks are key components of modern high-density orchards. They allow higher planting density and make pruning, harvesting, and spraying easier and more efficient. Rootstocks such as ‘Flying Dragon’, ‘FA 517’, ‘HTR-051’, ‘US-897’, and ‘Red tangerine’ have made it possible to test very high densities (up to 10,000 trees·$hm^{-2}$), such as in Japanese Wase satsuma systems. However, the best spacing still depends on the variety and location, and must be determined through long-term trials under modern production conditions (Hayat et al., 2022).

A study in Florida compared diploid and tetraploid rootstocks for ‘Valencia’ orange under Huanglongbing conditions. Tetraploid rootstocks reduced tree size by about 55% and increased yield efficiency by 27%. Although total yield per tree was lower, this shows their potential in compact high-density systems, where yield loss per tree can be offset by more trees per area (Kunwar et al., 2022).

New plant breeding techniques (NPBTs), especially gene editing and cisgenesis, provide new tools for developing ideal materials for high-density systems. Most current work focuses on disease resistance, such as editing CsLOB1 to improve resistance to citrus canker. However, once key genes are identified, these tools can also be used to improve tree architecture, growth vigor, and early bearing (Salonia et al., 2020). Major challenges in citrus breeding—such as long juvenile periods, apomixis, and high heterozygosity—are still limiting progress. Combining NPBTs with early flowering systems and marker-free selection could speed up the development of dwarf, early-bearing, and stress-tolerant genotypes. High-throughput phenotyping using UAV and imaging technologies has already been used to evaluate canopy size and health in rootstock populations. Controlled drought studies have identified genotypes such as X639 and RLC-4 with better water uptake, improved root systems, and stronger stress tolerance (Morade et al., 2025). In the medium term, combining genomic selection, NPBTs, and high-throughput phenotyping will support breeding programs designed specifically for high-density orchards under different climates and management levels.

### 7.3 Sustainable orchard design strategies

Future high-density citrus systems should not only focus on yield but also consider ecological sustainability, including soil quality, biodiversity, and long-term resilience. A framework for agroecological orchard design, based on studies in apple and citrus systems, highlights several key principles: (i) agronomic goals should be defined separately for non-bearing and bearing stages; (ii) variety selection and spatial arrangement of trees and ground cover are key management tools; (iii) perennial spatial design (such as row spacing, traffic lanes, and vegetation layers) must be planned in advance; (iv) long-term interactions (such as pest accumulation and soil fertility changes) require full life-cycle evaluation, not just short-term yield analysis (Simon et al., 2016). In tropical citrus systems, there is no clear dormant period, which leads to higher pest pressure. However, continuous vegetation can also support biological control through ground cover and hedgerows, as long as disruptive practices like broad-spectrum pesticides and intensive tillage are minimized.

Orchards managed under organic or biodynamic systems, including agroforestry systems, generally show better soil properties than conventional citrus orchards. These include improved chemical properties (higher pH, phosphorus, cation exchange capacity, and soil organic carbon), better physical structure (lower bulk density and improved porosity), and stronger biological activity (higher enzyme activity and soil fauna feeding) (Pilon et al., 2023). Agroforestry citrus systems can reach soil quality levels similar to forests aged 40-200 years. Rich herbaceous vegetation, especially species from the Fabaceae family, plays an important role by providing green manure and ecological services. In the future, high-density orchards can integrate agroforestry practices or diverse ground covers between rows to maintain soil structure, organic matter, and biodiversity.

Managing drip irrigation at about 70% of field capacity, combined with alginate oligosaccharide treatment, can improve yield, sugar content, sucrose levels, and the efficiency of potassium and water use (with potassium use efficiency increasing by up to 62%). It also improves root growth, soil aggregate stability, and increases available potassium and cation exchange capacity in the topsoil, while reducing deep leaching losses (Li et al., 2024). Low-input practices such as organic fertilization, field margin vegetation, and integrated pest management are practical and cost-effective ways to reduce environmental impact. However, better technical guidance and demonstration are still needed to promote their wider adoption.

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The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review and Outlook Open Access

# Integrated Orchard Management for High-Quality Bayberry Production

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**Abstract** This study focuses on the integrated management techniques for high-quality waxberry (*Myrica rubra*) orchards. Based on the biological characteristics, nutritional and medicinal value, and current status of the industry, the main problems in current production are analyzed. The study systematically summarizes key technical approaches to improving yield and fruit quality, including orchard site selection and establishment, cultivar selection and renewal, soil and fertilization management, water regulation, quality improvement, and green pest and disease control. By optimizing soil improvement and organic fertilizer application, implementing precise irrigation and drainage control, and reasonably regulating nutrient supply and orchard structure, fruit size, sugar content, and flavor quality can be significantly improved, while reducing environmental pressure. Combined with smart orchard technologies, ecological cultivation models, and the integration of agriculture and tourism, this research helps promote the transformation of the waxberry industry toward high quality, green development, and sustainability, and provides practical references for building a high-quality production system and upgrading the industry.

**Keywords** Waxberry (*Myrica rubra*); Orchard management; Quality improvement; Water and fertilizer regulation; Green control

## 1 Introduction

Chinese bayberry (*Myrica rubra* Sieb. et Zucc.), also known as red bayberry or waxberry, is one of the most representative subtropical fruit trees in East Asia. It is the only species with economic cultivation value in the family Myricaceae. It has been cultivated in southern China for at least 2 000~7 000 years, and the current planting area exceeds 330 000 hectares, with an annual production close to 1 million tons (Zhang et al., 2015). In addition to China, Myrica species are widely distributed in Asia, North America, South America, and parts of Europe, showing their global importance as both a specialty fruit and a medicinal resource. In major producing regions such as Zhejiang, Jiangsu, Fujian, and Guangdong, Chinese bayberry plays a key role in regional agricultural economies and farmers' livelihoods. This is mainly due to the development of specialized orchards, the promotion of superior cultivars (such as 'Dongkui' and 'Ding'ao'), and the continuous expansion of fresh fruit and processed product markets.

