RESEARCH ARTICLE

# Development of an Intelligent Fertigation Machine and Its Application Test in Soilless Cultivation of Mountain Blueberry

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## Abstract

**Conventional manual fertigation practices are generally limited by low control precision, considerable water and fertilizer waste, and poor adaptability to varied horticultural cultivation conditions. These limitations create particularly prominent challenges for high-value cash crops that are highly sensitive to root-zone substrate electrical conductivity (EC) and pH dynamics. To address these gaps, this study developed a digitally intelligent integrated fertigation system that integrates multi-sensor autonomous sensing, precise nutrient ratio regulation, and full-cycle operational monitoring modules. Systematic validation of both equipment performance and field production benefits was carried out via field plot experiments under typical mountainous soilless blueberry cultivation conditions. The test results showed that the developed fertigation system achieved a control uniformity of 95.28% for EC and 95.07% for pH. Under the prerequisite of identical total irrigation volume and total nutrient supply across the whole growing season, the precise control mode (PCM) of the proposed intelligent fertigation system exhibited significantly higher water use efficiency (WUE) and partial factor productivity of fertilizer (PFP) than the conventional simple fertigation management mode (SFM). Meanwhile, the unit-area yield of blueberries in the PCM treatment increased by 20.1%, and the commercial uniformity of individual fruit weight was significantly improved. This fully validated system can well meet the intelligent production requirements of mountainous soilless blueberry cultivation and provides a viable technical solution to support the intelligent upgrading of local soilless blueberry industries in Southwest China.**

**Keywords**: intelligent fertigation machine, water-fertilizer integration, mountain blueberry, soilless cultivation, equipment performance evaluation.

## 1 Introduction

Water and fertilizer are the core elements for crop growth and development, and irrigation and fertigation are the key production practices that determine crop yield and quality. According to

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statistics from the Food and Agriculture Organization of the United Nations, the average chemical fertilizer application rate in global farmland reached 116 kg/ha and the total annual application volume exceeded 190 million tons in 2023 [1, 2]; meanwhile, agricultural water use accounts for 72% of global freshwater withdrawal, and this proportion is still rising with the expansion of global agricultural production, making agricultural water shortage an increasingly severe challenge [1]. Low nutrient use efficiency is widely prevalent across major global crops [3]. Excessive water and fertilizer use not only increases agricultural costs but also poses environmental risks, such as non-point source pollution. Inefficient use of these resources has become a major bottleneck to global agricultural sustainability. Addressing this issue requires improving nutrient efficiency, optimizing fertilizer application regimes, and adopting precision water and fertilizer management systems [1].

Fertigation, as an advanced agricultural practice that delivers fertilizers directly to the plant root zone along with irrigation water, offers significant advantages over conventional fertilization practices, chiefly reflected in the greatly improved efficiency of nutrient delivery and water usage [4]. Against the backdrop of growing constraints on arable land and freshwater resources, fertigation offers an intelligent "more harvest with less input" solution, ensuring that every drop of water and every gram of fertilizer is fully utilized. It represents an optimal integration of efficiency, sustainability, and profitability for horticultural production: far beyond a single agronomic technique, it acts as a transformative approach that empowers growers to cultivate healthier crops, conserve critical agricultural resources, and achieve better economic returns [5].

With the rapid development of the Internet of Things and intelligent control technology, intelligent integrated fertigation technology has become a research hotspot in smart agriculture, greatly improving the water and fertilizer use efficiency of global agricultural production [4, 6]. The intelligent development of protected agriculture in developed countries began earlier, and the industrialization level and technical maturity of intelligent fertigation machines are highly advanced. As the birthplace of modern drip irrigation technology, Israel has extensively deployed drip fertigation systems for the cultivation of high-value horticultural crops. In the past decades, research on intelligent integrated fertigation systems, particularly in China, has advanced at a remarkable pace. Sun et al. [7] designed a programmable logic controller (PLC)-based multi-channel nutrient mixing machine for greenhouse fertigation. Wu et al. [8] developed a hybrid PID-fuzzy control algorithm based on an EC model for greenhouse fertigation systems. Lin et al. [9] proposed an Internet of Things-based fertigation management framework for sustainable precision agriculture. Zhu et al. [10] designed a hybrid optimized backpropagation neural network PID algorithm for the precise control of fertilizer flow in an integrated water and fertilizer system. Li et al. [11] developed a vision-based growth-stage determination and PLC-based fertigation parameter invocation system for greenhouse blueberry, enabling automated stage-specific adjustment of fertigation parameters. Fertigation equipment in China has seen substantial progress, yet current systems remain inadequate for practical production needs—especially regarding precision fertigation for specific crops and operational reliability in mountainous regions.

