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Design and Testing of an Online Fertilizing Amount Detection Device Based on the Moment Balance Principle

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Abstract

Based on the principle of moment balance, this paper designs a fertilizer application amount online detection device, which is mainly composed of two major parts: the fertilizer guide mechanism and the fertilizer metering and discharging mechanism.Under the electromagnetic reversing and buffering of the fertilizer guide mechanism, the fertilizer discharged into the device falls alternately into the storage box of the two metering units of the metering and discharging mechanism. Once the gravity of the fertilizer in the storage box is greater than the suction of the electromagnetic sucker, the fertilizer discharging board is automatically opened for fertilizer discharge, and the metering pulse signal is accumulated once. Meanwhile, the fertilizer guide plate is driven by the electromagnetic commutator to reverse the material, and then another storage box is started for fertilizer storage and metering. In this approach, online detection of fertilizer flow can be realized by repeatedly guiding and reversing and metering the incoming fertilizer. According to the single metering fertilizer quality and the number of metering pulse signals, the fertilization amount can be calculated in real-time.The performance of the device was verified by bench test. The test results indicated that: The established fertilizer application detection model is a quadratic function (R^2>0.98), and the verification error was less than 3.73% in the detection of alternating cycle fertilizer discharge; the coefficient of determination (R^2) and the root mean square error (RMSE) reached 0.992 and 9.858 respectively, indicating high detection accuracy of the device is.

Keywords: fertilization amount, fertilizer mass flow, mechanical fertilization, moment balance principle, fertilizer guide mechanism, fertilizer discharging mechanism

1. Introduction

Variable fertilizer application is an important part of precision agriculture because it can improve fertilizer utilization, increase crop yield, and reduce soil and water pollution, thus promoting sustainable agricultural development and reducing agricultural surface source pollution (Zhu and Jin, 2013; Kamilaris et al., 2017; de Araujo Zanella et al., 2020; Li et al., 2021; Jia et al., 2021). In the process of mechanical fertilization, online monitoring of fertilizer mass flow is a key link and technical prerequisite for precise variable fertilization contro (Chen et al., 2017; Hong et al., 2015; Chen et al., 2013; Zhai et al., 2022; Liu et al., 2020).

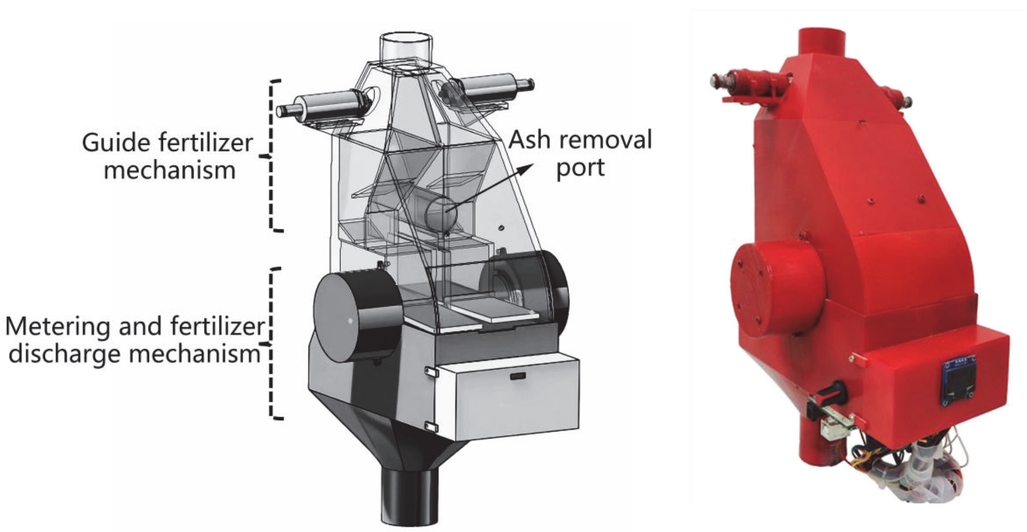
Currently, the main methods of fertilizer mass flow detection include the capacitance method, the mass method, the imaging method, the photoelectric method, and the indirect measurement of the fertilizer discharge shaft. The capacitance method uses fertilizer as a dielectric and designs an online detection system for fertilizer application based on the difference in the dielectric properties of fertilizer and air, thus achieving individual monitoring of fertilizer application in each discharge pipe (Zhou et al., 2010, 2017). Also, capacitive sensors consisting of adjacent electrode plates can be sued to detect the decline degree in the fertilizer tank level, and the relationship between the capacitance value between adjacent electrodes and the amount of fertilizer applied can be established, thereby enabling real-time detection of fertilizer flow (Zhao et al., 2019a, 2019b). The quality method realizes the real-time flow of fertilizer at the discharge port and the amount of fertilizer per unit area of the fertilizer applicator according to the difference between the total mass of fertilizer and the current residual mass by designing a dynamic weighing system (van Bergeijk et al., 2001) or a fertilization performance detection device based on belt scale (Yu et al., 2016). The imaging method uses a CCD (Charge Coupled Device) camera to obtain images of the falling of granular fertilizer, and then it adopts image recognition technology to obtain the diameter and quantity of fertilizer particles and combines fertilizer density information to achieve online monitoring of the mass flow of discharged fertilizer (Back et al., 2014). The photoelectric method mainly uses photoelectric sensors to realize online monitoring of fertilizer particle flow. For example, Swisher et al. (2002) designed a sensor for measuring the flow condition of fertilizer particles in the airflow by using a laser generator and a photoelectric sensor; Grift et al. (2001) investigated the relationship model between the output pulse width of the near-infrared photoelectric detector and fertilizer flow rate, and then the detection accuracy of photoelectric flow sensors was verified in the laboratory under different density and flow rate conditions. The indirect measurement method of fertilizer discharge shaft mainly uses Hall sensors and encoders (Zhao et al., 2010), etc. to monitor the rotation circumference and angle of the fertilizer discharge shaft in real time and establishes their relationships with the amount of fertilizer discharged to indirectly achieve real-time monitoring of fertilizer mass flow.

