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Design and Experiment of Water and Fertilizer Integrated Equipment for Solar Greenhouse Based on Yellow Sand Substrate Model

Yalong Song[1,2,3], Jiahui Xu[1,2,3], Xufeng Wang[1,2,3], Jianfei Xing[1,2,3,*], Long Wang[1,2,3]

[1]*College of Mechanical and Electrical Engineering, Tarim University, Alar 843300, China.*
[2]*Xinjiang Production and Construction Corps Key Laboratory of Utilization and Equipment of Special Agricultural and Forestry Products in Southern Xinjiang, Alar, 843300, China.*
[3]*Modern Agricultural Engineering Key Laboratory at Universities of Education Department of Xinjiang Uygur Autonomous Region, Alar, 843300, China.*

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Abstract

Compared to traditional soil cultivation, yellow sand substrate cultivation can reduce the probability of soil-borne diseases and secondary salinization in Gobi facility agriculture. However, traditional equipment for water and fertilizer integration faces problems of slow response speed, low control precision, and poor stability, making it challenging to meet requirements for water and fertilizer saving in the yellow sand substrate cultivation mode. Considering the mentioned problems, this study designed a water and fertilizer integration system for a solar greenhouse based on a fuzzy Proportional-Integral-Derivative (PID) control strategy. First, according to the nonlinearity characteristic and time delay of water and fertilizer concentration, a fuzzy PID control strategy was designed by combining fuzzy control with traditional PID control. Then, based on the water and fertilizer concentration variation model, the water and fertilizer integration system and equipment with a water and fertilizer supply unit, a mixing unit, and a control unit were designed as a core. Finally, the applicability and accuracy of the proposed equipment were verified by simulation and field tests. The simulation results demonstrate that, the average overshoot of the proposed fuzzy PID control strategy is 11.07 % and 7.99 % lower than that of the traditional PID control strategy when the mother liquor concentration is 7.2 mS/cm and 10.0 mS/cm, and the steady-state time is 39.05 s and 2.37 s earlier, respectively. Moreover, the results of the field experiments reveal that the steady-state performance of the proposed fuzzy PID control strategy is better than that of the traditional PID control strategy. In addition, the water and fertilizer concentration fluctuation in the control process is small, the time required to reach a steady state is relatively short, and the steady-state error is approximately ± 0.1 mS/cm. Furthermore, the water and fertilizer equipment using the proposed fuzzy PID control strategy can significantly improve the speed and stability of mixing fertilizer. Finally, the ratio error of water and fertilizer solution does not exceed 5 %, the temperature and humidity test errors are within 3 %, the stability is good, and the accuracy is high. The proposed algorithm provides evidence for the development of integrated water and fertilizer equipment for the yellow sand substrate cultivation mode.

Keywords: Yellow sand matrix, Integrated water and fertilizer, Fuzzy PID, Field experiment

1. Introduction

The combination of modern irrigation technology and precision fertilization technology has resulted in integrated technology of water and fertilizer, promoting sustainable development of agriculture [1,2]. The rational use of water and fertilizer has a promoting effect on agricultural production. At present, a low utilization rate of water and fertilizer is one of the key restricting factors of the large-scale development of facility agriculture [3,4]. Therefore, research on integrated water and fertilizer technology could improve the efficiency of water and fertilizer usage and enhance the mechanization level of facility agriculture. In recent years, this technology has been used in facility agriculture, which represents an important symbol of modern agriculture in China [5]. By the end of 2023, China's facility agriculture area exceeded 40 million mu, accounting for 80% of the global facility agriculture area [6]. However, integrating water and fertilizer equipment in traditional soil tillage generally faces problems of insufficient precision, weak stability, and inaccurate water and fertilizer ratio. These shortcomings can lead to soil secondary salinization and continuous cropping obstacles, which are not conducive to the sustainable development of Gobi facility agriculture [7,8], thus affecting economic development. Northwest China has a low level of precipitation, large evaporation, and poor environmental conditions, but the light and heat resources are sufficient, which is suitable for the development of facility agriculture [9,10]. In addition, the area of non-cultivated land resources is large, there are natural conditions, such as gobi and desert, and yellow sand resources are rich [11]. Combining yellow sand substrate with water and fertilizer integration technology to facilitate agriculture can improve the quality of crops [12] and effectively solve the problems of continuous cropping obstacles and soil-borne diseases [13]. However, traditional water and fertilizer integration equipment is not applicable to the yellow sand matrix mode. Therefore, it is necessary to develop more efficient agricultural production methods with technological innovation and improvement corresponding to the yellow sand matrix's characteristics.

*E-mail address: 120200012@taru.edu.cn
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In summary, considering the nonlinearity and time delay of water and fertilizer concentration adjustment, this study designs water and fertilizer integration equipment with parameter self-tuning fuzzy Proportional-Integral-Derivative (PID) control strategy aiming to satisfy the fertilization and irrigation requirements in the yellow sand substrate cultivation mode. The proposed equipment can adjust the PID controller's parameters in real-time according to the input error and the error change rate. In addition, it can be combined with the fuzzy rules, thus significantly improving the system control accuracy and response speed. The proposed equipment design aims to optimize the application of water and fertilizer in the cultivation mode of the yellow sand substrate, improve rationality and accuracy, and provide technical references for the optimization and application of water and fertilizer integrated equipment.