Blueberry demand in China has grown steadily in recent years. Owing to its unique climate and altitude, Southwest China's mountainous region has become a core production area for late-maturing blueberries, with the cultivation area expanding steadily. Soilless cultivation, which offers better environmental control and superior fruit quality, is increasingly being adopted for blueberries in these mountainous areas. Proper nutrient solution management requires maintaining optimal pH, EC, and ion concentrations. The pH of the nutrient solution is one of the most important factors affecting nutrient availability, uptake, and solubility [12]. Compared with other crops, soilless-cultivated blueberries impose stricter requirements on the precision of the water-to-fertilizer ratio and the stability of substrate pH.

Agricultural production across China's vast territory is highly heterogeneous, with diverse crop types, varied cultivation systems, regionally distinct growing seasons, and marked differences in infrastructure and management practices. This diversity calls for customized, integrated fertigation systems tailored to different production conditions [13]. Conventional fertilization equipment generally suffers from poor regulation precision, which often causes substantial fluctuations in EC and pH. Blueberry plants are highly sensitive to rhizosphere conditions, and frequent fluctuations in these parameters directly disrupt plant metabolism, ultimately causing poor vegetative growth, reduced yield, and inferior fruit quality.

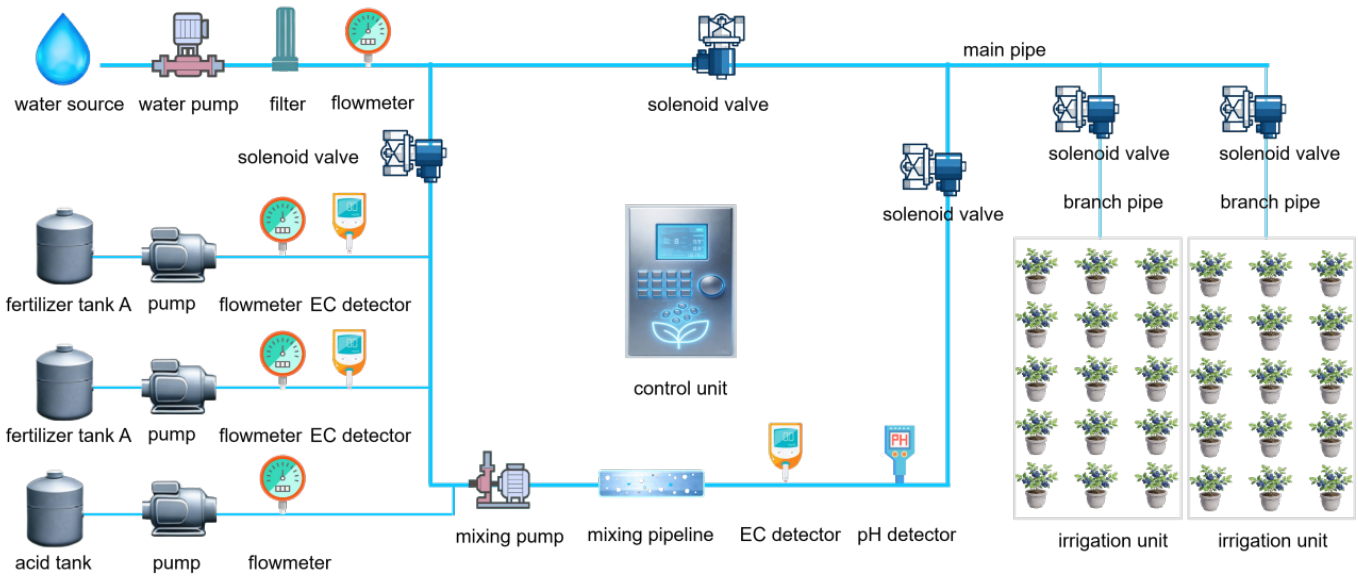



**Figure 1.** Schematic of the fertigation system working principle.

To tackle these bottlenecks in soilless blueberry cultivation in Southwest China's mountainous regions, this study developed a digitally integrated fertigation system that precisely regulates EC and pH. Field experiments were also conducted to evaluate the system's performance, providing a practical basis for improving fertigation management in mountain blueberry production.