The comprehensive analysis of the existing fertilizer mass flow detection methods shows that the capacitance method is less costly and more sensitive, but it is susceptible to electromagnetic interference, changes in fertilizer moisture content, and environmental humidity; the mass method has high measurement accuracy, but it cannot well adapt to practical applications; the photoelectric and image methods are fast, but their detection equipment is susceptible to fertilizer powder; the indirect measurement of the fertilizer discharge shaft is simple and easy to implement, but it suffers from a large measurement error. Besides, most of the above-mentioned detection methods require pre-assembly or have a high correlation with the mechanical fertilizer discharge structure (Gao, 2016; Yang et al., 2020; Jin et al., 2018). Aiming at the above problems, this paper designs an online fertilizer application amount device based on the moment balance principle. This device can be connected with the discharge pipe of the existing fertilizer application machinery to realize online real-time monitoring of fertilizer application amount in a low-cost universal post-installation way. It can provide real-time feedback to the fertilizer application machinery for precise variable fertilizer application control, thus improving the intelligence of the existing small and medium-sized fertilizer application machinery.

2. Structure Design

2.1 Overall Structure Design

The overall structure of the fertilizer amount online detection device and its prototype are shown in Figure 1. It is mainly composed of two parts: a fertilizer guide mechanism and a metering and discharging mechanism. The fertilizer guide mechanism is connected with the fertilizer discharge pipe of the external fertilizer applicator through its inlet port, and it is used to introduce the fertilizer into the device and change the flow direction, discharge, and buffering of the fertilizer. The metering and discharging mechanism detects and discharges the imported fertilizer in real-time, and it maintains the continuity of the fertilizer discharge through the device to the greatest extent.



(a) (b)

Figure 1. The structure and picture of the device. (a) The structure (b) The picture of the device

2.2 Design of Key Components

2.2.1 Fertilizer Guide Mechanism

The fertilizer guide mechanism is mainly composed of a feed fertilizer inlet, a fertilizer guide plate, two fertilizer guide tubes, and two electromagnetic commutators. Its structure is illustrated in Figure 2. The fertilizer guide plate is installed between the fertilizer inlet and the guide fertilizer pipe through the rotating shaft, and the fertilizer can only flow into one of the guide fertilizer pipes within a certain period. Through the installation of the fertilizer guide plate on both sides of the electromagnetic commutator (model XRN-19X42TL, energized to generate instantaneous thrust, power-off self-reset, voltage 12VDC, stroke 10 mm), fertilizer is fed into the switch two guide fertilizer pipe to drive the fertilizer guide plate to control the left and right commutation and guide fertilizer pipe embedded slope to buffer.

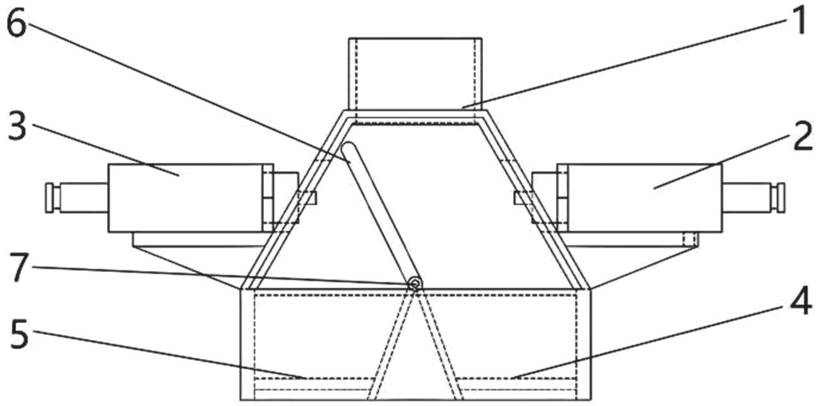


Figure 2. The schematic diagram of the guide fertilizer mechanism structure. 1. Fertilizer inlet 2. Electromagnetic commutator I 3. Electromagnetic commutator II 4. Guide fertilizer pipe I 5. Guide fertilizer pipe II 6. Fertilizer guide plate 7. rotating shaft