Chinese bayberry fruit is considered a "green and healthy food," rich in soluble sugars, organic acids, vitamins (especially vitamin C), minerals, and dietary fiber. Phytochemical studies have shown that it contains abundant bioactive compounds such as proanthocyanidins, anthocyanins, flavonols (e.g., myricetin and quercetin derivatives), and phenolic acids, which give it strong antioxidant capacity and diverse biological activities (Zhang et al., 2022). Extracts from its fruits, leaves, and bark have been reported to show antioxidant, anti-inflammatory, anti-allergic, anti-obesity, anti-diabetic, antibacterial, and anti-tumor effects, and may provide benefits for cardiovascular, cerebrovascular, and neuroprotective functions (Ren et al., 2019; Singh et al., 2025). These multifunctional properties support its wide industrial applications, ranging from fresh consumption and traditional processing (juice, wine, jam, preserved fruit, vinegar) to emerging uses such as extracting functional components, oils, and bioactive substances from seeds and processing residues (Mo et al., 2024).

The fruit ripening period of Chinese bayberry coincides with the rainy season in southern China. High humidity and insufficient sunlight often lead to yield reduction, sugar dilution, and shorter shelf life. The fruit has exposed skin and a soft texture, along with very high sugar and water content, making it highly prone to cracking, mechanical damage, rapid decay, and postharvest diseases. Under normal temperature conditions, its shelf life is usually only a few days. In many production areas, traditional orchard management still relies on high input levels, including heavy use of chemical fertilizers and frequent application of pesticides or even antibiotics to maintain yield and control pests and diseases (Yi et al., 2024). Problems such as a high proportion of small fruits, uneven coloration, unstable sweetness and flavor, serious fruit cracking, and significant pre- and post-harvest disease pressure are still common, limiting the improvement of economic benefits.

This study systematically integrates the biological characteristics, nutritional and medicinal values, and recent progress in orchard management of Chinese bayberry, and explains the theoretical basis and practical significance of integrated orchard management for achieving high-quality fruit production. It clarifies the important role of Chinese bayberry in regional and global fruit production systems, summarizes its nutritional, economic, and therapeutic values, and analyzes the main problems and limitations in current orchard and postharvest management. Based on research on Chinese bayberry and other fruit trees, this study discusses the key components, mechanisms, and practical effects of integrated orchard management. By identifying development directions, application potential, and research needs, this study provides a theoretical framework and technical reference for transforming the Chinese bayberry industry from a traditional high-input model to a high-quality, sustainable, and eco-friendly production system.

## 2 Orchard Site Selection and Establishment Techniques

### 2.1 Selection of suitable planting areas (slope, elevation, drainage)

Waxberry is suitable for growth in warm and humid subtropical climates, requiring sufficient sunlight, moderate rainfall, and good air circulation. In major production areas, it is usually planted on hilly or low mountain slopes (Chen et al., 2025). In the Taizhou region of Zhejiang Province, the most suitable areas are mainly distributed in mid-hill zones, while high mountains above about 800 m and low-lying plains prone to waterlogging or with high groundwater levels are not suitable for planting (Shou et al., 2011). Studies in ecologically fragile orchard areas show that gentle slopes of about 3-10° can achieve a good balance between drainage, erosion risk, and operational convenience, making them the most suitable for new orchard establishment (Hu et al., 2023). Elevation, slope, and aspect together determine temperature conditions, cold air movement, and solar radiation, all of which significantly affect flowering, fruit set, and fruit coloration of waxberry.

### 2.2 Soil improvement measures before orchard establishment

Surveys of waxberry orchards in Zhejiang Province show that local soils are generally acidic (pH 3.97~6.15), with low organic matter content. Phosphorus status is highly imbalanced, with low total phosphorus but very high available phosphorus. Available potassium is generally insufficient, and exchangeable magnesium deficiency is common, with some areas also showing calcium deficiency (Wang et al., 2019). These imbalances may lead to decline disease, weakened tree vigor, and reduced fruit quality.

The application of organic amendments such as farmyard manure, bio-organic fertilizers, and biochar has been proven to improve soil structure, increase organic matter content, raise pH, and enhance key nutrients (available N, P, K as well as Ca and Mg). At the same time, these practices can reshape the rhizosphere microbial community and metabolite composition (Ren et al., 2023). For compacted soils, deep plowing or subsoiling should be carried out, and organic amendments should be evenly incorporated into the planting zone. When soil pH or magnesium levels are too low, lime or magnesium fertilizers should be applied appropriately to create a deep and well-aerated root growth layer.

### 2.3 Orchard layout design (planting density, row spacing, roads, and drainage system)

Based on a 15-year study of waxberry orchards and decline disease trials in Zhejiang, a medium-density planting system with a spacing of about 4 m × 5 m (approximately 500 trees·$hm^{-2}$) can meet canopy growth needs while also facilitating mechanized operations (Ren et al., 2023).

For high-yield dwarf and dense planting systems, spacing should be adjusted according to variety vigor, rootstock type, and soil conditions to ensure good ventilation and light penetration. Planting patterns directly affect cultivation methods, plant health, yield, and fruit quality by regulating plant population per unit area and light interception patterns and intensity (Javaid et al., 2017; Haque and Sakimin, 2022). A row planting system (square or rectangular) is usually recommended, with rows oriented roughly north-south to optimize light distribution and facilitate mechanization. At the same time, a hierarchical road system (main roads and secondary paths) and drainage ditches designed along contour lines or slopes should be established to ensure rapid removal of excess surface water and prevent rill and gully erosion on slopes. Grass ditches or vegetative strips along drainage channels can further enhance soil stability and improve water quality (Simon et al., 2017).

