Development of a variable-rate spraying system for small amounts of liquid rhizobial inoculation based on incremental PID control

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Abstract: To improve the efficiency and reduce the labor intensity of rhizobial inoculation, a variable-rate spraying and control system for variable rate application (VRA) was developed. This system uses an incremental Proportional Integral Derivative (PID) closed-loop control algorithm to accurately regulate the spraying rate according to the target application rate, making it particularly suitable for the precision spraying of small volumes. Laboratory tests on precise flow control showed the variation coefficient of the spraying nozzle did not exceed 1.2% within the pressure range of 0.10-0.20 MPa, and a clear linear relationship was observed between the spraying rate and pressure. For small-flow control, the maximum response time was 1.93 s, with an average of 1.62 s. Field trials at Heilongjiang Agricultural Xianghe Farm in China demonstrated that soybeans inoculated with rhizobia exhibited better average seed counts and 100-seed weights compared to a control group. When applied together with a full base fertilizer, the average yield with liquid rhizobial inoculant increased by 232.5 kg/hm^2, representing a 6.9% improvement over the control. These results clearly indicate that this spraying and control system for liquid rhizobial inoculation offers superior performance and provides important technical support for promoting widespread adoption of rhizobial technology in agricultural practice.

Keywords: precision agriculture, liquid rhizobial inoculation, spraying and control system, variable rate application, incremental PID control algorithm

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1 Introduction

Leguminous plants are widely cultivated and represent one of the most important food crops globally. However, prolonged monoculture of leguminous plants can lead to depletion of soil nitrogen levels, which may restrict plant growth and reduce nitrogen uptake from the soil[1]. To address this challenge, various methods and technologies have been employed.

One approach involves the application of synthetic nitrogen fertilizers, which have been widely used for nearly a century. However, the use of synthetic nitrogen disrupts the biogeochemical cycle of nitrogen, leading to serious environmental consequences such as air and water pollution, and even contributing to climate change[2]. In certain regions, Gramineae legume polycultures, such as rotating wheat/corn and soybean cropping, have been adopted as primary agricultural production methods to promote microbial metabolic efficiency and foster the development of multifunctional microbial communities[3]. It has been demonstrated that legume intercropping can reduce dependency on chemical fertilizers, increase crop yield, and improve soil fertility[4]. In addition, biological nitrogen fixation (BNF) in legumes represents a highly effective strategy for soil nitrogen replenishment, offering notable benefits for environmental sustainability and energy efficiency[5]. Inoculating seeds with rhizobia before and during sowing can effectively promote nodule formation on the roots of leguminous plants[6]. This practice, in turn, has a profound impact on the survival rates and subsequent effectiveness of BNF, as well as plant survival and biomass accumulation[7]. Consequently, this practice significantly contributes to reducing the need for nitrogen fertilizers while enhancing crop yields[8,9], and has proven economically and ecologically beneficial in countries such as the United States and Brazil[10,11].

However, two traditional inoculation methods are commonly employed in China: seed dressing and soil application[12]. The seed dressing method involves manually diluting the rhizobial inoculant and evenly applying it to the surface of seeds. To ensure the survival rate, the dressed seeds must be promptly dried and sown immediately[13]. The soil application method is generally employed during land preparation. When sunlight is dim, rhizobia are evenly scattered into the soil and thoroughly mixed. Both traditional inoculation methods lack automatic control and extensive manual

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labor and preparation time. More critically, they often reduce rhizobial survival rate under adverse environmental conditions. Therefore, developing and implementing an automated precision inoculation system is crucial for improving the efficiency of the inoculation process.

Precision agriculture (PA) is a modern management strategy that uses integrated technologies and practices to assess crop and field variability, and to apply inputs at the right place, time, and amount[14,15]. The development of electrically driven control systems has significantly broadened the potential for integrating technological advancements in automation into various PA applications[16,17]. Proportional Integral Derivative (PID) control technology is a pivotal technique in variable rate (VR) control[18]. Numerous studies have explored PID control in VR systems for applying both solid and liquid fertilizer and insecticides. For instance, Zhang et al. developed an incremental PID control algorithm for a solid fertilizer application system. Based on a soil prescription map, the system achieved high application accuracies: 97.22% for urea, 98.60% for diammonium phosphate, and 97.73% for potassium chloride[19]. Additionally, Sun et al. developed a neural network PID variable application system to enhance the efficiency of existing variable spray control systems and mitigate delays associated with fuzzy decision-making. This system controlled flow rates with minimal steady-state error and reduced response time[20]. Beyond material application, PID control enhances machinery performance. Qiao et al. proposed a fuzzy PID control system, optimized using genetic algorithms, for a timely-started active hydro-pneumatic suspension. Results showed this active system offered far superior damping compared to a passive suspension[21]. Optimization algorithms further refine PID performance. For example, an improved particle swarm optimization (IPSO) algorithm was used to tune PID parameters for trajectory tracking, yielding accuracy improvements of 37.14% and 50.32% in key performance metrics[22].