2.2.2 Metering and Discharging Mechanism

The metering and discharging mechanism is composed of two identical units set side by side, each of which includes a fertilizer storage box, a fertilizer discharging board, an electromagnetic sucker, a reset motor for the fertilizer discharging board, a measurement and control circuit, a PWM voltage regulating module, etc. The schematic diagram of the structure is presented in Figure 3. The inlets of the two fertilizer storage boxes are connected with the outlets of the two guide fertilizer pipes respectively. The bottom of the fertilizer storage box is an open structure, and it is blocked by the fertilizer discharging board. The fertilizer discharging board is designed as a ‘seesaw’ structure that rotates counterclockwise around a fixed rotating shaft (with a maximum rotation angle of 78.6°). One end of the fertilizer discharging board is embedded with a magnetic sheet. Under the suction of a fixed electromagnetic sucker (model XDA-08/20, voltage range 0~12 V, suction range 0~150 g), the fertilizer discharging board is in a horizontal state, and the other end of the plate is completely enclosed at the bottom of the fertilizer storage box. Only when the gravity of fertilizer in the storage box is greater than the suction force of the electromagnetic disk, the horizontal state of the fertilizer drainage plate is broken, and a counterclockwise rotation is generated, which makes the bottom of the storage box open for fertilizer drainage. Because the fertilizer storage box is designed of 6.2, 4.0, and 3.6 cm and the fertilizer bulk density is about 900~1200 kg/cm^3, the maximum fertilizer storage capacity is 80.3~107 g. To adapt to different fertilizer application requirements and not affect the fertilizer application continuity, a PWM voltage regulating module is designed to adjust the suction force of the electromagnetic sucker, which in turn changes the single metering and fertilizer discharge of the fertilizer storage box, thus adjusting the quality of the fertilizer.

Meanwhile, a photoelectric fertilizer leakage detection sensor is designed on the inner wall of the housing in the rotation path of the fertilizer discharging board. The detection sensor is triggered when the fertilizer discharging board rotates counterclockwise and outputs a counting pulse, indicating that a mass measurement of the fertilizer storage box has been performed. Also, a limit-type detect the fertilizer guide sensor is designed under the fertilizer discharging board to detect the fertilizer discharge situation of the fertilizer discharging board, thus controlling the operation of the electromagnetic commutator and driving the fertilizer discharging board to change the direction of fertilizer flow from the left to right. In this way, fertilizer is alternately introduced into the fertilizer storage box to realize alternate metering and storage and discharge of fertilizer in the two units; a limit-type reset detection sensor is designed on the rightmost side of the fertilizer storage box to determine whether the fertilizer discharging board is reset to the horizontal after the fertilizer storage box is emptied. If the fertilizer discharging board is not reset, it will control the fertilizer discharging board reset motor to drive the drive rod to rotate, forcibly reset the fertilizer discharging board to the horizontal state, and make the fertilizer discharging board reset motor to return to the initial state, thus ensuring that the fertilizer discharging board can be reset properly next time.

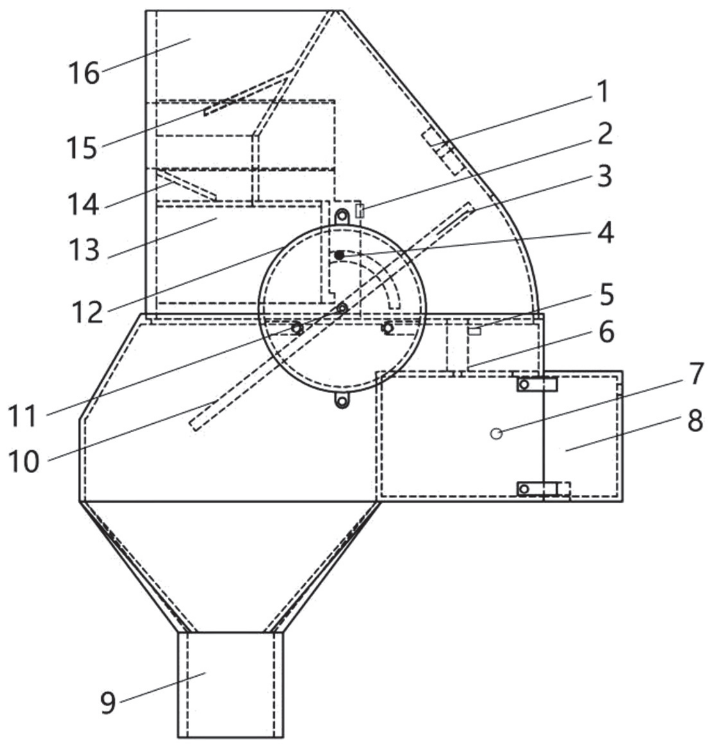


Figure 3. The structure diagram of the metering and fertilizer discharging mechanism. 1. Fertilizer leakage detection sensors 2. Reset detection sensors 3. Magnetic sheet 4. Discharge fertilizer board reset lever 5. Detect the fertilizer guide sensor 6. Electromagnetic sucker 7. PWM voltage regulating module 8. Circuit control box 9. Fertilizer outlet 10. Fertilizer discharging board 11. Rotating shaft 12. Reset motor 13. Fertilizer storage box 14. Buffer plate I 15. Buffer plate II 16. Guide fertilizer pipe