### 2.4 Shelterbelt and ecological buffer zone design

Shelterbelts, as key structural components, can effectively reduce wind speed, prevent soil erosion, regulate the microclimate, and enhance habitat diversity, and have been widely recognized worldwide. Well-designed shelterbelts (considering height, width, orientation, and internal permeability) can not only increase crop yield, reduce evapotranspiration, and protect environmentally sensitive fruit crops, but also provide multiple ecosystem services, including biodiversity conservation, carbon sequestration, and air quality improvement (Weninger et al., 2021; Enescu et al., 2025).

In orchard ecosystems, artificially established shelterbelts and riparian buffer zones can also protect soil and water bodies. When tree species are well matched to site soil conditions, and combined with appropriate planting spacing and soil preparation measures, tree survival rates and growth performance can be significantly improved (Mathieu et al., 2024). For waxberry orchards located on open slopes, multi-row shelterbelts or hedgerows can be used, selecting local or well-adapted woody species and arranging them at suitable intervals based on shelterbelt height, with orientation perpendicular to the prevailing wind direction. At the same time, herbaceous ecological buffer zones should be established along field edges and around water bodies.

## 3 Variety Selection and Orchard Renewal

### 3.1 Recommendation of high-quality bayberry varieties

China has abundant bayberry germplasm resources. In recent years, genomic and phenotypic studies have clarified that different varieties show clear differences in fruit size, color, flavor, antioxidant capacity, and disease resistance (Zhang et al., 2024). At present, widely cultivated varieties such as ‘Biqi’, ‘Dongkui’, ‘Dingao’, ‘Zaojia’, as well as local elite lines like ‘SY-2’, are considered core high-quality resources due to their large fruit size, red to purple color, high soluble solids and anthocyanin content, and strong market acceptance.

‘Zaojia’ has been successfully bred as a multi-resistant variety and has been used as a reference material for high-quality genome assembly, showing its important value in both breeding and production. ‘SY-2’, a new bayberry variety selected from Dongting Mountain, shows strong tree vigor, large and round fruits (average 12.63 g), deep purple color, high soluble solids and anthocyanin content, and matures 5~7 days earlier than ‘Xiaoye Xidi’. It is considered a highly promising early-maturing high-quality variety (Dai et al., 2012). At present, multi-omics platforms such as the Bayberry Database have integrated genomic, transcriptomic, molecular marker, and germplasm resource information, which greatly promotes the precise selection and application of superior varieties in production (Jiao et al., 2012).

### 3.2 Matching varieties with ecological environment

In Zhejiang and Yunnan, ecological zoning based on temperature, extreme low temperature, rainfall during fruiting period, air humidity, altitude, and terrain can divide bayberry planting areas into most suitable, suitable, marginal, and unsuitable zones. Among them, regions with warm winters, humid spring and summer, and hilly or semi-mountainous terrain are the best for high-quality bayberry production. In contrast, high mountains and low-lying plains are not suitable due to higher risks of frost or waterlogging (Shou-Zhi, 2004).

Soil factors such as pH, nutrient imbalance, and salinity also significantly affect variety performance. In the southeastern coastal areas, saline-alkali soils seriously limit the growth of traditional red bayberry rootstocks. However, using wax myrtle (Morella cerifera) as a rootstock allows ‘Biqi’ to maintain good growth under high Na, Mg, and Ca conditions. It shows dark green leaves and good fruit quality, with larger fruits, higher sucrose and citric acid content, and earlier flowering and fruiting (Huang et al., 2025). Studies on dwarf and high-density cultivation indicate that salt-tolerant wax myrtle rootstocks can promote early fruiting, improve fruit size and flavor, and adapt to saline-alkali soil conditions.

### 3.3 Grafting and variety renewal techniques

Grafting is a key technique for rapid renewal of bayberry varieties. It allows the combination of high-quality scions with rootstocks that have better adaptability or stress resistance, and also helps renew old orchards. From physiological and molecular perspectives, grafting can shorten the juvenile phase, regulate tree vigor and canopy structure, increase yield, and enhance resistance to soil stress and pathogens (Williams et al., 2021; Habibi et al., 2022; Loupit et al., 2023). Successful grafting depends on coordinated hormone regulation (such as auxin, cytokinin, ethylene, gibberellin, abscisic acid, and jasmonic acid), wound healing, vascular reconnection, and compatibility between rootstock and scion at physiological and molecular levels.

In practice, techniques such as cleft grafting, bark grafting, and top grafting are commonly used to replace inferior or mixed varieties with uniform high-quality ones, thus shortening the fruiting period and improving orchard uniformity.

Grafting ‘Biqi’ onto wax myrtle rootstock in saline-alkali soil shows good graft compatibility, normal growth, and excellent fruit quality, indicating that proper rootstock-scion combinations can effectively utilize marginal land (Huang et al., 2025). With the development of SSR markers, high-density SNP genotyping, and telomere-to-telomere (T2T) genome technologies, it is now possible to systematically screen rootstock-scion compatibility and rootstock effects, thereby shortening the breeding and evaluation cycle of new combinations.

## 4 Soil and Fertilization Management Measures

### 4.1 Annual fertilization regime (basal fertilizer, topdressing, and post-harvest fertilization)

Long-term investigations in red soil orchards have shown that imbalanced fertilization and declining soil organic matter are closely related to problems such as weakened tree vigor, smaller fruit size, and unstable yield (Zhuang et al., 2024). The annual fertilization regime for waxberry should align nutrient supply with phenological stages, while combining quick-acting mineral nutrients with slow-release organic nutrient sources.

In field trials on weakened waxberry trees, during key growth stages—flower bud differentiation and new shoot emergence—compound fertilizer (NPK 15-15-15) and bio-organic fertilizer (based on sheep manure) were applied in trenches near the canopy drip line and then covered with soil (Ren et al., 2021). Compared with the unfertilized control, this fertilization timing significantly improved vegetative growth, fruit traits, and the physicochemical properties of rhizosphere soil.

### 4.2 Combined application of organic fertilizers and green manure

Livestock and poultry manure, compost, cover crops, and other organic amendments can improve soil structure, increase organic carbon content, and enhance microbial and enzyme activities. They also often improve fruit quality traits such as sugar content and antioxidant capacity (Chatzistathis et al., 2021; Dhaliwal et al., 2023).