2. State of the art

After many years of research and development, the integration of water and fertilizer has achieved technological breakthroughs and has been applied on a large scale to traditional agricultural production. Trifonov et al. [14] studied the water and fertilizer integration model of low-flow drip irrigation potato in the Alava Desert, Israel. Their results showed that using water and fertilizer integration technology could reduce the amount of water and fertilizer applied during the potato growth phase and did not affect the normal growth of potatoes. However, the effectiveness of irrigation strategies was affected by differences in climatic conditions and soil properties. Omondi et al. [15] explored the relationship between fertilizer concentration and cassava yield using different concentrations of water and fertilizer. The results showed that the harvest index of cassava decreased with the excessive increase in fertilizer concentration. However, their study could not accurately adjust the proportion of water and fertilizer, resulting in unstable fertilizer concentration. Edelstein et al. [16] used tomato as a research object, provided selenium for plants through drip irrigation, and explored the relationship between plant growth and selenium. Their results showed that selenium supplementation by drip irrigation could effectively promote the growth of tomatoes. However, the amount and timing of selenium could not be accurately controlled, which affected the absorption efficiency of selenium and the effect on plant growth. Coates et al. [17] developed a variable rate ejector using a simple Venturi ejector, solenoid valve, conductivity sensor, and a small computer board (i. e., a controller). However, simple sensors and solenoid valves could not provide real-time feedback and dynamically adjust the control parameters. Bronson et al. [18] employed subsurface drip irrigation to analyze the relationship between cotton growth and nitrogen under different water evaporation conditions in the southwest desert of the United States. The results showed that when the evaporation was 70%, the drip irrigation method could not affect the growth of cotton and save fertilizer. However, the subsurface drip irrigation method could neither rapidly provide feedback nor perform the corresponding adjustment, and the response speed was slow. Chaudary et al. [19] demonstrated that balancing the ratio of water and fertilizer by drip irrigation, combined with an appropriate irrigation plan, could increase the yield of maize, save 48%of irrigation water, and improve water usage efficiency. Nonetheless, manual completion of the solid fertilizer ratio stage and its relatively low accuracy hindered the implementation of automatic fertilizer mixing. Kennedy et al. [20] used California tomato as a research object and aimed to reduce the nitric oxide and nitrogen dioxide content in the planting system by combining drip irrigation with water and fertilizer, thus improving crop yield along with water and fertilizer utilization. Their study emphasized the importance of improving nitrogen utilization efficiency and minimizing nitrogen emissions in agricultural production. Aotille [21] conducted a cotton field experiment in southern Australia and highlighted the benefits of the model-based control system in evaluating irrigation and fertilization management. Their results showed that the accuracy of irrigation and fertilization management could be improved using advanced control systems to achieve more efficient agricultural production. Hassan [22] and other scholars introduced various control strategies for automated agriculture and demonstrated that attention should be paid to improving the reliability and autonomy level of automatic control systems in the development of water and fertilizer integration technology to achieve more efficient and accurate water and fertilizer management and promote the development of agricultural production toward higher intelligence. Park et al. [23] proposed an RHC control algorithm for the irrigation process, combining prediction and optimization algorithms, to achieve soil moisture regulation and maintain a suitable growth range. Their results revealed that the introduction of advanced control algorithms should be considered in the development of integrated water and fertilizer equipment to achieve irrigation and fertilization. Contreras-Castillo [24] and other scholars designed a precision agriculture technology platform named the SAgric-IoT, which is based on the Internet of Things (IoT) and convolutional neural network (CNN) to monitor the environment and provide early disease detection. The experimental results showed that the accuracy of disease identification and detection was higher than 90%, proving that the IoT and artificial intelligence technology could be integrated into the water and fertilizer-integrated equipment design to enhance the intelligent level of agricultural production, further optimizing water and fertilizer management and improving crop yield and quality.

With the development of agricultural modernization and automation in China, an increasing number of institutions and researchers have begun to engage in the research and practical application of integrated water and fertilizer systems and devices. Chunying [25] used the PID control strategy to control the concentration of water and fertilizer. However, this strategy has a large overshoot and long steady-state time for large conductivity errors, which cannot solve the problem of nonlinear change of water and fertilizer concentration. Li et al. [26] and Prabakaran et al. [27] designed a fuzzy control strategy that does not rely on an accurate mathematical model when making logical judgments and can solve the problem of nonlinear changes in water and fertilizer. However, it is challenging to adjust water and fertilizer rapidly, accurately, and stably to the preset value to meet the needs of yellow sand substrate cultivation crops. Wen et al. [28] designed a PID control strategy based on the backpropagation (BP) neural network correction to adjust the concentration of water and fertilizer. Although the steady-state and learning ability was improved to a certain extent, the BP neural network required a certain amount of learning and training time to optimize the parameters; also, it required much historical data and many computing resources. Wei et al. [29] established an orchard water and fertilizer integrated control system with the PLC as a control core and used a fuzzy control algorithm to construct a decision system. However, there was a lack of a reasonable control strategy and an accurate control method in the adjustment process. Hong et al. [30] developed a set of integrated control systems of water, fertilizer, and medicine based on the PLC, which had stronger applicability and could achieve the purposes of saving water, improving fertilizer efficiency, saving medicine, saving working hours, reducing costs, and increasing production. However, there were certain defects in the rapid response of the PLC system. Lan [31] wirelessly transmitted the environmental parameters of crop growth using the Zigbee technology of the IoT. The detected environmental parameters included light intensity, air temperature, air humidity, and carbon dioxide concentration, which were of great significance to the development of water and fertilizer integration equipment. In addition, it could adjust the application scheme of water and fertilizer, realize intelligent management and precise fertilization, and improve crop yield and quality. Haiming [32] integrated information on farmers, regional locations, farmland, and crops using automatic fertilizer distribution equipment and software systems, where a fertilizer cloud platform management system was used as a core to realize automatic, intelligent, and remote management of irrigation management. The results showed that the real-time monitoring and adjustment of crop growth environment parameters could be realized through an intelligent management system in the development of water and fertilizer integration equipment, which could be helpful in protecting crop health and increasing yield. Jiahua [33] selected tomato as a research object, introduced an innovative type of fertilization and irrigation decision-making, and applied adaptive PID control technology to fertilizer solution configuration; this effectively improved the efficiency of fertilizer and water saving and ensured the growth of tomatoes. This study showed that using PID control technology in the development of water and fertilizer integration equipment could more scientifically fertilize and irrigate, reduce waste, and improve utilization efficiency.

In summary, the research on water and fertilizer integration technology in China started late, exhibiting variations in product variety and advanced degree compared to foreign equipment, which limited market acceptance and application scope. However, with scientific research and experimental application, the technology gap between domestic and foreign research has gradually reduced. In addition, due to the low nutrient content and poor water and fertilizer retention capacity of the yellow sand substrate, the current water and fertilizer devices on the market have not been optimized for the yellow sand substrate cultivation mode, and the equipment has poor applicability. Moreover, the traditional water and fertilizer control strategy cannot handle the nonlinearity and time delay of water and fertilizer concentration adjustment. Consequently, adjusting water and fertilizer rapidly, accurately, and stably to the preset value is challenging. Therefore, designing greenhouse water and fertilizer integration equipment suitable for the yellow sand substrate cultivation mode is particularly important.

3. Methodology

3.1 System composition and working principle

The overall structure of the greenhouse water and fertilizer integration equipment is presented in Fig. 1, where its integral role in the irrigation network as a comprehensive water and fertilizer irrigation system can be observed. This equipment consists of several essential components, such as a suction pump, a four-way suction pipeline, a fertilizer injection pump, a flow control valve, a flow sensor, a Venturi fertilizer injector, a one-way valve, and an irrigation solenoid valve, which features the main waterway and four fertilizer suction pipes with the similar structure and connection mode. The main waterway connects via a T-type three-way interface featuring electronically controlled flow regulating valves and flow meters placed between the T-type interface and the fertilizer bucket. These devices actively manage pressure through closed feedback loops, preventing pump damage and pipeline ruptures and adjusting the applied fertilizer quantity. In addition, a flow sensor, comprising one large-range flow sensor and three small-range flow sensors, is installed in both the main waterway and the fertilizer path to monitor the real-time flow rates within the respective pipelines.