3. Detection Principle

According to the design structure, after the discharge fertilizer from the fertilizer applicator falls into this device, online real-time detection of fertilizer application can be realized through alternate metering and discharge of fertilizer by two metering units under the synergistic action of the fertilizer guide mechanism and the metering and discharging mechanism, as shown in Eq. (1).

$$Q = m_1 f_1 + m_2 f_2 \quad (1)$$

where Q is the detected value of fertilizer application volume (unit: g); m_1 and m_2 are the single fertilizer discharge mass of the two fertilizer storage boxes at a specific metering voltage (unit: g), and their values are set by the PWM voltage regulating module, i.e., by adjusting the electromagnetic sucker suction force; f_1 and f_2 are the pulse signal counts of the two fertilizer storage boxes for fertilizer drainage.

The single measurement and discharge of fertilizer in each fertilizer storage box is conducted according to the principle of moment balance. Specifically, during the operation of the device, the fertilizer discharging board takes the rotating shaft as the rotating fulcrum, one end of which is subjected to the suction of the electromagnetic sucker, and the other end is subjected to the gravity of the fertilizer in the fertilizer storage box. When the gravity of the fertilizer is equal to the suction of the electromagnetic sucker, the moment reaches a critical equilibrium state, as shown in Formula (2). Once the gravity in the fertilizer storage box is greater than the suction of the electromagnetic sucker, the critical equilibrium state is broken, and the metering and discharging of the fertilizer are started. Figure 4 shows the stress analysis diagram of the fertilizer discharging board during fertilizer detection.

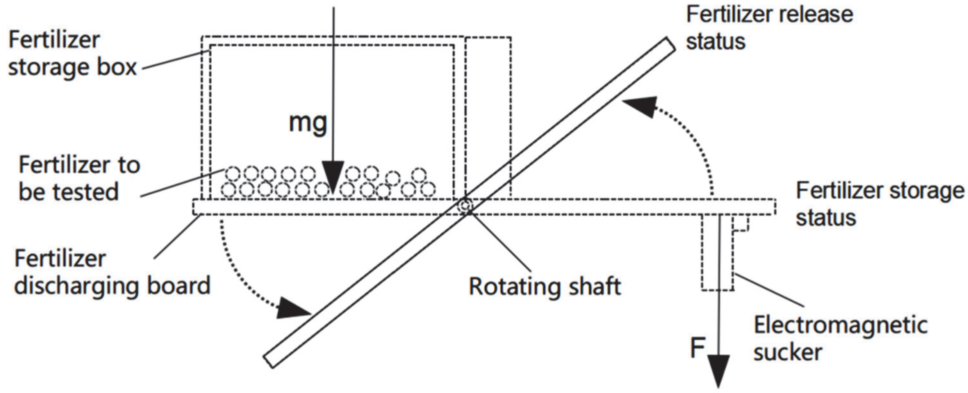


Figure 4. The schematic diagram of the force analysis of the fertilizer discharging board during fertilizer quality detection

$$mg = F \tag{2}$$

where m is the mass of fertilizer in the storage box (unit: kg); g is the coefficient of gravity (unit: N/kg); F is the electromagnetic suction force (unit: N). The specific value is closely related to the suction cup electromagnet structure and material (Jia et al., 2012; Liang et al., 2021; Tang et al., 2019; Ning et al., 2021; Ding et al., 2021), as shown in Eq. (3).

$$F = \frac{B^2 S}{2\mu_0} \tag{3}$$

where S is the effective area of the suction surface (unit: mm^2); μ_0 is the vacuum permeability, $4\pi\times10^{-7}$N/A2; B is the magnetic induction intensity of the air gap between the contact surfaces (unit: T), and its value is calculated by Eq. (4).

$$B = nI\mu_0 \tag{4}$$

where n is the number of turns of the coil, and I is the circuit current (unit: A). According to Equations (1) to (4) and Ohm's law, the calculation method of fertilizer application detection is derived and shown in Eq. (5).

$$Q = \frac{n^2 \mu_0 S}{20R^2}\left(f_1 u_1^2 + f_2 u_2^2\right) \tag{5}$$

Since n,μ_0, s, and R are constants, the fertilizer application quantity Q is only related to the drainage fertilizer pulse signal count f and metering voltage u. Usually, the metering voltage u is set by the PWM voltage regulating module before the device works, and once it is set, it determines the electromagnetic sucker suction force and thus the single discharge mass of the fertilizer storage box, i.e., establishes the correspondence between the metering voltage u and the single discharge mass of the fertilizer storage box. Therefore, online detection of fertilizer application can be achieved by detecting the number of pulses of the corresponding discharge signal of two fertilizer storage boxes at a specific metering voltage.

4. Online Detection System Design

4.1 Hardware Circuit Design

The hardware circuit mainly includes a power supply, signal acquisition circuit, an ATmega328 micro-controller main controller, metering and the control circuit of the metering and guide fertilizer mechanism, the reset circuit of the discharge board, an LCD module, etc., as shown in Figure 5.