Pulse-width modulation (PWM) is another crucial VR control technology, which regulates flow rates by adjusting the duty cycle of the signal to the control valve. One experiment compared Manual-PWM, Laser-PWM, and Disabled PWM control modes for nozzle flow rates. The results demonstrated that sprayers equipped with PWM solenoid valves showed great potential to enhance pesticide application efficiency, significantly reducing pesticide consumption and minimizing off-target drift loss to the environment[23]. Similarly, Jonathan Fabula et al. also utilized PWM control in agricultural sprayers to achieve precise flow rate while ensuring the desired droplet size. Therefore, both PID and PWM are essential methods and technologies for implementing variable-rate spraying in precision agriculture.

However, the production of leguminous plants requires only a small volume of liquid rhizobial inoculant. In practical applications, the required flow rate for rhizobial inoculation is substantially lower than that for common agrochemicals. For instance, in soybean production, the recommended volume of diluted rhizobial suspension typically ranges from 4.5 to 60 L/hm^2. This range is on the same order of magnitude as the low spray volumes commonly used by modern crop protection unmanned aerial vehicles (UAVs)[24]. When operating at a single-row width of 0.6 m and forward speeds of 5-8 km/h, the corresponding nozzle flow rate falls within 0.034-0.360 L/min. This is markedly lower than the typical flow rate for pesticide spraying[25,26]. This presents unique challenges: conventional actuators and control algorithms lack sufficient resolution and sensitivity at low flows, leading to instability and high minimum controllable flow; flow sensor accuracy decreases with increased noise; and dynamic response is hard to tune due to reduced fluid inertia and damping changes, causing oscillations or slow settling. Thus, existing high-flow systems cannot meet the precision, stability, and responsiveness needed for low-flow inoculation.

This research gap has significantly hindered improvements in rhizobia survival rate and the overall efficiency of field inoculation. Considering this situation, this research presents a novel rhizobial inoculation method incorporating a precise and efficient electric-driven control system that combines PID and PWM technologies. It seamlessly integrates four processes: ditching, seeding, spraying liquid rhizobia, and mulching, into a cohesive operational cycle. This approach ensures thorough mixing of seeds and rhizobia, thereby enhancing the effectiveness of rhizobial inoculation and bacterial survival rate. Therefore, the objectives of this study are: (i) to develop a precision spraying control system tailored for small-volume rhizobial inoculation; (ii) to integrate the small-flow control system with a conventional seeder to enable synchronous operation; and (iii) to evaluate the system’s technical performance, with a focus on flow control accuracy, stability, and response characteristics under small-volume application conditions.

2 Materials and methods

2.1 System structure and process design

The schematic structure of the spraying and control system designed for liquid rhizobial inoculation is illustrated in Figure 1. Prior to sowing, rhizobia must be diluted according to specific crop and soil characteristics. The liquid rhizobia tank is mounted on the load-bearing bracket at the front of the tractor. The controller for the spraying and control system is installed on the seeder’s bracket. The liquid nozzles are positioned between the seeding and mulching devices, facing into the seeding furrows. The outlet of the spraying pump is sequentially connected to the flow controller, flow sensor, liquid distributor, and nozzles. Any rhizobia exiting the flow controller are redirected back to the liquid rhizobia tank. The main control unit (MCU) is interconnected with speed sensors, flow sensors, flow controllers, spraying pumps, and the on-board battery to ensure seamless operation of the entire system.

Throughout the sowing operation, MCU precisely controls the flow rate of rhizobial inoculant based on the target application rate, real-time tractor speed, and preset parameters. This ensures the rhizobia are delivered onto the seeds at the precise desired rate. The seeds and rhizobia are simultaneously buried in the soil using a mulching device, ensuring that the rhizobia remain concentrated around the seeds, thereby improving the efficiency of rhizobial inoculation.

Additionally, the Control System app is connected to the MCU through a Bluetooth module to facilitate human-machine interaction (HMI). Before sowing, parameters such as liquid rhizobial concentration, target application rate, and seeding area can be configured on the app terminals.

Figure 2 illustrates the operational flow of the control system. During initialization, the spraying and control system conducts a self-diagnostic check. If any faults are detected during this self-test, the system will shut down to prevent damage or erroneous operation. Subsequently, the flow controller is activated until it reaches full reflux, after which the spray pump is activated. Equipped with an incremental PID control algorithm, the controller achieves precise spraying of rhizobia using PWM technology. This ensures optimal performance and efficiency in the inoculation of rhizobia. After completing the spraying task, the control system is shut down, ensuring a smooth operational cycle.