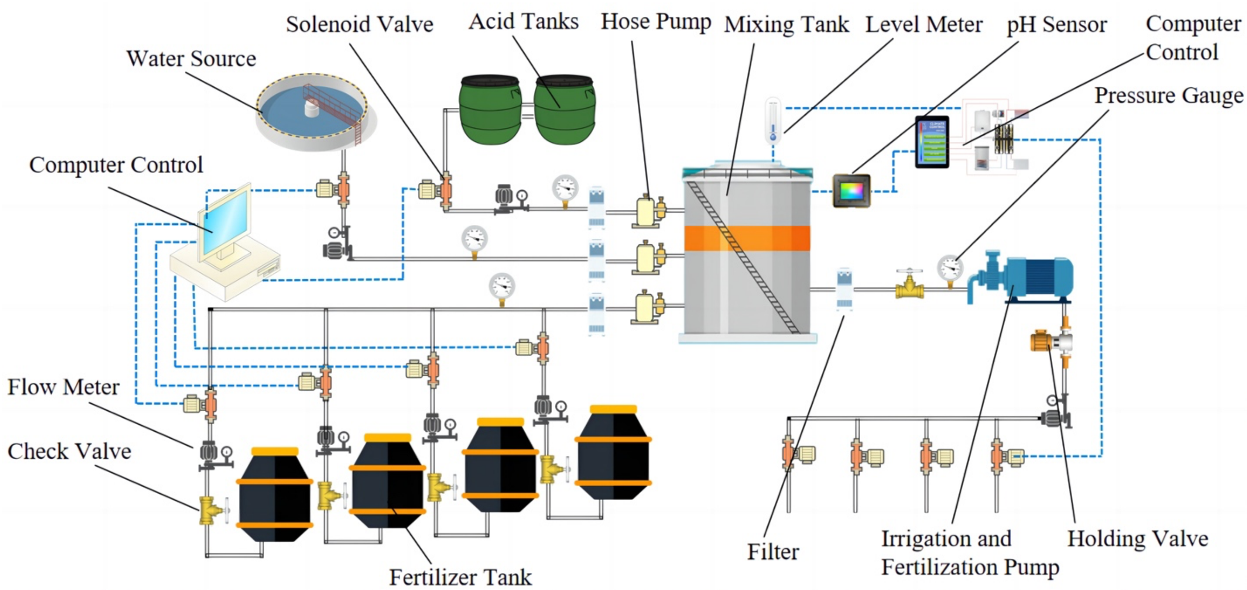


Fig. 1. The overall structure diagram of the water and fertilizer integrated control equipment.

After determining the total amount and duration of irrigation, the greenhouse water and fertilizer integration equipment are used for timing and quantitative fertilization. Throughout the irrigation operation, the system controls the self-priming pump and solenoid valve based on the user-defined total irrigation amount and fertilization ratio. The self-priming pump extracts the irrigation water from the water tank, and the fertilizer injection pump extracts the mother liquid from the fertilizer barrel and monitors the fertilizer's flow rate using a float flowmeter at the outlet. Subsequently, the fertilizer solution is mixed with irrigation water in a static mixer, forming the nutrient solution, and the corresponding solenoid valve is opened based on a specific irrigation type. If only irrigation is required for the crop, the solenoid valve of the four-way suction pipeline should be closed and only the main waterway should be opened. In addition, a pressure relief valve is arranged in the pipeline to protect the pipeline's normal operation. Then, the system can adjust the irrigation flow and time in real-time. When the soil moisture reaches a reasonable range, the water and fertilizer integration equipment stops operating. To prevent excessive watering and unreasonable irrigation plans from affecting crop growth, the proposed system sets a soil moisture threshold, ensuring an accurate ratio for optimal water and fertilizer.

3.2 Fuzzy PID control strategy

3.2.1 Fuzzy PID control principle

The regulation of water and fertilizer concentration denotes a significant challenge due to the inherent nonlinearity of the process. Therefore, it is very difficult to develop an accurate mathematical model, and traditional PID control systems should mainly be used in linear continuous systems [34]. However, fuzzy control offers an alternative approach that does not require accurate mathematical models and can handle the effects of nonlinear changes, but its control accuracy is low [35]. Therefore, this study combines the advantages of the two control strategies and designs a fuzzy PID control strategy to enhance the control accuracy and

The traditional PID control equation is given in Eq. (1). Calculating the proportion, integral, and differential of the error $e(t)$ and weighting the results, the control quantity $u(t)$ can be obtained; the control parameters Kp_0, Ki_0, and Kd_0 are fixed values, which cannot be adjusted based on the actual operational environment. Moreover, this method cannot fit the controlled object, and control accuracy and stability are poor. Consequently, certain corrections are necessary to correct the three PID control parameters.

$$u(t) = Kp_0 e(t) + ki_0 \int_0^t e(t)dt + kd_0 \frac{de(t)}{dt} \tag{1}$$

The fuzzy control error e of water and fertilizer conductivity and a change rate ec of error e are input variables of the system. After fuzzy reasoning, three tuning parameters Δkp, Δki, and Δkd are output, as expressed by Eq. (2). Each tuning parameter is multiplied by the corresponding scale factor and added to the PID parameters before tuning to obtain the system's parameters after tuning. Subsequently, the control parameters of fuzzy PID are used to realize the self-tuning of PID parameters. The fuzzy PID control strategy represents a combination of fuzzy control and PID control. The control flow chart is shown in Fig. 2.

$$\begin{aligned} Kp &= \Delta kp \times x_p + Kp_0 \\ Ki &= \Delta ki \times x_i + Ki_0 \\ Kd &= \Delta kd \times x_d + Kd_0 \end{aligned} \tag{2}$$

where Kp represents the proportion coefficient after setting, Ki denotes the integral coefficient after setting, Kd indicates the differential coefficient after setting, Δkp symbolizes the proportion correction coefficient after setting, and Δki signifies the integral correction coefficient after setting. In addition, Δkd represents the differential correction coefficient after setting, x_p indicates the scale factor of the scale coefficient, x_i denotes the scale factor of the integral coefficient, and x_d symbolizes the scale factor of the differential coefficient. Moreover, kp_0 is the proportional coefficient before setting, ki_0 indicates the integral coefficient before setting, and kd_0 represents the differential coefficient before setting.