In waxberry studies, bio-organic fertilizer based on sheep manure significantly increased exchangeable calcium and magnesium, as well as available phosphorus and potassium in the soil. At the same time, it reshaped the rhizosphere microbial community and metabolite composition, which were closely associated with the alleviation of decline disease and improvement of tree health (Ren et al., 2021).

Returning green manure to the field, combined with balanced chemical fertilization, can significantly increase soil organic carbon and its active fractions, total nitrogen content, and enzyme activities. It can also increase the yield of the following crop by 34%-53%, while reducing soil bulk density and slightly lowering soil pH (Xu et al., 2023).

### 4.3 Soil testing and precision fertilization

Precision fertilization for waxberry should begin with diagnosing soil limiting factors, such as strong acidity, low organic matter content, and imbalances in nutrients like phosphorus, potassium, calcium, and magnesium. Based on this, targeted fertilizer types, application rates, and methods should be developed to improve fruit quality and tree health.

In waxberry orchards affected by decline disease, exchangeable calcium, magnesium, and available phosphorus are key factors influencing the structure of rhizosphere microbial communities. Regulating these nutrients through compound fertilizers and bio-organic fertilizers can significantly alter microbial communities and soil metabolite composition.

Specialized waxberry fertilizers and foliar nutrient products, when applied at appropriate rates and frequencies, can increase soil organic matter, leaf chlorophyll content, and fruit sugar and soluble solids content (Guo et al., 2009).

From a broader perspective, soil testing should be used as the basis to guide the partial replacement of mineral NPK fertilizers with organic and bio-fertilizers. This helps maintain soil nutrient balance, enhance carbon sequestration capacity, and achieve long-term sustainability of crop production (Selim, 2020; Urmi et al., 2022).

## 5 Water Management and Drainage Control

### 5.1 Critical water demand periods (flowering stage and fruit expansion stage)

Effective water management in waxberry orchards needs to balance avoiding drought, maintaining root aeration, and improving fruit quality. Water shortage and improper irrigation are among the main limiting factors in global fruit production, especially when water stress coincides with key phenological stages, which can significantly reduce tree growth, yield, and fruit size (Devin et al., 2023; Ru et al., 2025). The flowering-fruit set stage and the fruit expansion stage are critical water-demand periods. Water deficit during flowering usually reduces fruit number, while water shortage during fruit expansion has the most significant impact on final fruit size and marketable yield (Berríos et al., 2023).

### 5.2 Irrigation methods under orchard conditions

The choice of irrigation method should consider local water resource conditions, orchard terrain, and soil type, with a focus on covering the active root zone. Drip irrigation, widely used in orchards in China, can deliver water directly to the root system, reduce evaporation loss, decrease leaf wetness and disease occurrence, and maintain a good soil water-air balance throughout the growing season. Compared with surface irrigation and sprinkler irrigation, drip irrigation can significantly improve yield and water use efficiency, especially under water-limited conditions, and can also reduce fertilizer leaching and soil salinization (Yang et al., 2023; Fareed et al., 2024; Long et al., 2025).

Micro-sprinkler irrigation systems also perform well in orchards. When irrigation timing is optimized, they can improve the uniformity of soil moisture distribution and water storage efficiency. Reducing irrigation time from 24 hours to 19 hours can significantly increase water storage efficiency (from 72% to 89%) and reduce deep percolation losses (Ortega-Farías et al., 2022).

In hilly or semi-arid orchards, constructing rainwater collection systems and infiltration-enhancing measures to guide runoff into the main root zone can increase soil moisture in the 0-60 cm layer by 24%-44%, while also increasing fine root density and yield. This shows good potential under water-scarce conditions (Guo et al., 2021).

### 5.3 Drainage in rainy seasons and root protection

In regions with concentrated rainfall and high humidity, rapid drainage and root protection are as important as supplemental irrigation. Excess rainfall can raise the groundwater level and cause excessive soil saturation in the root zone, leading to root hypoxia, diseases, and tree decline. Subsurface drainage systems such as buried pipes or blind ditches can significantly reduce soil moisture and groundwater levels, shorten the duration of waterlogging, and increase yield by 6%-8% compared with surface drainage alone (Qi et al., 2025).

Optimizing subsurface drainage spacing can also increase crop yield by promoting root biomass and adjusting aboveground growth allocation, indicating that proper drainage can effectively reduce the negative physiological effects of excess water. In medicinal plants that are prone to root diseases, rain-shelter facilities can effectively reduce the direct impact of rainfall on soil, lower soil moisture and root rot incidence, and increase soil enzyme activity and beneficial microbial populations, sometimes performing even better than fertilization measures (Abd El-Hafez et al., 2020).

### 5.4 Technical measures to prevent fruit cracking

Preventing fruit cracking requires careful control of fruit water relations, especially during the rapid fruit expansion and ripening stages. In many fleshy fruits, heavy rainfall or excessive irrigation before harvest can cause a sudden increase in soil or fruit water content, leading to a large water gradient between the peel and the flesh. Applying mild deficit irrigation (80%-100% of full irrigation) at appropriate stages can maintain or slightly increase yield while improving water productivity. This approach works well around the flowering period but is not suitable during the late fruit expansion stage (Wen et al., 2023).

## 6 Fruit Quality Improvement Techniques

### 6.1 Measures to improve fruit size, color, and sugar content

Compared with open-field cultivation, greenhouse cultivation significantly increases single fruit weight, fruit diameter, soluble solids content, and the sugar–acid ratio of bayberry. This is mainly due to enhanced sucrose accumulation and increased activity of related enzymes, indicating that optimizing the microclimate and carbohydrate metabolism is a key way to improve fruit size and sweetness (Wu et al., 2021). In Chinese bayberry, the use of insect-proof and rain-proof nets can increase fruit diameter and weight by 22.6% and 82.4%, respectively, with the proportion of high-grade fruit exceeding 91%. At the same time, soluble solids and sucrose content are increased while titratable acidity is reduced. This shows that isolating fruit from rainwater and pests not only protects the fruit but also promotes sugar accumulation and flavor balance (Yu et al., 2021) (Figure 1). Under controlled light conditions, supplementing with LED light can significantly increase fruit weight, fruit diameter, soluble solids, and vitamin C content in the 'Black Charcoal' bayberry cultivar, while reducing organic acid content. This again highlights the key role of light quality and intensity in determining fruit size and sweetness (Tang et al., 2025).