## 2 Overall Research and Design of the Intelligent Fertigation Machine

### 2.1 Structure of the Fertigation Machine

#### *2.1.1 Hardware Composition*

This work developed an automated fertigation machine with real-time monitoring, which consists of five modules: the core control unit, the water supply unit, the fertilizer supply unit, the acid supply unit, and the monitoring unit. The core control unit is built around a PLC. The water supply unit comprises water pump, main pipeline, impurity filter, and mixed-solution control valve. The fertilizer supply unit includes multiple fertilizer supply branches, the corresponding variable-frequency fertilizer supply pumps, and various fertilizer sources. The acid supply unit consists of acid supply branch, variable-frequency acid supply pump, and acid source. The monitoring unit is equipped with EC and pH sensors. The overall schematic of this intelligent fertigation system is shown in Figure 1.

#### *2.1.2 System Integration and Component Functionality*

**Water delivery line:** The inlet of the water pump is connected to the water source, and its outlet is plumbed sequentially to the impurity filter and the main distribution pipeline for water transmission across the entire system. A mixed-solution control valve is installed at the outlet end of the main pipeline to regulate the discharge of the final water-nutrient mixture.

**Nutrient and acid injection lines:** All nutrient supply branches and the acid supply branch are connected to the main pipeline as parallel branches. Each nutrient supply branch is linked to the corresponding concentrated fertilizer stock solution tank via an independent variable-frequency fertilizer injection pump, which enables simultaneous injection of different fertilizer stock solutions. The acid supply branch is connected to the acid source tank through a variable-frequency acid injection pump to dynamically adjust the pH value of the mixed nutrient solution.

**Monitoring and control loop:** On the mixed solution section of the main pipeline, EC and pH sensors are installed sequentially along the direction of water flow. Both sensors are wired to the controller, which receives real-time nutrient concentration and pH readings. The controller is directly connected to the water pump, all nutrient injection pumps, the acid injection pump, and the mixed solution control valve. It adjusts the operating frequency of each pump based on real-time monitoring data to regulate the EC and pH of the final mixed nutrient solution.

## 2.2 Digital Control System Design

### 2.2.1 Overall Composition of the Controller

The controller consists of four functionally independent modules, which work together to achieve closed-loop intelligent control with a clear division of responsibilities. The data analysis module is the core processing unit, responsible for receiving signals and computing control decisions. The data storage module stores a standard database of planting parameters for the different growth stages of blueberry plants. The command output module converts the control decisions into executable control signals and transmits them to the actuators. The command input module supports manual parameter setting and human intervention. The control schematic of the intelligent fertigation system controller is shown in Figure 2.

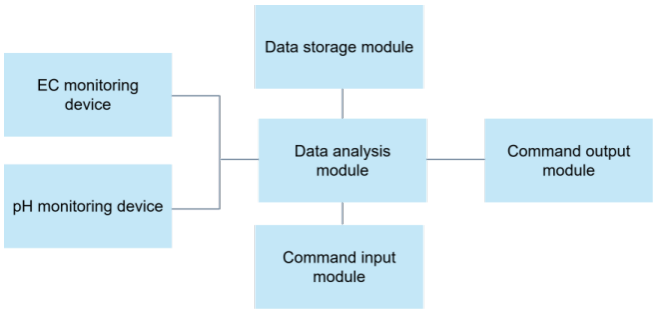



**Figure 2.** Control schematic of the intelligent fertigation system controller.

### 2.2.2 Module Interconnection and Control Logic

**Signal input channel:** The EC and pH sensors are directly wired to the data analysis module and transmit the collected dynamic data to it in real time. A manual command input module is also integrated, allowing manually set parameters to be directly imported into the data analysis module.

**Data comparison and analysis workflow:** The data storage module is interconnected with the data analysis module and pre-stores the standard EC and pH thresholds required for blueberry growth under different environmental conditions and crop phenological stages. After receiving real-time measurement data, the data analysis module automatically compares the measured values with the pre-calibrated standard values and outputs targeted optimized control decisions.

**Actuation control output:** The control decisions generated by the data analysis module are transmitted to the water pump, nutrient injection pumps, and acid injection pump through the command output module. These actuating pumps dynamically adjust the flow rates of water, concentrated nutrient stock solution, and acid solution in real time, thereby keeping the EC and pH of the mixed nutrient solution steadily within the preset target ranges, and precisely matching the nutrient and pH regulation requirements for blueberry growth under specific environmental conditions. The operating logic of this integrated intelligent fertigation system is visualized in Figure 3.