2.2 Hardware design

The spraying control system is built on the STM32F407 master controller and employs the CAN bus protocol for robust communication. A Bluetooth module (ATK-HC05-V13) provides a wireless interface for the control app. Tractor speed is calculated by the controller based on pulse signals from encoders (E38S6G5-100B-G24N) mounted on the seeder's slave drive wheel. Flow control is achieved by a dedicated actuator—a small steering engine that regulates the pressure valve assembly and adjusts the internal pressure of the spraying device to control the flow of liquid rhizobia.

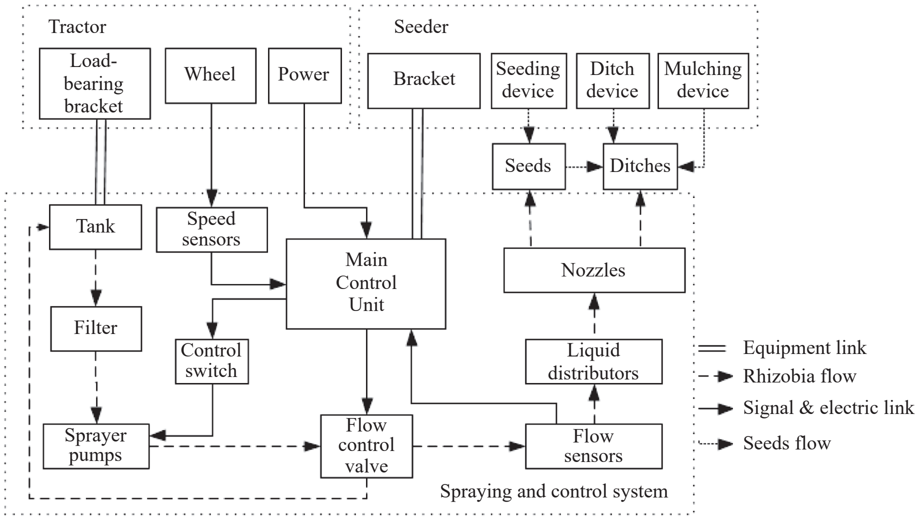


Figure 1 The structure of spraying and control system for liquid rhizobial inoculation