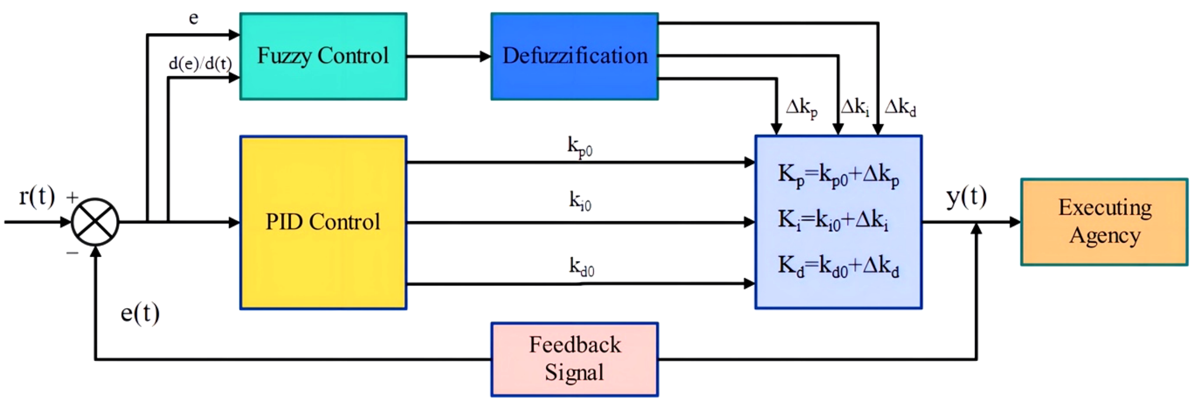


Fig. 2. Control flow chart

3.2.2 Design of membership degree and writing of fuzzy rules

This study uses the Mamdani inference algorithm. The design process of a fuzzy controller is mainly divided into two parts. The first part sets the fuzzy language value and fuzzy domain of the system's input and output variables. The second part implements the expert experience in fuzzy rules and forms a fuzzy set.

First, error e of the conductivity value of water and fertilizer and error change rate ec of error e are set as two input parameters of the two-dimensional fuzzy control system, where the fuzzy domain values of *e* and *ec* are as follows: *e* = *ec* = ｛-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6｝.

The language values of *e* and *ec* are: *e* = *ec* = {NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium), PB (positive large)}

The fuzzy subsets of *e* and *ec* adopt the triangular membership function, and the membership curve is shown in Fig. 3(a).

The fuzzy domain values of the three output parameters, namely *Δkp*, *Δki,* and *Δkd* of the two-dimensional fuzzy control system are defined as follows: *Δkp* = *Δki* = *Δkd* = {-7, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7};

Further, the linguistic values of *Δkp*, *Δki*, and *Δkd* are: *Δkp* = *Δki* = *Δkd* = {NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium), PB (positive large)};

The fuzzy subsets of the three output parameters of *Δkp*, *Δki*, and *Δkd* have the triangular membership function, which is shown in Fig. 3(b).

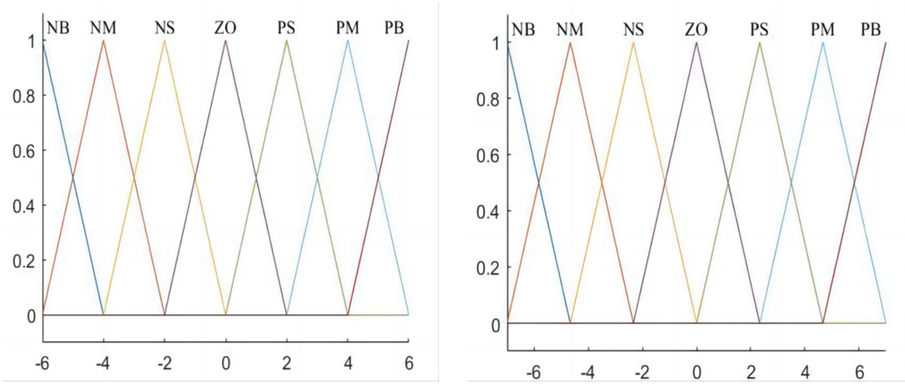


Fig. 3. The membership function curve. (a) Affiliation curves for *e* and *ec*. (b) Affiliation curves for *Δkp*, *Δki*, *Δkd*

According to the values of system input deviation *e* and deviation change rate *ec*, the corresponding control quantity is output, and 49 fuzzy control rules are written accordingly as follows:

(1) If (*e* is NB) and (*ec* is NB), then (*kp* is PB), (*ki* is NB), and (*kd* is PS);

(2) If (*e* is NB) and (*ec* is NM), then (*kp* is PB), (*ki* is NB), and (*kd* is PS);

(49) If (*e* is PB) and (*ec* is PB), then (*kp* is NB), (*ki* is PB), and (*kd* is PB).

The fuzzy control rules are presented in Table 1, where the language values are *Δkp*, *Δki*, and *Δkd* from left to right. The three-dimensional surfaces of fuzzy rules *Δkp*, *Δki*, and *Δkd* are shown in Fig. 4(a), 4(b), 4(c). The area barycenter method is employed to solve the ambiguity. The rule surface transits smoothly from the highest point to the lowest point, and there is no mutation rule that does not conform to the overall changing trend. As can be seen, the control rules can achieve good control effects.

Table. 1. Fuzzy rule control table

Δkp, *Δki*, *Δkd* language values	**Error *e* language value**						
	NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PS/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NM/PM/NS	NM/PM/ZO
PS	PS/NM/ZO	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PB/ZO
PM	PS/ZO/PB	PS/ZO/NS	NS/PS/PS	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PM	NM/PM/PS	NB/PB/PS	NB/PB/PB

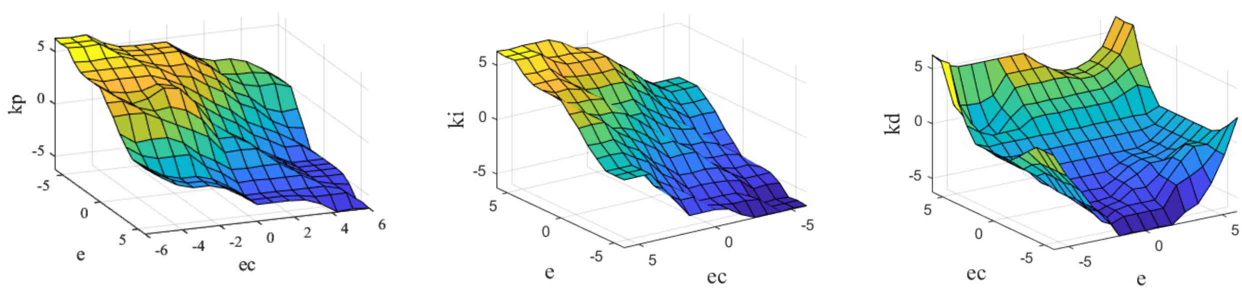


Fig. 4. Three-dimensional surface diagram of fuzzy rules. (a) Fuzzy regular three-dimensional surfaces with *Δkp*. (b) Fuzzy regular three-dimensional surfaces with *Δki*. (c) Fuzzy regular three-dimensional surfaces with *Δkd*.