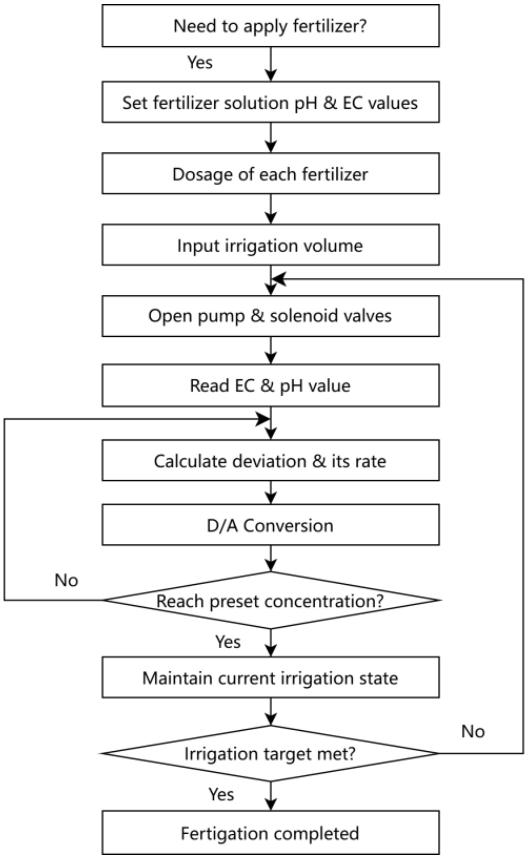



**Figure 3.** Flow chart of the fertigation operational workflow.

## 3 Evaluating the Performance of the Fertigation Machine

### 3.1 Evaluation of EC Control Uniformity and Accuracy

The developed intelligent fertigation machine was activated, and the target EC value was set to 2.0 mS/cm. After the system ran stably for 3 minutes, five consecutive mixed nutrient solution samples were collected at the pipeline outlet at 1-minute intervals, and the EC value of each sample was measured using a pre-calibrated conductivity meter. The control uniformity and accuracy of EC were calculated according to Equations (1)-(4) [14]:

$$\bar{x} = \frac{\sum_{j=1}^{5} x_j}{5} \quad (1)$$

where $\bar{x}$ is the mean EC value (mS/cm), and $x_j$ is the measured EC value of the $j$-th measurement (mS/cm).

$$s_d = \sqrt{\frac{\sum_{j=1}^{5}(x_j - \bar{x})^2}{5-1}} \tag{2}$$

where $s_d$ is the standard deviation of the measured EC values (mS/cm).

$$v = \left(1 - \frac{s_d}{\bar{x}}\right) \times 100\% \tag{3}$$

where $v$ is the EC control uniformity (%).

$$p_e = \left(1 - \left|\frac{\bar{x} - x_r}{x_r}\right|\right) \times 100\% \tag{4}$$

where $p_e$ is the EC control accuracy (%), and $x_r$ is the target EC value (mS/cm).

### 3.2 Evaluation of pH Control Uniformity and Accuracy

The developed intelligent fertigation machine was activated, and the target pH value was set to 6.0. After the system ran stably for 3 minutes, five consecutive mixed nutrient solution samples were collected at the pipeline outlet at 1-minute intervals, and the pH value of each sample was measured using a pre-calibrated pH meter. The pH control uniformity and accuracy were calculated according to Equations (5)-(8) [14]:

$$\bar{z} = \frac{\sum_{j=1}^{5} z_j}{5} \tag{5}$$

where $\bar{z}$ is the mean of the pH values, and $z_j$ is the pH value of the $j$-th measurement.

$$s_z = \sqrt{\frac{\sum_{j=1}^{5}(z_j - \bar{z})^2}{5-1}} \tag{6}$$

where $s_z$ is the standard deviation of pH.

$$v_z = \left(1 - \frac{s_z}{\bar{z}}\right) \times 100\% \tag{7}$$

where $v_z$ is the pH control uniformity (%).

$$p_h = \left(1 - \left|\frac{\bar{z} - z_r}{z_r}\right|\right) \times 100\% \tag{8}$$

where $p_h$ is the pH control accuracy (%), and $z_r$ is the target pH value.