### 6.2 Nutrient management during fruit expansion stage

Nutrient management during the fruit expansion stage should meet the high demand for carbohydrates, nitrogen, and mineral elements, while avoiding excessive promotion of vegetative growth. The soluble solids content and sugar–acid ratio of greenhouse-grown bayberry are higher than those in open-field cultivation, which is closely related to the increased activities of sucrose phosphate synthase and acid invertase. This suggests that maintaining leaf photosynthesis and the activity of sugar metabolism enzymes during the fruit expansion stage can directly improve fruit sweetness and flavor (Wu et al., 2021). Insect-proof and rain-proof nets not only protect bayberry fruits from pests and cracking, but also alter the microbial community structure on the fruit surface, which is beneficial for carbon and nitrogen metabolism and mineral transport. In other fruit trees, a balanced supply of nitrogen and potassium (often combined with biofertilizers) can promote fruit enlargement and increase soluble solids and vitamin content. However, excessive nitrogen in the later growth stage may delay coloration, dilute sugar content, and increase the risk of diseases (Kumar et al., 2022; Zahid et al., 2022).

## 7 Integrated Pest and Disease Management Measures

### 7.1 Identification of major pests and diseases in waxberry orchards

Waxberry is seriously threatened by twig blight, mainly caused by Pestalotiopsis versicolor and P. microspora. These pathogens have been confirmed as the key agents responsible for large-scale branch dieback in major production areas. In recent years, several other fungi have also been identified as important causal agents of twig blight (Ren et al., 2013; Li et al., 2020; Chen et al., 2021). Meanwhile, new leaf diseases continue to emerge. For example, leaf spot caused by Nigrospora aurantiaca shows a relatively high incidence and damage level in commercial orchards, especially on young leaves. This indicates that the disease spectrum of waxberry is expanding, and accurate diagnosis of newly emerging pathogens is critical for timely control (Fu et al., 2025).

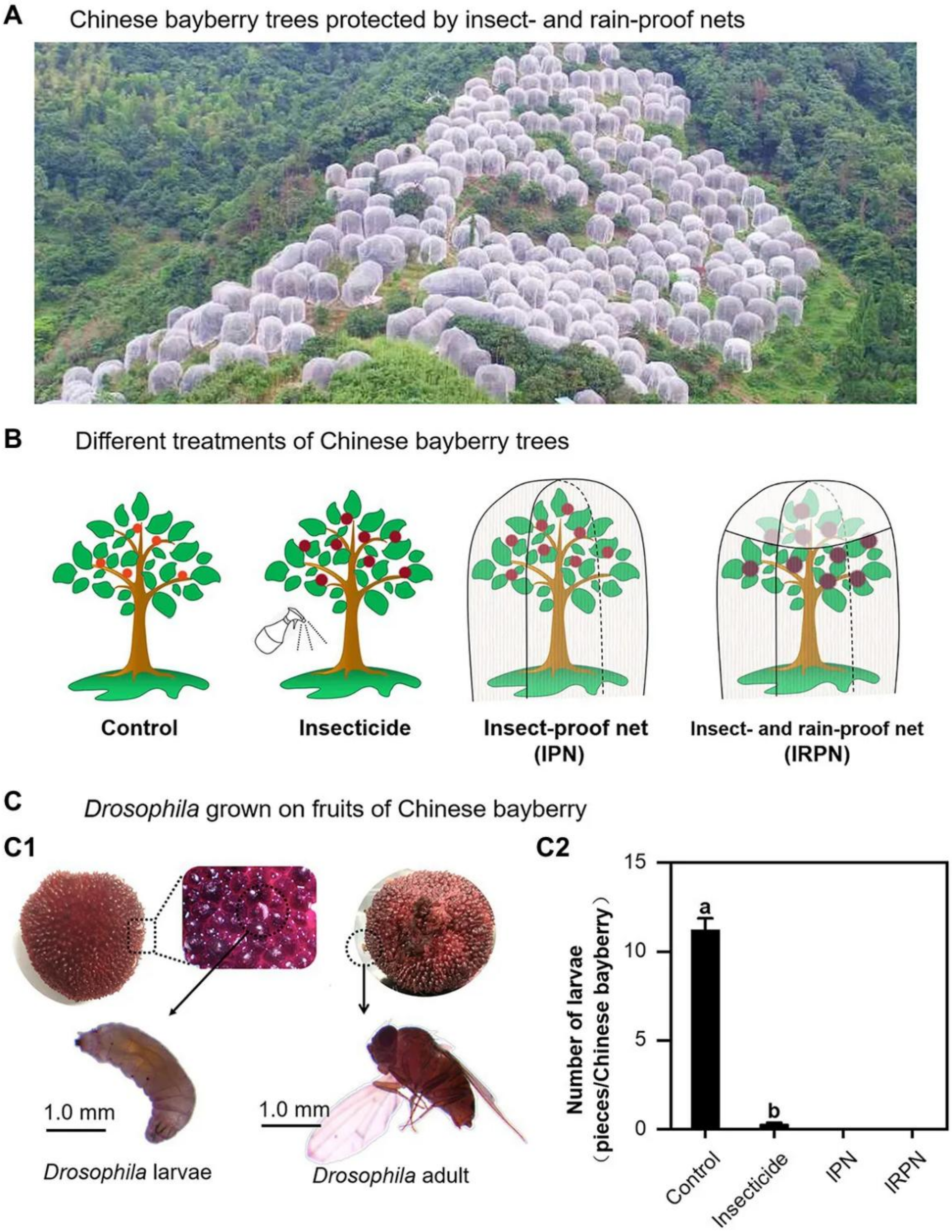


Figure 1 Drosophila growth on Chinese bayberry fruits collected from trees grown in different environments. (A) Field image of Chinese bayberry trees protected by insect-proof nets (IPNs) and rain-proof films during the fruit maturation period. (B) The trees were grown under natural conditions (controls) or treated separately with insecticides, IPNs or insect- and rain-proof nets (IRPNs). (C) Drosophila (C1) and number of Drosophila (C2) on Chinese bayberry fruits collected from untreated and treated trees (Adopted from Yu et al., 2021)