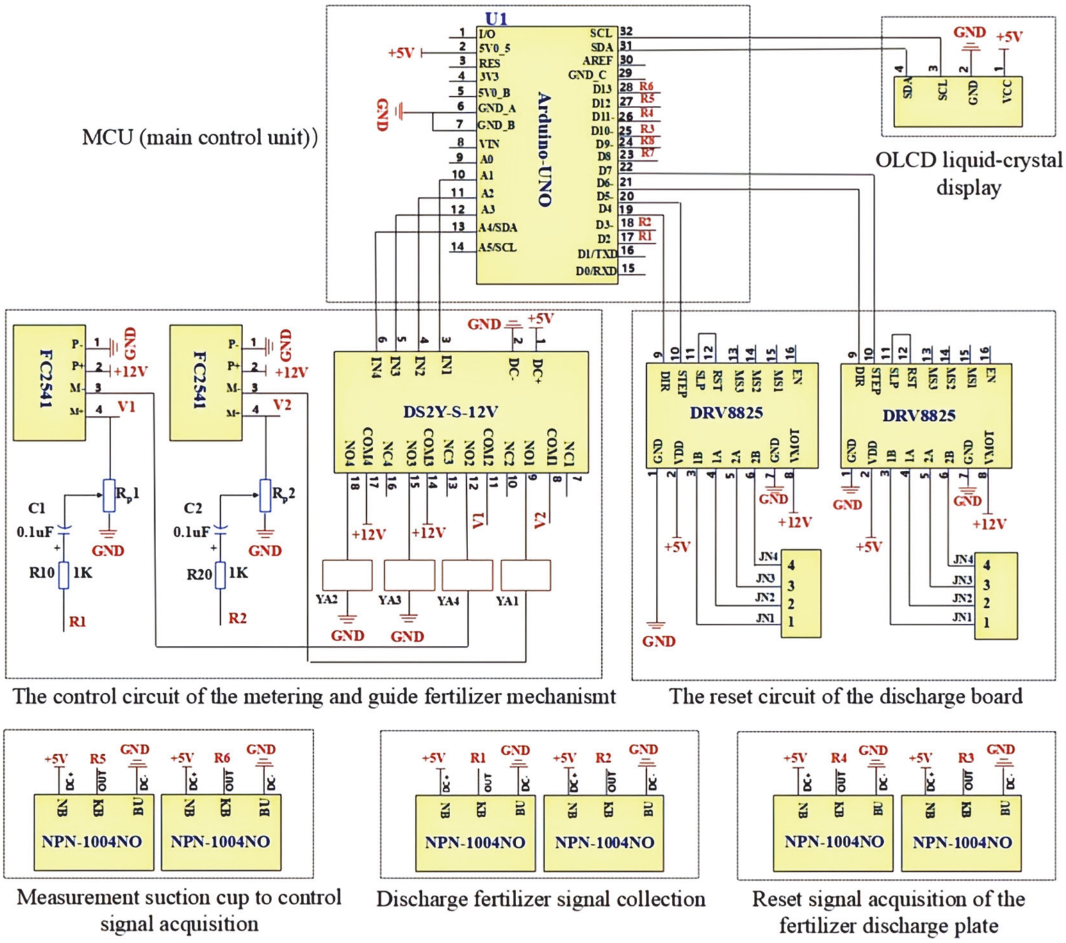


Figure 5. The diagram of the Device core control circuit

12V linear DC stabilized voltage power supply is used, and it provides a stable operating voltage after step-down for each circuit unit. The main control system of the ATmega328 single-chip microcomputer is exploited to collect the measurement voltage and the signal of each sensor, realize interrupt counting, calculate fertilizer amount, and drive the electromagnetic commutator to control the commutation of the guide plate, thus controlling the reset of the stepper motor and driving the LCD. The LCD module is used to display the relevant information of the online detection of fertilizer amount.

The signal acquisition circuit mainly includes the infrared photoelectric sensor and the limit sensor to detect the fertilizer discharge action of the fertilizer discharging board (each time the fertilizer is discharged, a counting pulse is output), the reset situation, and the measurement suction cup to control signal. The control circuit of the metering and fertilizer guide mechanism is composed of a PWM voltage regulating module, an RC filter circuit, an electromagnetic commutator, and a sensor. It controls the power acquisition of the metering sucker, guides fertilizer application with the electromagnetic commutator, and resets the fertilizer discharging board. The reset circuit of the fertilizer discharging board consists of a 12V stepping motor and its driver DRV8825 When the main controller detects that the fertilizer discharging board is not reset, the reset stepper motor is controlled to rotate 78.6° clockwise to drive the fertilizer discharging board to quickly reset to the initial position. Besides, the control and execution of the mechanism are assisted by a control 4-way 12V relay.