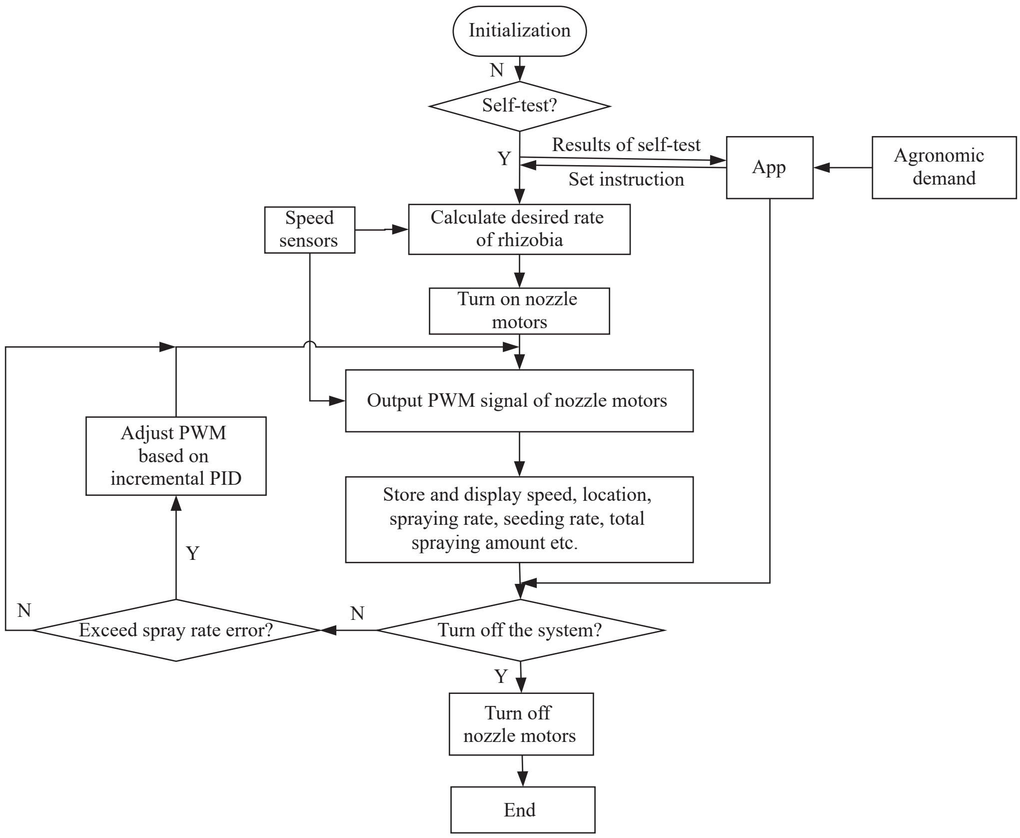


Figure 2 Overall workflow diagram

To meet the requirements of precise low-flow spraying, this study configured the system with the following key components based on performance comparisons and operational parameters: the Licheng VP11002 nozzle, which provides a flow rate of 0.65-1.04 L/min within a working pressure range of 0.2–0.5 MPa; a mini high-precision Hall flow sensor (Yihai MH-S650) capable of withstanding water pressure up to 1.75 MPa, with a measurement range of 1-30 L/min; a diaphragm pump (Dafengda 5G-210); a three-way water distributor (Shuangding); a pressure sensor (HK 12-P145B) covering 0-1.2 MPa with an error of ±1.5% FSO; and a pressure gauge (Hongsheng Instrument Factory, model N710) with a range of 0-0.25 MPa.

2.3 Speed measuring module

To ensure uniform application of the rhizobial inoculant, the spraying rate must be adjusted in real time based on the seeder's ground speed. The Hall sensor was selected for speed measurement due to its strong anti-interference capability, reliable accuracy, stable performance, and minimal susceptibility to environmental variations in field operations. During operation, the main control system calculates the tractor's speed based on the pulse signals generated by the Hall sensor. The equation for the tractor speed is derived as follows:

$$v = \frac{N}{Z}\frac{\pi D(1+\sigma)}{T} \tag{1}$$

where, v is the moving speed of tractor, m/s; T is the speed measurement period, s; Z is the number of pulse signals rotated around the Hall sensor; N is the number of pulses counted within period T; D is the effective diameter of the ground wheel, m; and σ is the wheel slip coefficient (taken as 0.05-0.12 in field conditions)[27,28].

2.4 Incremental PID closed-loop control algorithm

To enhance the precision of rhizobial spraying systems, the incremental PID closed-loop control algorithm is implemented to regulate the spraying device[29]. The control deviation, defined as the difference $e(t)$ between the target rate $r(t)$ and the actual spraying rate $y(t)$ is:

$$e(t) = r(t) - y(t) \tag{2}$$

where, $e(t)$ is the input of PID controller; and $u(t)$ is the output of PID controller and the input signal of the controlled object. The control law of the analog PID controller is as follows:

$$u(t) = K_p\left[e(t) + \frac{1}{T_I}\int_0^t e(t)\mathrm{d}t + T_D\frac{\mathrm{d}e(t)}{\mathrm{d}t}\right] + u_0 \tag{3}$$

where, K_p is the proportional coefficient; T_I is the integral time constant; and T_D is the derivative time constant. The integral coefficient is K_p/T_I, and the derivative coefficient is K_p/T_D.

Incremental PID control algorithm needs to calculate the increment of control. The output value of sample time k_{th} and $k\text{-}1_{\text{th}}$ are determined with the following expression:

$$u_k = K_p\left[e_k + \frac{T}{T_I}\sum_{j=0}^{k} e_j + \frac{T_D}{T}(e_k - e_{k-1})\right] + u_0 \tag{4}$$

$$u_{k-1} = K_p\left[e_{k-1} + \frac{T}{T_I}\sum_{j=0}^{k-1} e_j + \frac{T_D}{T}(e_{k-1} - e_{k-2})\right] + u_0 \tag{5}$$

The incremental PID control algorithm is derived by subtracting Equations (4) and (5) as follows:

$$\begin{aligned}\Delta u_k =& K_p\left[e_k - e_{k-1} + \frac{T}{T_I}e_k + \frac{T_D}{T}(e_k - 2e_{k-1} + e_{k-2})\right] = \\ & K_p\left(1 + \frac{T}{T_I} + \frac{T_D}{T}\right)e_k - K_p\left(1 + \frac{2T_D}{T}\right)e_{k-1} + K_p\frac{T_D}{T}e_{k-2} = \\ & Ae_k - Be_{k-1} + Ce_{k-2}\end{aligned} \tag{6}$$

Equation (6) shows that with a constant sampling period T and predetermined coefficients A, B, and C, the control increment can be calculated from the deviations of the last three measured values.

The incremental PID algorithm computes the control increment based on the current and two previous errors, offering minimal computational burden, robustness against system faults, and a built-in actuator memory function that permits reset with minimal operational disruption (Figure 3).