## 4 Field Evaluation of Fertigation Modes for Blueberry Growth and Yield

### 4.1 Overview of the Blueberry Experimental Site

The experiment was conducted in a multi-span plastic greenhouse located in the dry-hot valley region of the Jinsha River, at an altitude of 1,420 m, where annual sunshine duration exceeds 2,700 hours. The site is representative of a typical mountain blueberry cultivation system in Southwest China. Three-year-old southern highbush blueberry (*Vaccinium corymbosum* L. interspecific hybrid) 'O'Neal' plants that were uniformly vigorous and free of visible pests and diseases were selected for use in this study. A potted soilless cultivation system was adopted, with all plants grown in standardized 40 cm diameter pots (volume of approximately 38 L), each equipped with drainage holes to prevent waterlogging. All pots were filled with the same specifically formulated substrate (peat:perlite:coconut coir = 4:2:4, v/v), ensuring uniform physical properties and eliminating treatment-related differences in water and nutrient retention. The planting density was 1 m × 2 m (plant spacing × row spacing), equivalent to 5,000 plants/ha (approximately 333 plants per mu; 1 mu ≈ 667 $m^2$). Each pot received a water-soluble fertilizer specifically designed for soilless blueberry production via one pressure-compensating dripper with a flow rate of 2.5 L/h. The two treatments differed solely in their fertigation strategy, while all other routine management practices—including environmental control (temperature, humidity, and light), pest and disease management, and pruning-were kept identical between treatments. Pollinizer cultivars were evenly planted along the borders of the experimental area, accounting for 10% of the total plant number, and were excluded from yield measurements.

### 4.2 Field Experimental Design and Treatments

Two fertigation strategies were compared in a randomized block design with three replicates per treatment, each replicate containing 30 uniform plants. Both treatments received identical total irrigation volumes and total nutrient inputs to ensure that these factors did not confound the experimental results. The two treatments differed solely in fertilization scheduling and application method.

**Precise control mode of the intelligent fertigation machine (PCM):** The self-developed dedicated intelligent fertigation machine was used, which automatically executed batch operations and maintained dynamic closed-loop regulation of both

EC and pH of the fertilizer solution, requiring no manual intervention for water-fertilizer ratio adjustments.

**Simple fertigation management mode (SFM):** A manually controlled water-fertilizer operation mode was adopted. Fertigation was managed according to local empirical practices. The fertilizer solution was manually prepared in a mixing tank, and irrigation events were initiated and terminated by manually switching valves in the delivery system. Total N, P, K application rates and total irrigation volume over the entire growth cycle were recorded and matched those of the PCM treatment.

### 4.3 Field Experiment Measurement Indices and Calculation Methods

Irrigation volume and total fertilizer application were recorded throughout the experiment. Yield-related parameters were determined, and both irrigation water use efficiency and fertilizer use efficiency were subsequently calculated.

**Individual fruit weight:** Five uniformly growing plants were selected per treatment, and 50 fruits were harvested from each plant at 10 days post color break. Individual fruit weights were determined using an electronic balance [15].

**Yield determination:** The total fruit yield from each treatment was recorded and expressed as yield per unit area.

**Water use efficiency (WUE):** WUE was calculated using Equation (9) [16, 17]:

$$\mathrm{WUE} = \frac{Y}{I} \tag{9}$$

where WUE is the irrigation water use efficiency ($\mathrm{kg/m^3}$), $Y$ is the blueberry yield (kg/ha), and $I$ is the total irrigation amount over the entire growth period ($\mathrm{m^3/ha}$).

**Partial factor productivity of fertilizer (PFP):** PFP is used to characterize fertilizer use efficiency and was calculated using Equation (10) [16, 18, 19]:

$$\mathrm{PFP} = \frac{Y}{F} \tag{10}$$

where PFP is the partial factor productivity of fertilizer (kg/kg), $Y$ is the blueberry yield (kg/ha), and $F$ is the total nutrient input ($\mathrm{N + P_2O_5 + K_2O}$) during the entire growth period (kg/ha).

### 4.4 Statistical Analysis

Statistical analysis and data visualization were performed using IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA). Differences between treatments were tested by one-way analysis of variance (ANOVA), and differences were considered significant at $P < 0.05$.