Excessive use of pesticides and antibiotics in waxberry orchards has led to increased residues in soil and along the "soil–fruit–fruit fly" chain. This promotes the accumulation of antibiotic resistance genes and virulence factors in soil and fruit-associated microbial communities, highlighting the need for more restrained and scientifically guided use of chemical inputs (Yi et al., 2024).

### 7.2 Field monitoring and early intervention

Efficient field monitoring and early intervention are central to IPM systems. Pest and disease management should begin with accurate species identification, followed by a clear understanding of their biology and behavior. Population dynamics and risk levels should be systematically monitored before economic thresholds are exceeded (González-Núñez et al., 2022).

Remote sensing and advanced detection technologies—such as multispectral imaging, UAV platforms, and rapid field diagnostic tools—can detect pest and disease stress before visible symptoms appear. This is achieved through canopy reflectance changes or rapid molecular detection, allowing earlier and more precise spatial interventions while reducing the need for large-scale pesticide applications (Abd El-Ghany et al., 2020; Iost Filho et al., 2020; Buja et al., 2021; John et al., 2023).

### 7.3 Biological and physical control methods

Biological and physical control methods should be prioritized to reduce reliance on synthetic chemical pesticides. In the control of waxberry twig blight, Bacillus siamensis S3 and B. tequilensis S5, isolated from the rhizosphere, show strong antagonistic activity against P. versicolor (Figure 2). Their culture broth and extracellular filtrates can inhibit mycelial growth by more than 75%-80% and significantly reduce lesion size on detached leaves. Microscopic observations suggest that this inhibition is closely related to the production of chitinase, protease, and lipopeptides such as surfactin, iturin, and mycosubtilin. These strains have potential for development as spray agents or soil treatments and may serve as alternatives or supplements to fungicides (Ali et al., 2020).

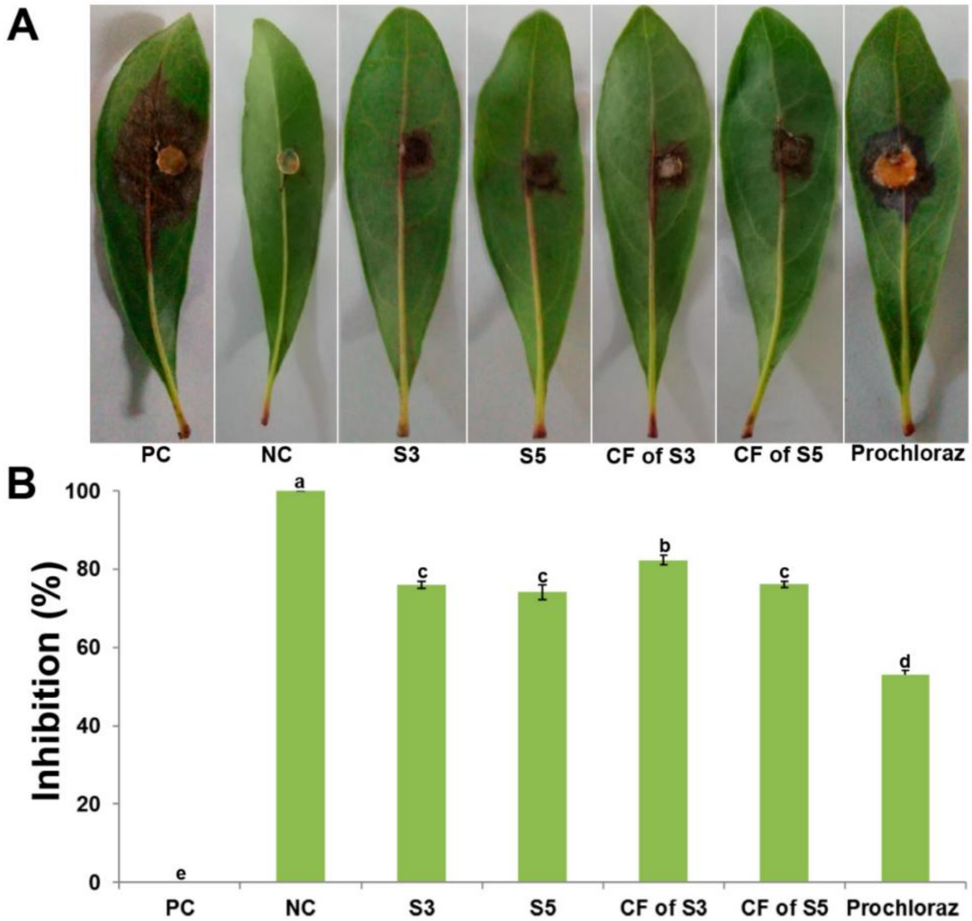


Figure 2 Detached leaf assay for antifungal activity. (A) Effects of antagonistic bacteria and their extracellular culture filtrate on bayberry leaves against P. versicolor XJ27. (B) Disease inhibition (%) relative to positive control. Data are mean ± SE of three replications for each treatment. Same letters are not significantly different at $p \leq 0.05$. For positive control (PC), only the fungal mycelial plug was inoculated. For negative control (NC), a sterile PDA plug without mycelia was used. CF, extracellular culture filtrate. Prochloraz denotes fungicide (Adopted from Ali et al., 2020)

More broadly, biological control strategies—such as the use of antagonistic microorganisms, bacteriophages, microbiome regulation, and engineered biocontrol agents—are becoming key components of sustainable disease management. These approaches should be integrated with resistant varieties, agronomic practices, and limited chemical control (Pandit et al., 2022).