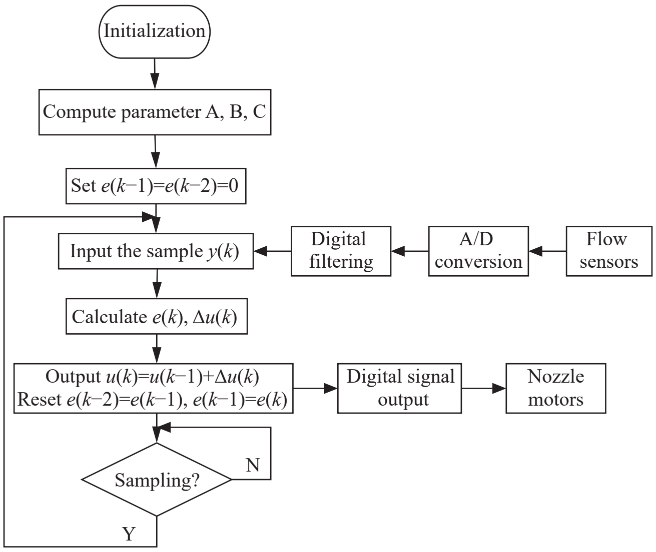


Figure 3 Flow chart of incremental PID algorithm

The parameters of the incremental PID controller (K_p, K_i, K_d) were tuned to optimize the system's response for small-flow spraying. Initial estimates were derived using the Ziegler-Nichols step-response method[30,31]. Subsequently, an iterative empirical tuning process was conducted in the laboratory. The performance was evaluated under step changes in the setpoint flow rate (0–1.00 L/min), with the objective of minimizing rise time, settling time, and overshoot while maintaining zero steady-state error. The final parameters selected for all experiments were: K_p = 2.5, K_i = 0.8, K_d = 0.1. These parameters ensured a robust compromise between dynamic response speed and stability across the operational range.

2.5 Spray rate measurement and coefficient of variation

The spraying rates of nozzles under a specified working pressure are measured with at least three tests in each group. These rates are computed using Equation (7), while the standard deviation (*STD*) and coefficient of variation (*CV*) are determined using Equations (8) and (9), respectively.

$$\bar{q} = \frac{q_1 + q_2 + \ldots + q_n}{n} = \frac{\sum q}{n} \tag{7}$$

$$STD = \sqrt{\frac{\sum (q - \bar{q})^2}{n}} \tag{8}$$

$$CV = \frac{S}{\bar{q}} \times 100\% \tag{9}$$

where, q_i is the spraying rate of the i_{th} nozzle, L/min; n is the number of nozzles; $\bar{q}$ is the average spraying rate, L/min; *STD* is standard deviation, L/min; and *CV* is the coefficient of variation of spraying, %[24,32].

3 Results

3.1 Laboratory test

3.1.1 Variability test of spraying rate

Spraying rate variability evaluation took place at the Engineering Training Center of Northeast Agricultural University, located in Heilongjiang Province, China. The test platform was equipped with a double diaphragm plane, a three-way water distributor, three nozzles, a pressure sensor, a pressure gauge, and several hoses.

The pressure sensor and pressure gauge collaborated to monitor real-time pressure at the nozzles, establishing a robust foundation for reliable quality control within the system. The internal pressure of the spraying device was manually adjusted via a pressure regulating valve positioned on the water distributor.

The spraying rates of three nozzles were measured at pressures of 0.10 MPa, 0.12 MPa, 0.15 MPa, 0.18 MPa, and 0.20 MPa, respectively. Each group of tests was repeated three times, and the mean value, *STD*, and *CV* of the spraying rate were subsequently calculated, as listed in Table 1. It can be observed that the *CV* of the spraying rate was relatively low, indicating that these nozzles demonstrated excellent performance in spraying liquid during laboratory testing.

Table 1 Spraying rate under different pressures

Pressure/MPa	0.10			0.12			0.15			0.18			0.20		
Nozzle No.	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
Attempt 1/L·min^{-1}	0.450	0.440	0.450	0.505	0.495	0.505	0.585	0.570	0.570	0.620	0.635	0.630	0.660	0.640	0.660
Attempt 2/L·min^{-1}	0.470	0.450	0.450	0.500	0.495	0.495	0.570	0.555	0.570	0.620	0.625	0.620	0.660	0.640	0.640
Attempt 3/L·min^{-1}	0.460	0.450	0.460	0.500	0.500	0.500	0.585	0.585	0.570	0.615	0.62	0.610	0.640	0.620	0.640
Mean±*STD*	0.453±0.005			0.499±0.002			0.573±0.005			0.622±0.004			0.644±0.008		
CV/%	1.2			0.4			0.8			0.5			1.2		

According to Figure 4, when the range of pressure was from 0.10 to 0.20 MPa, the linear model of spraying rate was established as follows:

$$SR = 1.9471P + 0.2661 \quad (10)$$

where, *P* was the pressure, MPa; and *SR* was spraying rate; L/min. The average coefficient of determination of this model was 0.9842.