## 5 Experimental Results and Analysis

### 5.1 EC Control Performance of the Fertigation Machine

The EC of the nutrient solution delivered by the intelligent fertigation machine was measured five times at a setpoint of 2.0 mS/cm. The results are presented in Table 1. The EC control uniformity and accuracy were 95.28% and 98.10%, respectively. Those values indicate that the device maintained stable EC control and complied with the national agricultural industry standard.

### 5.2 pH Control Performance of the Fertigation Machine

The pH of the nutrient solution delivered by the intelligent fertigation machine was measured five times at a setpoint of 6.0. The results are presented in Table 2. The pH control uniformity and accuracy were 95.07% and 97.83%, respectively, indicating that the device maintained stable pH control and complied with the national agricultural industry standard.

### 5.3 Effects of Fertigation Modes on Individual Fruit Weight and Blueberry Yield

For 'O'Neal', the median individual fruit weight under PCM was 2.27 g, which was significantly higher than the 2.0 g recorded for SFM, indicating that PCM improved the average individual fruit weight of blueberries. Regarding data distribution, the PCM box plot exhibited a narrow interquartile range and low dispersion, indicating improved fruit size uniformity. In contrast, the SFM treatment showed a wider interquartile range and greater dispersion, reflecting lower uniformity (Figure 4).

Because 'O'Neal' blueberries are harvested multiple times across the growing season, a cumulative approach was used in this study, summing all harvests over the entire growth cycle and converting the total to yield per unit area. The yield was 16,000.65 kg/ha under PCM, compared with 13,320.00 kg/ha under SFM. This represented a 20.1% increase, and the difference was statistically significant by analysis of variance ($P < 0.05$) (Figure 5).

**Table 1.** EC control uniformity and accuracy of the fertigation machine.

| Detection Index | Number of Replicates | Average Value (mS/cm) | Standard Deviation (mS/cm) | EC Control Uniformity | EC Control Accuracy |
|---|---|---|---|---|---|
| EC | 5 | 1.962 | 0.0926 | 95.28% | 98.10% |

**Table 2.** pH control uniformity and accuracy of the fertigation machine.

| Detection Index | Number of Replicates | Average Value | Standard Deviation | pH Control Uniformity | pH Control Accuracy |
|---|---|---|---|---|---|
| pH | 5 | 5.87 | 0.2895 | 95.07% | 97.83% |

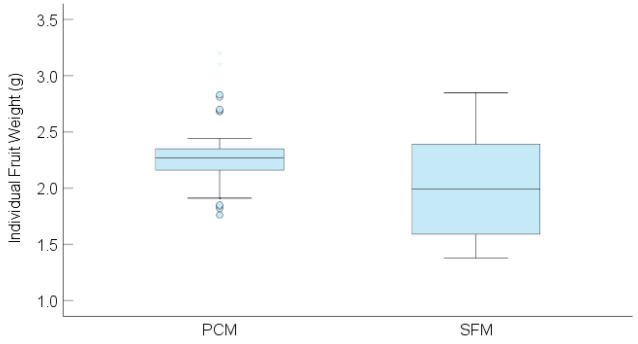



**Figure 4.** Effects of different fertigation modes on individual fruit weight of blueberries. PCM: precise control mode of the intelligent fertigation machine; SFM: simple fertigation management mode.

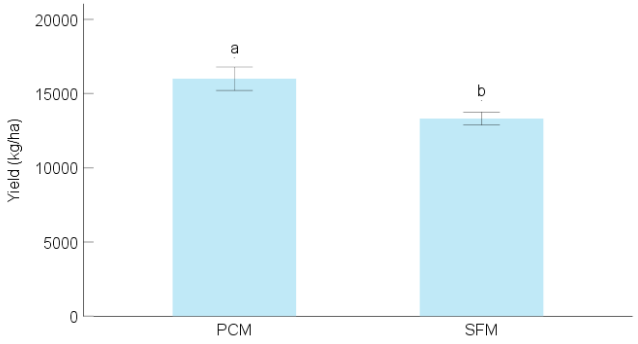



**Figure 5.** Effects of different fertigation modes on blueberry yield. Vertical bars indicate SE, and different letters indicate significant differences at $P < 0.05$. PCM: precise control mode of the intelligent fertigation machine; SFM: simple fertigation management mode.

PCM applied a high-frequency, low-volume fertigation strategy (214 events in total) to accommodate the shallow root system of blueberry, whereas SFM involved only 84 events. This high-frequency approach minimized fluctuations in substrate EC and moisture, thereby maintaining a more stable root-zone environment and better matching nutrient supply to plant demand.