3.3 Analysis of water and fertilizer concentration model

During the water and fertilizer concentration adjustment process, the control algorithm outputs the control command to the actuator through fuzzy reasoning to increase the amount of fertilizer absorbed by the proportional fertilizer applicator when the EC value that the sensor monitors, indicating the conductivity value of water and fertilizer in the mixed fertilizer tank, is lower than the preset value.

Conversely, when the water and fertilizer conductivity value is higher than the preset value, the actuator reduces the amount of absorbed fertilizer. When the conductivity value of water and fertilizer is equal to the preset value, the system enters a stable state. However, there are many uncertain interference factors in the adjustment process, which cannot be all expressed by an accurate mathematical relationship model. Therefore, this design analyzes the variation of water and fertilizer concentration by establishing a simple mixed fertilizer model.

Suppose the volume of the mixed fertilizer tank remains constant when the system reaches equilibrium. In that case, the system follows the laws of mass conservation and flow conservation, and the output quality of the system fertilizer is equal to its input quality, which can be as expressed by:

$$\frac{d[V(t)C(t)]}{dt} = C_1 q_1(t) + C_2 q_2(t) - C(t) q_3(t) \tag{3}$$

where $V(t)$ represents the liquid volume of fertilizer in the mixed fertilizer tank, L; $c(t)$ is the output fertilizer concentration, g/L; C_1 is the input mother liquor concentration, g/L; $q_1(t)$ is the input mother liquor flow, L/s; C_2 symbolizes input water concentration, g/L; $q_2(t)$ represents the input water flow, L/s; $q_3(t)$ denotes output fertilizer flow, L/s.

At the same time, the value of conductivity Ec can be replaced by the liquid concentration because the conductivity Ec is proportional to the concentration of water and fertilizer, which can be as expressed by:

$$\frac{d[V(t)C(t)]}{dt} = Ec_1 q_1(t) + c_2 q_2(t) - Ec(t) q_3(t) \tag{4}$$

where $Ec(t)$ is the output conductivity value of mixed fertilizer solution, mS/cm, Ec_1 is the input mother liquor conductivity value, mS/cm, and Ec_2 is the input water conductivity value, mS/cm.

Since the conductivity value Ec_2 of clean water is very small, approximately zero, it is brought into Eq. (4). After Laplace transform, it can be obtained that:

$$E(s) = \frac{Ec_1 q_1}{V_t s + q_3} m(s) \tag{5}$$

where s represents the complex variable of the Laplace transform.

As shown in Eq. (5), the control response characteristic is a first-order linear system. Let the conductivity value Ec_1 of the mother liquor of the whole system be 7.2 mS/cm, V_t is 107 L, q_1 is 1 L/s, and q_3 is 2 L/s. Considering a certain lag in the actual control process, set the lag time to 7 s. Then, the transfer function of the system can be defined as follows:

$$G(s) = \frac{E(s)}{m(s)} = \frac{7.2}{107s + 2} e^{-7s} = \frac{3.6}{53.5s + 1} e^{-7s} \tag{6}$$

3.4 The feasibility of fuzzy PID control strategy is verified by experiments

3.4.1 Simulation experiment

The Simulink module of the MATLAB R2022b was selected as the simulation software platform, and the simulation hardware CPU was Intel Core i5-7300HQ. In addition, the PID control strategy and fuzzy PID control strategy were used. The proportional, integral, and differential coefficients of PID control were obtained by the critical ratio method [37], and they were Kp_0 = 0.3621, Ki_0 = 0.02, and Kd_0 = 0.001, respectively. The proportional, integral, and differential coefficients of fuzzy PID control were the same as those of PID control. Then, the quantization and scale factors for the input error *e* and error change rate *ec* were obtained by the empirical trial and error method. The comprehensive performance of the two control strategies in reaching different conductivity setting values and the effects of different mother liquor conductivity values on the two algorithms were tested. Two control strategies adjusted the conductivity of mixed water and fertilizer to 1 mS/cm, 1.5 mS/cm, and 2.3 mS/cm. Moreover, the conductivity values of two different mother liquors were 7.2 mS/cm and 10.0 mS/cm. The volume of the fertilizer tank remained 107 L, the flow rate of the proportional fertilizer applicator was 1 L/s, the output flow rate of the fertilizer tank was 2 L/s, and the simulation sampling time was set to 300 s. All other parameters remained unchanged.

The above parameters were input into the simulation platform, and the simulation results are shown in Table 2. For a mother liquor concentration of 7. 2 mS/cm, the two control strategies reached three preset values and maintained a steady state. The fuzzy PID control strategy exhibited a lower overshoot of 12.79 % and a shorter average steady-state time of 250.99 s compared to the traditional PID control strategy, with an average overshoot of 23.86 % and an average steady-state time of 290.04 s. The overshoot of the fuzzy PID control strategy was 46.40% lower than that of the traditional PID control strategy, and the steady-state time was 39.05 s in advance, which represented a significant improvement in stability and response speed.

Under the condition that the mother liquor concentration was 10.0 mS/cm, the average overshoot of the fuzzy PID control strategy was 19.18 %, and the average steady-state time was 246.07 s when the two control strategies reached the preset value and maintained the steady-state. The average overshoot of the traditional PID control strategy was 27.17 %, and the average steady-state time was 248.44 s. The overshoot of the fuzzy PID control strategy was 29.41 % lower than that of the traditional PID control strategy, and the steady state time was 2.365 s shorter. As can be seen, the steady-state times of the two control methods were similar after the increase in the conductivity value of the mother liquor, and the traditional PID control exhibited a significant increase in overshoot.