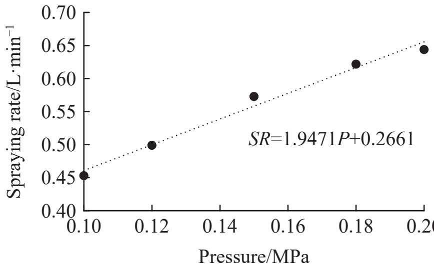


Figure 4 The relationship between pressure and spraying rate

This statistical analysis confirms that the system's response across the entire tested pressure range is highly linear and predictable, providing a reliable theoretical foundation for precise pressure-based inverse control to achieve target flow rates. Once the theoretical spraying rate is determined, the required working pressure can be derived using Equation (10).

3.1.2 Precision spraying test of control system

In this study, the incremental PID closed-loop control algorithm was employed, utilizing pressure sensor data as control feedback to dynamically adjust the internal pressure of the rhizobial spraying device via the electric pressure regulating device. This ensured accurate control of the liquid rhizobial spraying rate at varying tractor speeds. In the laboratory, the experiment was conducted with an incremental rate of 0.20 L/min within the range of 0 to 1.00 L/min, recording the spraying rate at each stage.

Experimental results under identical conditions showed that the classical PID controller had maximum and average response times of 2.33 s and 1.96 s, respectively. In contrast, the incremental PID controller reduced these two times to 1.93 s and 1.62 s, representing a reduction of 17.2% and 17.3%, respectively. Figure 5 demonstrates how the incremental PID effectively matched the actual liquid rhizobial inoculation amounts with the setpoints.

3.2 Field trial

From 2019-2023, the rhizobial inoculant spraying and control system was installed on 2-row and 9-row soybean no-till seeders in Heilongjiang Province, as well as 6-row seeders in Shandong and Anhui Provinces. Field trials utilizing these seeders have operated cumulatively more than 3200 h and covered more than 2000 hm^2 of land across multiple provinces. The test machine and the seeding-spraying process are shown in Figure 6 and Figure 7, respectively. During operation, all parameters and real-time status can be set and monitored via the onboard interactive interface (Figure 8).

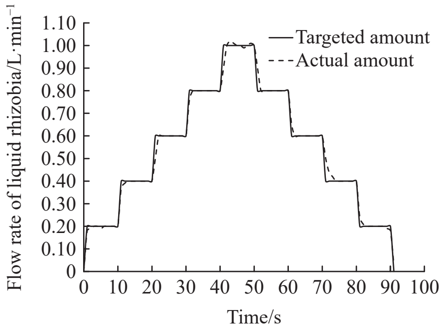


Figure 5 Control accuracy test

Figure 6 Soybean seeder equipped with control system

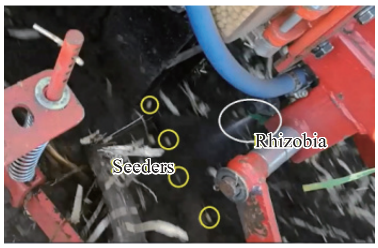


Figure 7 Work process of rhizobial inoculation

The comparative field experiment conducted at Xidian Farm in Shandong Province showed that soybean plants inoculated with rhizobia exhibited significantly superior growth, as well as larger and more numerous nodules, compared to conventionally seeded plants without rhizobia (Figure 9). The inoculated plants developed a robust main root system bearing large, plump nodules, along with dense, long fibrous roots covered by abundant small nodules. In contrast, the root morphology of non-inoculated soybeans was less vigorous.