In terms of physical control, insect-proof and rain-proof nets have proven effective in waxberry production. They not only reduce pest damage but also improve fruit size and quality, while lowering infection risks caused by rain splash and mechanical injury (Furmańczyk et al., 2022). Other measures commonly used in organic orchards and IPM systems can also be applied, such as mass trapping, pheromone-based mating disruption, and mechanical removal and pruning of diseased branches.

### 7.4 Rational reduction of chemical pesticide use

Laboratory screening studies on waxberry twig blight show that prochloraz performs best, followed by pyraclostrobin, difenoconazole-prochloraz mixtures, difenoconazole alone, and myclobutanil (Li et al., 2020). However, excessive use of antibiotics and pesticides in waxberry systems can select for resistant pathogens and pest populations, while also increasing the abundance of resistance genes, mobile genetic elements, and virulence factors in soil, fruit, and associated fruit flies.

Waxberry production should follow these principles: make decisions based on thresholds, rotate modes of action, avoid calendar-based preventive spraying, strictly observe pre-harvest intervals, and prohibit unnecessary antibiotic use. This aligns with the IPM concept, where chemical control is used only as a last line of defense after preventive, biological, agronomic, and physical measures (Bai et al., 2023; Golan et al., 2023).

### 7.5 Green control technologies

Non-chemical management strategies for berry crops emphasize the central role of biological control, the use of resistant or tolerant varieties, agronomic practices that enhance plant immunity, and improved diagnostic techniques. At the same time, an increasing number of validated commercial biocontrol products are available for effective control of fungal diseases (Taoussi et al., 2024).

Mycoviruses isolated from Pestalotiopsis-infecting fungi in waxberry branches show high diversity and may reduce pathogen virulence (hypovirulence effect), providing a potential resource for a new type of biological control based on “internal regulation” of pathogens (Chen et al., 2021).

The theory and policy of biological control suggest that long-term success depends on balancing production efficiency, ecological function, social acceptance, and economic feasibility. This requires the development of integrated, adaptive, and multi-stakeholder-supported “green” control systems (He et al., 2021).

In practice, green management in waxberry orchards should include: the use of resistant varieties and disease-free seedlings, creation of habitats that support biodiversity, precise application of microbial agents (such as Bacillus spp.), use of low-risk inputs and physical barriers, and integration with advanced monitoring and early warning systems.

## 8 Harvesting and Postharvest Handling Techniques of Bayberry

### 8.1 Determination of appropriate harvest maturity

Bayberry is a typical climacteric fruit. After harvest, it shows a peak in ethylene release and softens rapidly, especially under room temperature conditions. When fruits are harvested at an “immature” stage or judged as “mature” only by color, they can still exhibit a clear climacteric respiration rise and ethylene peak within 48 hours at 20 °C. At the same time, the contents of sugars and organic acids change significantly. In contrast, fully “mature” fruits do not show a climacteric peak, but they deteriorate and decay quickly. During storage, total soluble solids (TSS) increase, while titratable acidity (TA) decreases. However, if fruits are overripe on the tree, shelf life is shortened and the risk of decay increases (Zhang et al., 2005).

With the development of machine vision and hyperspectral technologies, objective and non-destructive maturity evaluation in the field has become possible. By combining multiple features such as color and texture, maturity prediction accuracy can reach about 91%. The chromatic parameter a*/b* ratio is highly correlated with anthocyanin accumulation and visual maturity (Kai et al., 2021; Zheng et al., 2025). Image-based intelligent maturity detection helps determine optimal harvest timing for different varieties and orchard zones, reducing variability within batches and improving allocation between fresh consumption and processing markets.

### 8.2 Standardized harvesting methods to reduce damage

Due to the characteristics of bayberry fruit, including high respiration intensity, susceptibility to mechanical damage, and rapid softening, its harvesting method should be similar to that used for berry crops such as strawberries and raspberries, adopting gentle and standardized manual picking practices. Fruits intended for the fresh market should be hand-harvested at the target maturity stage. During harvesting, fruits should be handled carefully to avoid finger pressure damage, and a short fruit stalk should be retained by cutting or gently twisting the fruit during picking. After harvest, fruits should be graded directly in the field and packed into the final packaging containers to reduce repeated handling (Horvitz, 2017; Jain et al., 2023).

Harvesting should be carried out in the early morning or evening when temperatures are lower. Wet fruits should be avoided, because surface moisture increases friction damage and decay (Shah et al., 2023). Increasing harvest frequency (for example, harvesting blueberries every 2-3 days) can effectively reduce the proportion of overripe fruits, minimize cumulative mechanical damage, and significantly improve storage performance (Godara et al., 2025).

### 8.3 Sorting, packaging, and short-term storage

After harvest, bayberries should be sorted immediately. Fruits with mechanical damage, disease, or those that are immature or overripe should be removed, because mixed batches accelerate decay and act as sources of pathogen spread. Standard postharvest handling includes cleaning, grading, pre-cooling, proper packaging, and refrigerated storage. These steps are key to reducing losses.

For bayberry, shallow and rigid packaging containers should be used to limit stacking height and distribute weight evenly. This helps avoid compression and juice leakage, both of which accelerate microbial spoilage (Kunwar et al., 2024).

Temperature and relative humidity management are especially important. Rapid pre-cooling to the proper storage temperature after harvest is considered the most critical factor in delaying senescence and decay (Palumbo et al., 2022). In areas without a cold chain, low-cost cooling technologies such as zero-energy cooling chambers or “pot-in-pot” systems can be used to provide short-term preservation (Hassan et al., 2025).