4.2 Software Design

Based on the Arduino IDE development environment, the design is implemented with C++ programming language in a modular approach. Its main functions include system initialization, real-time acquisition and processing of metering voltage, calling delay function, real-time acquisition of sensor signal, interrupt signal detection and interrupt counting, fertilization calculation based on the detection model, and driving the OLED LCD screen to display fertilization information in real-time. The main program flow is presented in Figure 6.

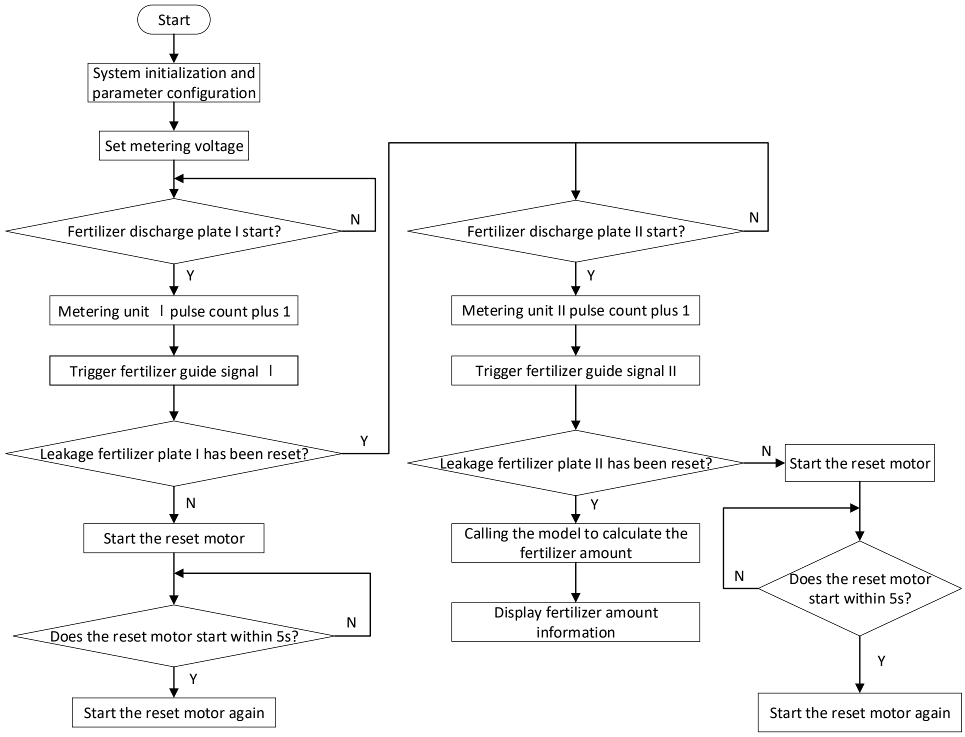


Figure 6. The program flow of the fertilizing amount detection system

After the system is powered on and initialized, the metering voltage is obtained in real-time through the A/D conversion port of the single-chip microcomputer. Meanwhile, the single-discharge fertilizer quality of the current two fertilizer storage boxes is determined according to the mathematical relationship between the metering voltage obtained by the experiment and the single-discharge fertilizer quality of the two fertilizer storage boxes. Then, the fertilizer discharge is detected in real-time, and fertilizer discharging board I and II are set: when the fertilizer discharge signal of fertilizer discharging board I is detected, the pulse signal of the metering unit I is added to 1 by interrupt counting, and fertilizer guide signal I is triggered to drive the fertilizer discharging board to guide the material. Also, reset and the corresponding control are performed according to the detection of fertilizer discharging board I; when the reset situation of fertilizer discharging board I is not detected within 5s, the delay function is called, and the reset motor is energized to forcibly reset fertilizer discharging board I. The measurement and control of the discharge and reset of fertilizer discharging board II is the same as that of fertilizer discharging boardI. Finally, the number of pulses of metering units I and II are substituted into the calculation model of fertilizer application amount based on Eq. (5) and the experiment, and the real-time information of fertilizer application amount can be obtained and displayed on the OLED LCD screen.

5. Test results and Analysis

5.1 Test Materials and Methods

To test the performance of the device designed in this paper, a test bench shown in Figures 7 and 8 was built with a uniform and non-clumping granular compound fertilizer commonly used in agricultural production.