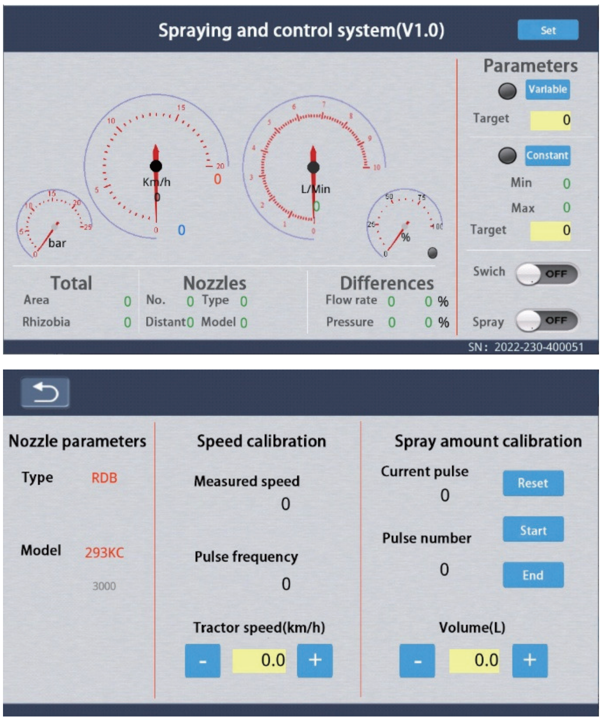
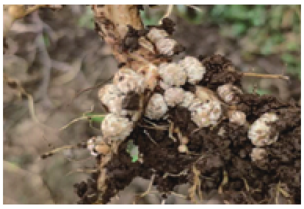


Figure 8 Spray control system interface

a. Field performance comparison

b. Individual plant morphology

c. Root nodules without inoculation



d. Root nodules with inoculation

Figure 9 Comparison of soybean plants with and without rhizobial inoculation

The field experiment for the rhizobial spraying and control system was conducted at Heilongjiang Agricultural Xianghe Farm in 2022. The soybean variety used for the test was Heihe43. The base fertilizers consisted of 46% urea, 18%-46% diammonium phosphate, and 50% potassium sulfate, formulated according to soil fertility as detailed in Table 2.

The comparative experiment on rhizobial inoculation and nitrogen reduction was designed as listed in Table 3. Each seeding method was applied to a 3.5 hm^2 plot. The "Doulebao" liquid rhizobia from China Agricultural University was selected and diluted from a concentrated solution of 450 mL/hm^2 to a dilute solution of approximately 53.45 L/hm^2. The soybean rhizobia bacterial agent contained more than 2×10^9 Colony-Forming Unit (CFU)/mL. The tractor speed was maintained between 8 and 12 km/h.

Table 2 Basic soil fertility of experimental field

Item	Alkaline hydrolysis nitrogen/ $mg\cdot kg^{-1}$	Available phosphorus/ $mg\cdot kg^{-1}$	Rapidly-available potassium/ $mg\cdot kg^{-1}$	Organic matter/ $g\cdot kg^{-1}$	pH
Contents	200	36	195	52	5.6

Table 3 Comparative experiment of seeding methods

No.	Treatment	Description
1	Seed dressing with rhizobia	2 mL liquid rhizobia per 1 kg seeds
2	Spraying liquid rhizobia	150 mL liquid rhizobia per hm^2
3	Spraying rhizobia with 30% urea reduction	150 mL liquid rhizobia per hm^2
4	Spraying rhizobia with 50% urea reduction	150 mL liquid rhizobia per hm^2
5	Normal base fertilizer (control group)	No rhizobia input

At the mature stage of soybean, a diagonal sampling method was employed in the field trial. Three 2-m^2 sampling points were randomly selected, and the soybean plants from these points were brought back to the laboratory for seed examination and yield measurement.

The total growth duration was 115 d, with key stages starting on May 7 (seedling), May 21 (germination), July 31 (flowering), and September 16 (maturity), as listed in Table 4.

Table 4 Field survey during the growth period

Period	Seeding period	Germination period	Flowering period	Maturity period	Total days to maturity
Day	May 7	May 21	July 3	Sep. 16	115

Field investigation during the soybean growth period revealed consistent growth processes across all treatments, with no significant effects from rhizobial inoculation or nitrogen reduction.

Plant height did not show any significant difference. The average height of the bottom pod with rhizobia was 14.35 cm, which was 1.45 cm shorter compared to the control group. The number of pods and seeds per plant increased by approximately 2.75, and the weight of 100 seeds was approximately 0.275 g heavier. The average number of root nodules increased by about 24 with inoculation (Table 5).

Table 5 Comparison of different seeding methods (for treatment descriptions refer to Table 3)

Treatment No.	Plant height/ cm	Bottom pod height/cm	Pods number per plant	Grains number per plant	Hundred-grain weight/g	Nodules number per plant
1	92	14.2	25	54	18.4	79
2	90	13.4	27	60	18.4	99
3	90	14.6	26	55	18.7	101
4	89	15.2	25	52	18.8	97
5	93	15.8	23	48	18.3	70

Overall, the yield of soybean was significantly improved by rhizobial inoculation compared to the control group. Among all inoculation methods, Treatment 2 achieved the highest yield, corresponding to a 6.9% increase (Table 6). Based on the soybean market price of 5.8 CNY/kg in China (2022), the economic analysis indicates that Treatment 2 also provided the greatest net benefit increase (1288.5 CNY/hm^2), owing to its substantial yield gain with relatively low additional cost.