Anwar et al. [20] demonstrated that optimizing the $NH_4^+$-N:$NO_3^-$-N ratio in the nutrient solution significantly improved the growth, nutrient uptake, and yield of soilless-cultivated blueberries, confirming that precise nutrient regulation is essential for high-yield blueberry production. Feng et al. [21] showed that increasing fertigation frequency under alternate partial root-zone drip irrigation significantly increased tomato yield. The yield increase observed under precise, high-frequency fertigation in this soilless blueberry study is consistent with previous findings across diverse horticultural crops. These results suggest that a precision fertigation strategy—combining optimized nutrient formulation and high-frequency delivery tailored to root architecture and crop demand—can improve both fruit quality and yield in soilless blueberry production systems.

### 5.4 Effects of Fertigation Modes on Water Use Efficiency of Blueberries

Although the total irrigation volume was kept constant between treatments, WUE differed significantly. The WUE under PCM was 12.26 kg/m$^3$, compared with 10.21 kg/m$^3$ under SFM, representing a 20.1% increase (Figure 6). This indicates that the high-frequency, precision-delivery strategy effectively improved irrigation water use efficiency in this soilless blueberry system.

This outcome is in good agreement with previous findings. Previous studies have shown that precise management of irrigation water using drip irrigation combined with soil mulching increases yield and improves the WUE of lettuce crops [22]. Soilless cultivation has inherent water-saving advantages,

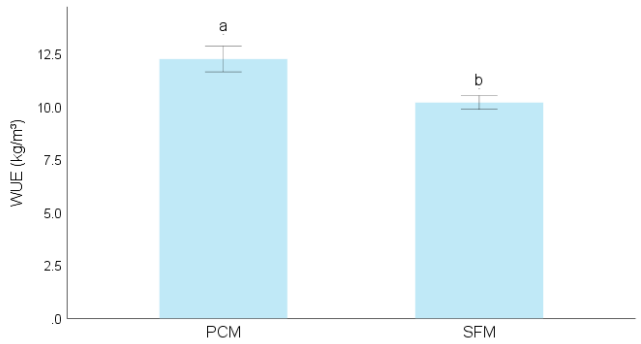



**Figure 6.** Effects of different fertigation modes on blueberry WUE. Vertical bars indicate SE, and different letters indicate significant differences at $P < 0.05$. PCM: precise control mode of the intelligent fertigation machine; SFM: simple fertigation management mode.

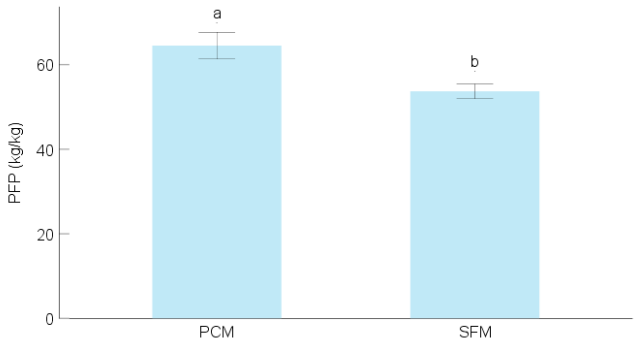



**Figure 7.** Effects of different fertigation modes on blueberry PFP. Vertical bars indicate SE, and different letters indicate significant differences at $P < 0.05$. PCM: precise control mode of the intelligent fertigation machine; SFM: simple fertigation management mode.

leading to faster growth and a dramatic decrease in water and nutrient use; hydroponics typically uses at least 90% less water than soil-based methods. In contrast, in traditional open-field soil systems, much of the water and nutrients are wasted because only a small portion reaches the roots and the rest is lost to local waterways [23]. In terms of irrigation regulation, optimizing irrigation strategies is also a key approach for improving WUE. Existing studies have confirmed that irrigation frequency can affect root water potential by altering the average water content in the root zone and thereby influence crop growth, and that an appropriate high-frequency irrigation regime can significantly improve the water uptake efficiency of crop roots, simultaneously improving both WUE and yield [24]. The improvement in WUE achieved by the PCM treatment in this experiment can be attributed to the application of the aforementioned water-saving and efficiency-enhancement principles in blueberry cultivation.