### 8.4 Transportation and preservation technologies

Transportation is the stage where bayberry is most vulnerable. Vibration, collision, and poor temperature control can quickly offset the benefits of earlier careful handling. In many fruits, poor transport conditions and long distances are the main causes of mechanical damage and postharvest losses (Bisht and Singh, 2024).

For bayberry, maintaining a continuous cold chain, using vibration-resistant packaging, and delivering fruits quickly to the market are essential. During loading, transport, and distribution, temperature should be kept at 0 °C-4 °C with high relative humidity to suppress ethylene-induced ripening, softening, and decay (Saeed et al., 2024).

Advanced postharvest technologies provide more options to extend freshness during transportation. Slightly acidic electrolyzed water combined with ultrasound treatment (US + SAEW) can significantly reduce pesticide residues, dirt, larvae, and microorganisms on the fruit surface. It can delay the onset of decay by about 6 days, reduce weight loss and color changes, maintain fruit firmness, improve the sugar-acid ratio, and preserve phenolics, anthocyanins, and antioxidant capacity (Suo et al., 2023). In addition, applying hot air treatment at 48 °C for 3 hours before cold storage can significantly reduce decay by regulating fungal community structure (increasing beneficial endophytes and reducing pathogenic fungi), while maintaining fruit quality (Dai et al., 2021).

## 9 Practical Development Trends and Optimization Directions

### 9.1 Application of simple smart orchard tools (monitoring and irrigation control)

Multi-parameter IoT-based orchard monitoring platforms can track real-time data such as air temperature, soil moisture, light intensity, rainfall, and wind speed, and upload them to mobile terminal interfaces. Through more precise environmental regulation, these systems can reduce labor input, stabilize yields, and improve fruit quality (Hu et al., 2025).

In terms of irrigation, integrating soil, plant, and meteorological data into closed-loop or model-based control systems can significantly improve water use efficiency compared with traditional open-loop scheduling methods (Bwambale et al., 2022; Gamal et al., 2025). Smart irrigation platforms based on cloud computing and IoT show that connecting multiple small-scale farms to a centralized data analysis system helps optimize water allocation and supports climate-adaptive agricultural production in water-scarce regions (Et-Taibi et al., 2024). For the waxberry industry, priority should be given to promoting cost-effective tools such as soil moisture sensors, simple weather stations, and mobile data platforms to support fertilization and irrigation decisions, rather than relying on high-end automated systems that are difficult for small farmers to maintain.

### 9.2 Expansion of eco-friendly orchard models

Moderately reducing nitrogen and phosphorus inputs in waxberry orchards can improve soil quality (e.g., slowing acidification and increasing organic carbon levels) without affecting yield or fruit quality, indicating that optimized fertilization can achieve both production and ecological goals.

Introducing ryegrass as a cover crop under the waxberry canopy can significantly increase fruit sugar, vitamin C, and flavonoid content, while also improving soil physicochemical properties, rhizosphere microbial community structure, and secondary metabolism, which overall benefits orchard ecosystem optimization (Li et al., 2023).

More broadly, plant growth-promoting microorganisms and biofertilizers are important components of sustainable orchard systems. When combined with organic amendments, conservation agriculture, and agroforestry practices, they can effectively promote nutrient cycling, improve soil health, and enhance system resilience (Freitas and Silva, 2022). Agroforestry systems based on fruit trees, which combine fruit production with crops or livestock and optimize resource use throughout the life cycle, are considered an effective approach to improving orchard sustainability. Model tools are already available to design such systems under different soil and climate conditions (Barbault et al., 2024). In major waxberry-producing regions, eco-friendly orchard models that integrate cover crops, reduced and precise fertilization, biofertilizer use, and structural diversification should be promoted to achieve both high-quality fruit production and low environmental impact.

### 9.3 Integration with agritourism and brand building

Agritourism centered on orchards has been shown to bring clear socio-economic benefits. It not only provides additional income for farmers and creates jobs, but also promotes environmental and cultural sustainability through visitor education and nature-based experiences. Participatory activities such as fruit picking, science popularization displays, and direct farm sales can significantly increase tourists' willingness to purchase local agricultural products (Brune et al., 2021). From a destination perspective, value co-creation in agritourism—through visitor participation, interaction, and "citizen behavior"—can significantly enhance the brand equity of rural tourism destinations via enjoyable experiences, meaningful experiences, and perceived value (Zhou and Chen, 2023).

Successful agritourism regions often rely on producer cooperation networks, shared marketing platforms, and recommendation mechanisms. Digital marketing tools such as social media, visual storytelling, and online reviews further strengthen the attractiveness of agritourism destinations and support personalized experiences (Kulikova et al., 2024). For the waxberry industry, combining orchard production with seasonal picking festivals, ecological orchard education activities, processed product tasting, and unified regional branding can simultaneously increase farmers' income and enhance the brand value of "high-quality waxberry."

### 9.4 Directions for orchard standardization improvement

Sustainable orchard systems based on clear principles of nutrient management and soil biodiversity have already provided a technical basis for developing standards in fertilization, cover crop use, biofertilizer application, and soil protection. With the rapid development of smart agriculture and IoT technologies, it is necessary to establish unified monitoring indicators, threshold settings, data formats, and decision rules, so that even simple systems can be connected to regional decision support and benchmarking frameworks (Ali et al., 2023).

Eco-farms that successfully integrate with rural tourism usually rely on clear market demand orientation, endogenous development motivation, resource endowment, technical support, and resource integration. This suggests that establishing clear standards for product quality, service design, and environmental performance can promote the integration of agriculture and tourism and drive farm upgrading (Xiao et al., 2025).

Future optimization of the waxberry industry should focus on establishing standardized systems for varieties and rootstocks; regulating ecological fertilization, cover crop planting, and biological control practices; defining basic monitoring and irrigation control requirements; and aligning production standards with agritourism service standards and branding systems. At the same time, coordinated support from policies, technology extension, and producer organizations is needed, along with dynamic updates, to ensure the continuous development of waxberry orchards toward an integrated system that is smart, eco-efficient, and market-oriented.

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