Table 6 Comparison of yield and output value (for treatment descriptions refer to Table 3)

Treatment No.	Yield /kg·hm^{-2}	Yield increase /kg·hm^{-2}	Yield increase /%	Yield rank	Increasing output value	Increasing costs /CNY·hm^{-2}	Increasing benefits /CNY·hm^{-2}
1	3279.0	129.0	4.0	3	748.5	67.5	681.0
2	3382.5	232.5	6.9	1	1348.5	60.0	1288.5
3	3300.0	150.0	4.5	2	870.0	30.0	840.0
4	3232.5	82.5	2.6	4	478.5	–15.0	493.5
5	3150.0	-	-	5	-	-	-

4 Discussion

The variable-rate spraying system developed in this study addresses the long-standing technical bottleneck of precise, low-flow control for rhizobial inoculation. Traditional agricultural spraying systems are typically designed for high-flow pesticide application, with optimal operating ranges far exceeding the micro-flow rates (0.034-0.360 L/min) required for rhizobial inoculation[24]. Our results demonstrate that by integrating an incremental PID control algorithm with PWM technology and optimizing control parameters (K_p=2.5, K_i=0.8, K_d=0.1) for low-flow conditions, the system achieves stable control with an increment as low as 0.20 L/min, an average response time of 1.62 s, and a coefficient of variation≤1.2%. This technological advancement represents a critical step in practically applying precision agriculture principles to the field of microbial inoculation.

In terms of system performance, this study demonstrates significant optimization of the incremental PID controller over the conventional PID controller in response time. Under identical test conditions, the incremental PID reduced the maximum response time from 2.33 to 1.93 s (a 17.2% reduction) and the average response time from 1.96 to 1.62 s (a 17.3% reduction). This performance improvement is crucial for achieving precise spraying synchronized in real time with the forward speed of the seeder, especially in field operation environments where tractor speed frequently varies.

In the field trial results, Treatment 2 performed optimally, increasing yield by 232.5 kg/hm^2 (6.9%) and raising net profit by 1288.5 CNY/hm^2. Treatment 3 exhibited the highest nodule count (101 nodules per plant), which may suggest that moderate nitrogen limitation promotes symbiotic investment between the host plant and rhizobia. This finding resonates with research by Cafaro La Menza et al.[9], indicating that plants may adjust resource allocation to enhance symbiotic nitrogen fixation under nitrogen-limiting conditions. However, Treatment 4 showed the smallest yield increase, suggesting that rhizobial nitrogen fixation and chemical nitrogen fertilizer are not simple substitutes but rather form a complementary system requiring careful balance.

At the mechanistic level, the results of this study indicate that successful symbiotic nitrogen fixation provides a critical nitrogen source for soybean growth. The significant advantages of Treatments 2 and 3 in pods per plant, grains per plant, and hundred-grain weight (Table 5) directly reflect the positive impact of effective nitrogen fixation on yield formation. Comparative root observations (Figure 9) further reveal that soybean plants inoculated with rhizobia developed a more robust taproot system and denser fibrous roots, potentially enhancing the plant's water and nutrient absorption capacity, thereby supporting greater biomass accumulation and yield formation.

Future work could integrate soil sensors or remote sensing technologies to achieve prescription-based variable-rate inoculation according to spatial variability in soil fertility. Furthermore, the compatibility of different rhizobial formulations (e.g., peat-based vs. liquid inoculant) with the spraying system and their field performance remain subjects for further investigation.

5 Conclusions

This study developed a variable-rate spraying control system that integrates an incremental PID algorithm with PWM technology to achieve high-precision, real-time control for small-volume liquid rhizobial inoculation. The following conclusions were drawn:

1) The system addresses the core challenge of small-volume application in rhizobial inoculation. It achieves a minimum controllable flow rate of 0.20 L/min with high stability.

2) Laboratory tests demonstrated high-precision flow control performance. Using the incremental PID closed-loop control algorithm, the laboratory experiment tested flow rates increasing in increments of 0.20 L/min within the range of 0-1.00 L/min. The system exhibited a maximum response time of 1.93 s and an average response time of 1.62 s.

3) Field validation confirmed the system's agronomic and economic benefits. At Heilongjiang Xianghe Farm, inoculated soybeans showed significant improvements in nodule count, pods per plant, and 100-grain weight. The treatment combining liquid rhizobia with full base fertilizer increased yield by 232.5 kg/hm^2 (6.9%) and raised net income by 1288.5 CNY/hm^2, demonstrating the practical value of this low-cost, precision inoculation system.

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