### 5.5 Effects of Fertigation Modes on Fertilizer Use Efficiency of Blueberries

PFP is a key indicator of fertilizer use efficiency, quantifying the yield per unit of nutrient input. The total nutrient input was kept constant for both treatments throughout the growing season, ensuring that nutrient supply did not confound the results. PFP was 64.49 kg/kg under PCM, compared with 53.69 kg/kg under SFM, representing a significant difference ($P < 0.05$) (Figure 7).

Farneselli et al. [25] reported that, in processing tomato grown with high nitrogen and water supply, a high fertigation frequency increased the uptake of fertilizer nitrogen and promoted crop growth. Silber et al. [26] grew lettuce as a model crop in perlite-filled pots and found that higher fertigation frequency significantly improved yield, an effect particularly pronounced at low nutrient concentrations. Frequent fertigation enhances plant nutrient uptake through two core mechanisms: it continuously replenishes nutrients in the depletion zone near the root interface, and the higher average water content in the medium enhances mass flow of dissolved nutrients. This dual effect compensates for nutrient deficits at low concentrations, thereby contributing to substantial yield increases. This experiment indicates that precise, growth-stage-specific regulation of nutrient solution concentration and timing, combined with a high-frequency, low-volume fertigation strategy, maintained stable nutrient availability in the blueberry rhizosphere. The higher yields achieved with identical nutrient input were associated with improved fertilizer use efficiency. These findings are consistent with previous reports on high-frequency fertigation in other horticultural crops.

## 6 Discussion

### 6.1 Challenges and Equipment Limitations for Commercial Blueberry Soilless Culture

Blueberry is a shallow-rooted crop with limited root absorptive capacity and is highly sensitive to EC and pH fluctuations in the root-zone substrate. Most existing fertigation studies have focused on broadacre field crops, whereas this study specifically addresses the rhizosphere sensitivity of blueberry in soilless production. Traditional manual fertigation often causes nutrient concentration spikes and pH imbalances, leading to growth inhibition, root necrosis, and yield losses-a long-standing challenge

in large-scale soilless blueberry production [27]. Moreover, commercial fertigation machines, typically designed for field crops, often lack the precision required for blueberry soilless systems.

### 6.2 Performance and Suitability of the Intelligent Fertigation Machine

The intelligent fertigation machine maintained solution EC and pH within the target ranges without manual calibration, meeting the agricultural industry standard for control accuracy and uniformity. Compared with conventional fertilization equipment, the developed system achieves faster dynamic response and higher EC and pH control precision, making it better adapted to the strict nutrient management requirements of blueberry soilless cultivation.

### 6.3 Comparison of Fertigation Modes and Mechanisms for Yield and Quality Improvement

Under equal water and nutrient inputs, PCM outperformed SFM in water and fertilizer use efficiencies, yield, and fruit uniformity. The underlying mechanism is that the intelligent fertigation machine precisely regulates the fertilizer concentration and application timing at different growth stages, keeping the fine fibrous roots of blueberries in a root-zone environment with a stable nutrient supply, while greatly reducing water and fertilizer losses. This allows water and fertilizer supply to match blueberry demand at different growth stages, ultimately achieving higher yield and improved quality at the same input level [28].

### 6.4 Application Value of the Equipment

Overall, this intelligent fertigation machine is designed for specialty crops such as blueberries that are highly sensitive to pH. It closely addresses the core practical needs of soilless cultivation, and improves both water and fertilizer use efficiency and yield per unit area with water and fertilizer inputs held equal. As the development of green agriculture requires effectively reducing the risk of non-point source pollution in mountain agriculture caused by excessive discharge of water and fertilizer [29, 30], the application of this equipment aligns well with green agricultural development requirements [31, 32].

## 7 Conclusions

This study developed an intelligent fertigation machine capable of precise EC and pH control. Under identical total irrigation and nutrient inputs, the PCM treatment significantly improved water and fertilizer use efficiencies and yield per unit area compared with the SFM treatment. Additionally, PCM reduced fruit weight variability, thereby improving commercial fruit uniformity. This work provides a technological basis for the modernization of blueberry production in the mountainous regions of Southwest China.

## Data Availability Statement

Data will be made available on request.

## Funding

This work was supported without any funding.

## Conflicts of Interest

Chunxiang Yang is affiliated with the GourmetMore (Beijing) Technology Co., Ltd., Beijing 100081, China. The author declares that this affiliation had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

## AI Use Statement

The author declares that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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