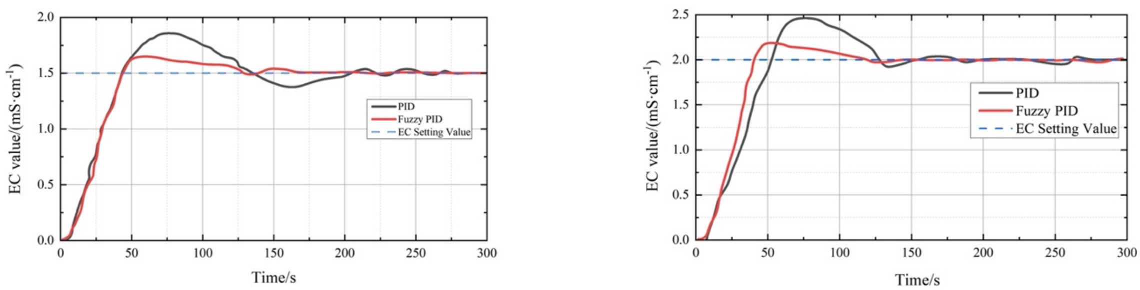
Table 2. Simulation test comparison of different EC setting values and mother liquor EC values

Control Mode	EC set point ($mS \cdot cm^{-1}$)	The EC value of mother liquor ($mS \cdot cm^{-1}$)	Steady-state EC value ($mS \cdot cm^{-1}$)	Thermal balance time (s)	Overshoot (%)
PID Control	1.0	7.2	1.003	285.693	23.152
	1.5	7.2	1.504	290.122	23.773
	2.3	7.2	2.304	294.325	24.671
	1.5	10.0	1.502	242.983	27.162
	2.3	10.0	2.300	253.891	27.171

Fuzzy PID Control	1.0	7.2	1.002	209.630	13.73
	1.5	7.2	1.503	252.652	11.781
	2.3	7.2	2.306	290.681	12.791
	1.5	10.0	1.502	220.232	18.642
	2.3	10.0	2.303	271.910	19.710

3.4.2 Field experiment
To verify the performance of the proposed control strategy further, the experiment was conducted at the industrial training center of the School of Mechanical and Electrical Engineering, Tarim University. The water pressure at the water supply end of the system was 2 MPa. Potassium nitrate fertilizer was used to configure the mother liquor in the mixed fertilizer barrel, and its conductivity was adjusted to 7.2 mS/cm. Two control strategies were used to adjust the water and fertilizer concentration to 1.5 mS/cm and 2.0 mS/cm. In addition, a DJS-1CF conductivity sensor was used to measure the concentration of fertilizer solution in the mixed fertilizer barrel. The conductivity data were collected every two seconds and measured continuously for 300 s. The test results are presented in Fig. 5(a), 5(b), where it can be seen that both control strategies could make the water and fertilizer concentrations reach the preset value.

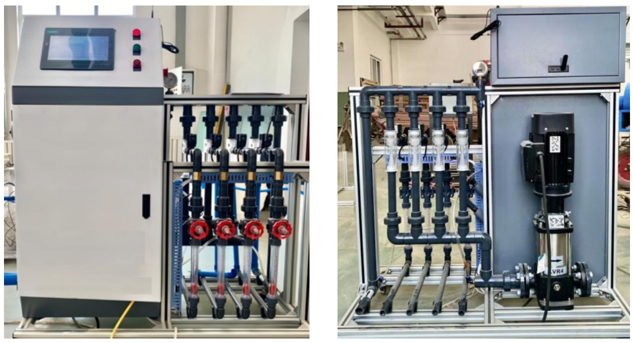
However, it could be easily affected by other factors due to the complex changes in water and fertilizer in the actual control process. The steady-state error of the two control strategies was approximately ± 0.1 mS/cm. Under the two EC set values, the steady-state performance of the fuzzy PID control strategy was better than that of the traditional PID control strategy. The water and fertilizer concentration fluctuations in the control process were small, and the time to reach the steady state was advanced. With the increase in the EC set value concentration, the overshoot of the traditional PID control strategy also increased; also, the time to reach the steady state of the two control strategies increased significantly. However, the response speed of the fuzzy PID control strategy was slightly improved.



(a) (b)

Fig. 5. Comparison test results obtained using different EC values. (a) Control performance when water-fertilizer concentration was adjusted to 1.5 mS/cm. (b)Control performance when water-fertilizer concentration was adjusted to 2.0 mS/cm.

3.5 Control system design
The key control components of the water and fertilizer integration equipment included the head control device of the water source, the fertilizer pipeline, the irrigation pipeline, and the fertilizer distribution device. The list of key structural components is shown in Table 3, and the physical object is presented in Fig. 6.



(b)

(a)

Fig. 6. The physical map of water and fertilizer integration equipment. (a) Front view. (b) Rear view

Table. 3. Key components of integrated water and fertilizer system

Order number	Equipment	Parameter
1	ZK3U-64MRT PLC	64-point input and output, 10 analog inputs, 2 analog outputs, 1 RS-232 communication port, 2 RS-485 communication ports, 1 network interface.
2	Self-spring pump	Rated power 750 W, rated flow 2,400 L/h, rated head 25 m.
3	The injector pump	Rated power 45 W, rated flow 240 L/h, rated head 100 m.
4	Small range flow sensor	Rated voltage DC 5 V, detection range 5 L/h–600 L/h.
5	Large range flow sensor	Rated voltage DC 24 V, detection range 60 L/h–7,200 L/h.
6	Cut-off valve	The diameter is 25 mm, the material is HPb59-1, the operating temperature is -10°C-120°C, and the nominal pressure is 1. 6 MPa.
7	Soil temperature-moisture sensor	The diameter is 25 mm, the material is HPb59-1, the operating temperature is -10°C-120°C, and the nominal pressure is 1. 6 MPa.

8	Air temperature and humidity sensor	The air temperature measurement range is -40°C-80°C, and the accuracy is ± 0.5°C. Air humidity measurement range 0-100%, accuracy ± 3 %.

3.5.1 Control system hardware design
The control center module included a programmable controller (PLC) and an embedded touch screen, as shown in Fig. 7. The control system principle defined that the PLC first received the signal from the device through the input port and then performed logic processing; finally, it sent the control signal to the components, including the pump, electric valve, and pressure pump, through the output port for start-stop control. The sensing equipment included a soil temperature and humidity sensor, a soil nitrogen, a phosphorus and potassium sensor, a water pH sensor, and a soil pH sensor. The sensing device continuously monitored changes in soil and fertilizer solution properties in real-time and transmitted the collected data to the PLC. Then, the PLC fed the signal transmitted by the sensor to the touch screen for visualization. The wiring is depicted in Fig. 8

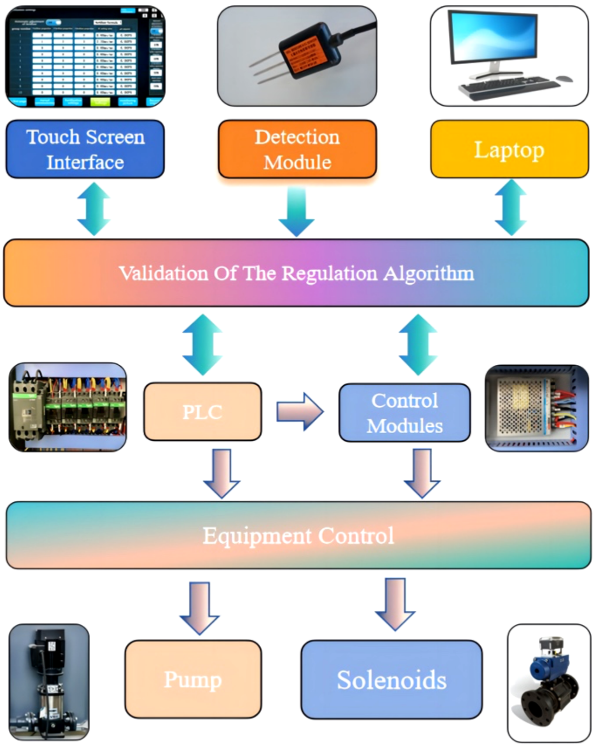


Fig. 7. The schematic diagram of the control system of water and fertilizer integration equipment.