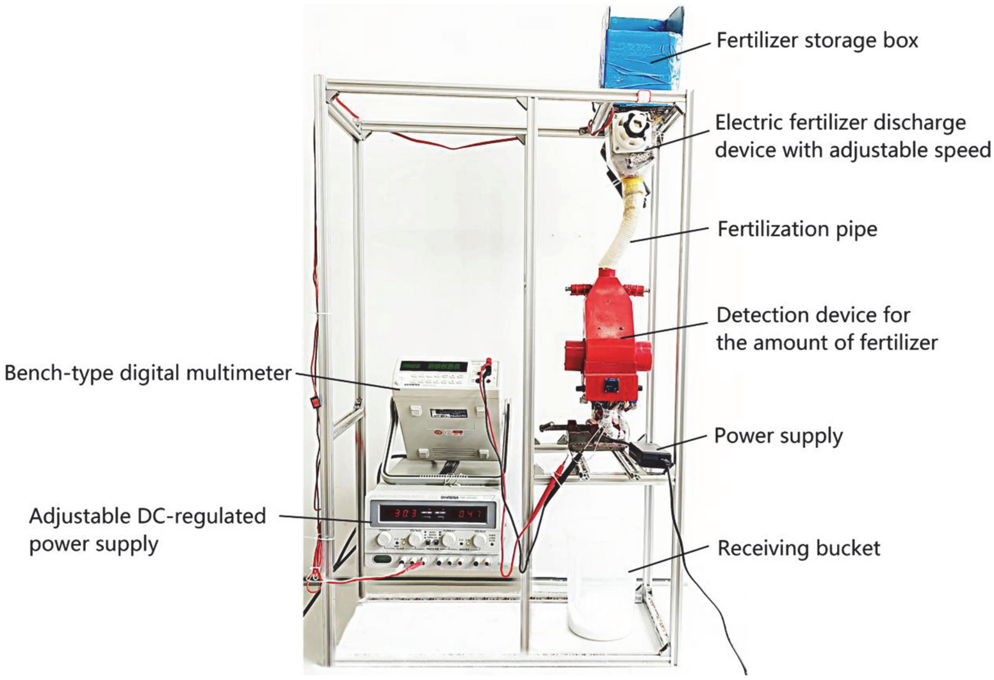


Figure 7. The test bench of the online fertilizer application amount detection device

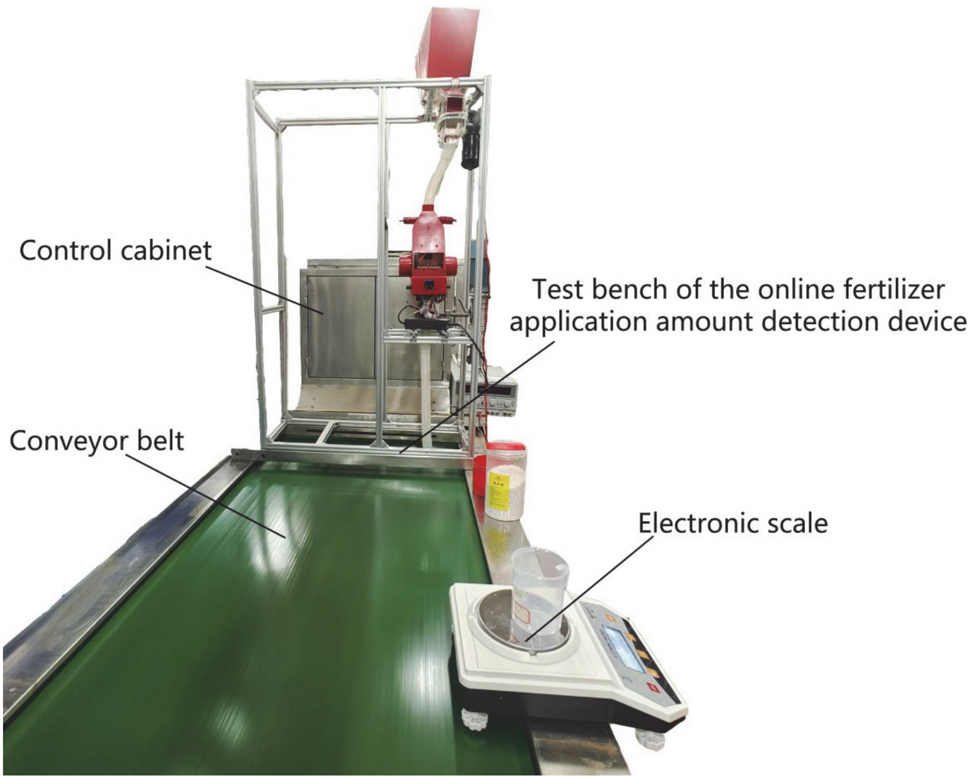


Figure 8. Performance verification test bed for fertilizer application amount detection

In the test bench, the electric fertilizer discharge device with adjustable speed (Xingbang, 12V/50W) driven by a stepping motor is used to feed the detection device for the amount of fertilizer, and the multi-channel adjustable DC regulated power supply (Suzhou Guwei Electronics GPC-3060D, 30V/3A) is used to supply power to the fertilizer device. By adjusting the power supply voltage, the rotation speed and the fertilizer amount of the fertilizer applicator are changed to test the fertilizer detection performance of the device at different rotation speeds, and the test bench is placed on the conveyor belt device to carry out the fertilizer detection performance verification test. The experiments were mainly conducted in three aspects: the influence of fertilizer discharging speed of the fertilizer applicator on the detection device, the mathematical relationship between fertilizer quality and metering voltage, and the fertilizer application volume detection model and its performance verification.

Through the test bench shown in Figure 7, the influence of the fertilizer discharge speed of the fertilizer applicator on the detection device and the mathematical relationship between the fertilizer quality and the measurement voltage were investigated. The measurement voltage of the detection device was verified by the bench-type digital multimeter (model GDM-8352). The quality of the fertilizer flowing through the detection device was measured by the mass weighing method, i.e., the fertilizer quality collected at the electronic scale (model SL4001, 4000±0.1 g) was used for confirmatory measurement.