Fig. 8. The photo of the plate connection of water and fertilizer integrated equipment.

3.5.2 Operation interface design and function
In system interfaces, users can view real-time data, such as temperature and humidity data in the space and soil, and control equipment to obtain environmental planting information and make necessary adjustments in time. In the fertilization interface, which is illustrated in Fig. 9, users could process data, such as the total amount and proportion of fertilization. In addition, users could monitor the fertilizer concentration in the water in real-time to ensure that the fertilization met the predetermined plan. If the concentration exceeded the set threshold, the alarm function reminded users to perform an adjustment.

Fig. 9. The photo of the fertilizer setting interface.

In the watering interface, shown in Fig. 10, users could set the irrigation time, configure the irrigation frequency through the combination of field solenoid valves, and adjust the interval days and daily irrigation times in each irrigation cycle. The field solenoid valve was employed to control the amounts of water and irrigation water at each time and provide real-time feedback through flowmeters and soil moisture sensors.

Fig. 10. The photo of the watering setting interface.

The monitoring screen, displayed in Fig. 11, provides information on the irrigation and fertilization status and updates the dynamics of soil temperature, humidity, EC value, and pH value in real-time. In addition, it displayed the current state of the key components, such as the solenoid valve and fertilizer valve in real time, and the time series chart of the historical trend of irrigation amount, fertilizer use amount, and environmental conditions.

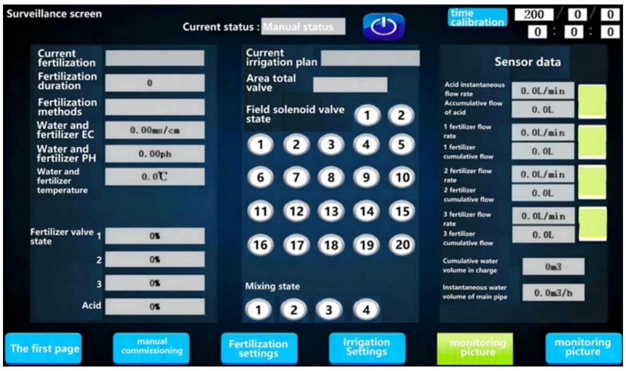


Fig. 11. The photo of the monitoring setting screen.

4 Result Analysis and Discussion

4.1 Experimental design

Next, an experiment was conducted at the training center of the School of Mechanical and Electrical Engineering, Tarim University, to assess the precision operation performance of the proposed water and fertilizer integration equipment. In the experiment, the variable frequency constant pressure water supply system provided the constant water pressure of the main pipe required for the test, as shown in Fig. 12. Furthermore, a data acquisition accuracy analysis test and a precision operation control test were performed, focusing on two aspects: 1) environmental data collection accuracy; 2) equipment accuracy in terms of the water and fertilizer ratio accuracy.


Fig. 12. The overall experimental setup.

The temperature and humidity in the natural environment of the work training workshop were considered to verify the reliability of data acquisition. The touch screen was used to record and analyze the temperature and humidity data from 10:00 a.m. to 10:00 p.m., which were used as a test value, and the results of the handheld thermometer at the same time were used as a standard value. Further, it was examined whether the data results conformed to the law of environmental change. The accuracy of data collection was also analyzed. The test results are shown in Table 4.

Then, the precision test of water and fertilizer ratio was conducted on the water and fertilizer integration equipment. By keeping the outlet flow of the main pipe at 2.5 m^3/s, the mother liquor of 100 g/L urea, potassium sulfate of 100 g/L, calcium superphosphate of 100 g/L, and calcium magnesium nitrate of 100 g/L were placed in four fertilizer tanks of A, B, C, and D fertilizer roads, respectively. All four fertilizer roads and the main pipeline operated normally. Moreover, the upper computer system transmitted information on the total irrigation amount and water and fertilizer ratio to the water and fertilizer control module to optimize the allocation and irrigation efficiency. In addition, the PLC was used to accumulate the pulse signal output by the flowmeter, and the volume of the mother liquor and water of the irrigation fertilizer was recorded by the cumulative pulse count. A 1000 L water and fertilizer solution was prepared, and the commonly used proportion of the water and fertilizer in agricultural irrigation was selected to ensure the practicability and relevance of the test.

4.2 Experimental results

The experiment was performed from 10:00 a.m. to 10:00 p.m., and the diurnal variation during the day was recorded. The data were collected by combining the measurement layout of the four-angle method and the center method, and the average value of the five measurements was used as a final result to ensure the accuracy and reliability of the data. As shown in Table 4 and Fig. 13, the temperature trend in the training center first increased and then decreased, whereas the humidity first decreased and then increased. This trend was consistent with the general environmental temperature and humidity law. From the data, the error between the temperature and humidity test value and the standard value was within 3%, which was within the error range, demonstrating that the proposed equipment had good accuracy and reliability.

The test results of the water and fertilizer ratio accuracy are shown in Table 5, and the error analysis results are shown in Table 6.

Table 4. Data acquisition accuracy analysis test results

Time	Temperature results			Humidity results		
	Test the temperature value (℃)	Standard temperature value (℃)	Error (%)	Test the humidity value (%)	Standard humidity value (%)	Error (%)
10:00	16.5	16.3	1.23	97.1	95.3	1.89
11:00	22.0	21.7	1.38	77.8	75.8	2.64
12:00	31.9	31.2	2.36	59.4	57.8	2.77
13:00	32.0	31.5	1.59	41.6	40.9	1.71
14:00	34.4	33.6	2.35	39.4	38.6	2.07
15:00	36.5	35.4	2.97	35.8	35.2	1.70
16:00	35.9	35.3	1.57	34.6	33.8	2.37
17:00	33.3	32.7	1.98	37.2	36.5	1.92
18:00	26.1	25.4	2.63	40.6	40.1	1.25
19:00	22.4	21.8	2.96	57.2	56.3	1.60
20:00	22.9	22.4	2.23	68.6	67.5	1.63
21:00	21.7	21.1	2.84	86.4	85.3	1.29
22:00	19.8	19.4	2.14	89.1	87.1	2.30

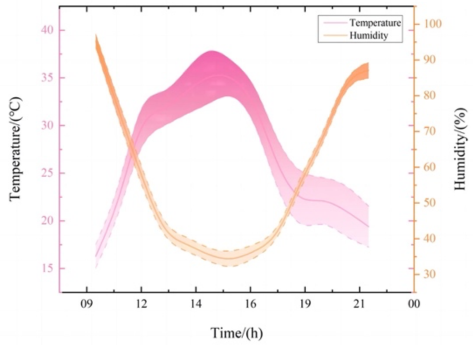


Fig. 13. The temperature and humidity error.

Table 5. Test results of water and fertilizer ratio regulation in four fertilizer roads A, B, C, and D

Number	Total allocation (L)	Ratio of water and fertilizer (water:A:B:C:D)	Theoretical cumulative flow (L)					Actual Cumulative Flow (L)				
			water	A	B	C	D	Water	A	B	C	D
1	1000	100:3:5:6:2	862.07	25.86	43.10	51.72	17.24	864.58	25.12	43.99	51.70	17.45
2	1000	100:3:5:6:2	862.07	25.86	43.10	51.72	17.24	873.36	25.33	43.55	51.12	17.21
3	1000	100:3:5:6:2	862.07	25.86	43.10	51.72	17.24	868.14	25.98	44.01	50.25	17.33
4	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	883.46	43.87	34.12	17.15	43.25
5	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	864.11	42.79	35.16	17.65	43.66
6	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	868.96	43.12	34.78	17.46	43.28
7	1000	100:6:4:3:3	862.07	51.72	34.48	25.86	25.86	872.35	51.43	34.52	25.77	25.16
8	1000	100:6:4:3:3	862.07	51.72	34.48	25.86	25.86	863.12	52.78	34.65	26.19	26.45
9	1000	100:6:4:3:3	862.07	51.72	34.48	25.86	25.86	867.55	53.10	35.14	25.69	25.69
10	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	879.37	43.15	35.11	17.48	43.56
11	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	865.13	43.56	35.23	17.67	43.74
12	1000	100:5:4:2:5	862.07	43.10	34.48	17.24	43.10	871.98	44.13	33.78	17.48	43.69

Table 6. Error analysis of the water and fertilizer ratio control test in the four fertilizer roads denoted by A, B, C, and D

Number	Total allocation (L)	Ratio of water and fertilizer (water:A:B:C:D)	Relative error (%)				
			water	A	B	C	D
1	1000	100:3:5:6:2	0.29	2.86	2.06	0.04	1.22
2	1000	100:3:5:6:2	1.31	2.05	1.04	1.16	0.17
3	1000	100:3:5:6:2	0.70	0.46	2.11	2.84	0.52
4	1000	100:5:4:2:5	2.48	1.79	1.04	0.52	0.35
5	1000	100:5:4:2:5	0.24	0.72	1.97	2.38	1.30
6	1000	100:5:4:2:5	0.80	0.05	0.87	1.28	0.42
7	1000	100:6:4:3:3	1.19	0.56	0.12	0.35	2.71
8	1000	100:6:4:3:3	0.12	2.05	0.49	1.28	2.28
9	1000	100:6:4:3:3	0.64	2.67	1.91	0.66	0.66
10	1000	100:5:4:2:5	2.01	0.12	1.83	1.39	1.07
11	1000	100:5:4:2:5	0.35	1.07	2.18	2.49	1.48
12	1000	100:5:4:2:5	1.15	2.39	2.03	1.39	1.37

According to the measurement and error analysis results of Tables 5 and 6, the use of water and fertilizer integration equipment can be adjusted in real-time. This capacity allows for maintaining the ratio error of water and fertilizer solution consistently below 5 %. These findings demonstrate that the system has good stability and high accuracy and can meet the actual production needs.

5. Conclusions

The traditional water and fertilizer integration equipment cannot accurately control water and fertilizer in the yellow sand substrate cultivation mode. To address this problem, this study proposes a fuzzy PID control strategy combining fuzzy control and traditional PID control based on the nonlinearity and time delay of water and fertilizer concentration. In addition, the simulation of the fuzzy PID control strategy and the comparison test of two different control strategies are conducted to adjust the conductivity value according to the variation law of water and fertilizer concentration. Finally, an integrated water and fertilizer system and equipment are developed using a water and fertilizer supply unit, mixing unit, and control unit as a core. The applicability and accuracy of the greenhouse water and fertilizer integration equipment that uses the fuzzy PID control strategy are verified, and the field experiment is carried out.

The following conclusions are drawn from the experimental results:

(1) Simulation results show that the average overshoot of the fuzzy PID control strategy is 11.07 %, which is 7.99 % lower than that of the traditional PID control strategy. Moreover, the steady-state time for fuzzy PID control and traditional PID control is 39.05 s and 2.365 s, respectively. Hence, it is shown that the fuzzy PID control strategy can be well adapted to the workplace, where the fertilization formula changes significantly;

(2) The experimental results show that the two control strategies can make the concentration of water and fertilizer reach the preset value. However, due to the complex changes in water and fertilizer in the actual control process, it can easily be affected by other interference factors. The response speed and system stability of the fuzzy PID control strategy are better than those of the traditional PID control strategy, which can significantly improve the speed and stability of a

mixed fertilizer. In addition, the steady-state error of the two control strategies is approximately ± 0.1 mS/cm;

(3) The experimental results indicated that the error is maintained within 3 % between the temperature and humidity test value and the standard value of the equipment, with the ratio error of the water and fertilizer solution of up to 5 %. Hence, the equipment has good stability and high accuracy and can meet the actual production requirements of the water and fertilizer integration system. In addition, the equipment can effectively alleviate the problem of poor water and fertilizer retention capacity under the yellow sand substrate cultivation mode, ensuring an accurate and efficient supply of water and fertilizer for crop growth and meeting the operation demand of precision fertilization under the yellow sand substrate cultivation mode.

This study utilizes simulation experiments and field trials to demonstrate that the fuzzy PID control strategy effectively reduces overshoot and improves steady-state response time. It is particularly suitable for regulating water and fertilizer in yellow sand substrate cultivation systems, with significant practical implications for advancing facility agriculture in desert regions. However, the strategy may encounter instability due to variations in environmental conditions and system nonlinearity. Therefore, future research will focus on increasing the number of fuzzy rules and refining the fuzzy set to enhance the controller's ability to accurately respond to system changes and improve overall stability.

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