Since the device is used to detect the fertilizer mass flow rate of the external fertilizer applicator, the performance of fertilizer application amount detection is verified by the test bench shown in Figure 8 according to the 'Fertilization Machinery Quality Evaluation Specification' (NY/T1003-2006) and the 'Fertilization Machinery Test Method' (GB/T20346.2-2006, Part2: Standards for Inter-row Fertilizer Applicators). During the test, the tape measure was used to measure the length of the strip, the 6236P tachometer was used to detect the speed of the conveyor belt (Lai et al., 2022; Chen et al., 2015; Ding et al., 2019), and the stopwatch was used for fertilizer timing.

5.2 Test Results and Analysis

5.2.1 Effect of the Rotation Speed of Fertilizer Applicator on Detection Performance

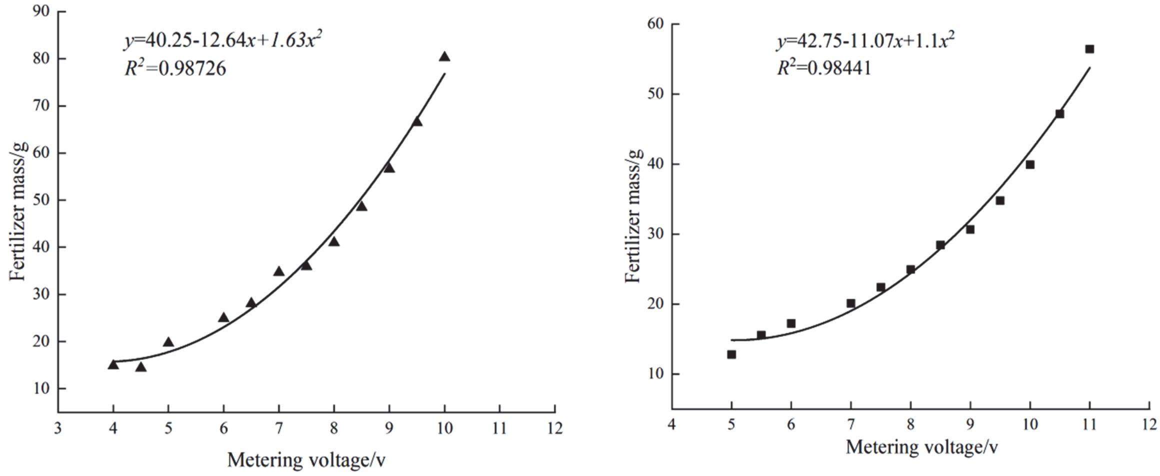
According to the field operation speed of the machine, the fertilizer discharging speed of the fertilizer applicator is generally 10-60 r/min (its discharging fertilizer mass range is about 200-900 g/min) (Chen et al., 2015; Ding et al., 2019). To test the effect of fertilizer applicator discharge speed on the detection performance of the device, the fertilizer applicator discharge speed was set to 10 r/min, 25 r/min, 35 r/min, 45 r/min, 55 r/min, and 60 r/min, respectively. Meanwhile, the working voltage range of the metering electromagnetic sucker is 0-12 V. After the pre-test, it was found that when the metering voltage of the electromagnetic sucker is set below 4 V, the single fertilizer metering value of the metering unit is smaller than 10 g, and there is a large detection error. When the metering voltage is set to 10 V or higher, the single fertilizer measurement value of the metering unit is larger than 40 g, and the continuity of the fertilizer discharge after the fertilizer application volume detection does not meet the fertilization requirement. Therefore, the working voltage range of 4-10 V, 5 V, 7 V, and 9 V were selected as the metering voltage of metering units I and II, respectively. Then, the single-factor test was conducted, and the significance of the influence of the rotation speed of the fertilizer under each metering voltage was analyzed. Each test was repeated six times, and the average value was taken as the final test result. During the test, the fertilizer flow direction was manually controlled and switched, the two metering units were tested under different metering voltages, and the fertilizer metering values of the two metering units were weighed and compared one at a time. As indicated by the ANOVA in Table 1, the P values among the groups are 0.13, 0.76, 0.14, 0.55, 0.28, and 0.49, and they are all greater than 0.05. This demonstrates that the guide mechanism of the device has a good buffering effect on fertilizer falling at different speeds and achieves good applicability and detection performance within the conventional discharge speed (10-60 r/min) of the fertilizer applicator. Thus, the influence of the external fertilizer applicator speed on the detection of fertilizer applied to the device is not significant and can be ignored.

Table 1. Analysis of variance results for different metering voltages in metering units I and II

metering unit	metering voltage		SS	df	MS	F	P-value	F crit
I	5V	Inter-group	2.73	7	0.39	1.71	0.13	2.25
		Within Group	9.13	40	0.23			
		Grand total	11.86	47				
	7V	Inter-group	5.71	7	0.82	0.59	0.76	2.25
		Within Group	55.21	40	1.38			
		Grand total	60.93	47				
	9V	Inter-group	4.76	7	0.68	1.69	0.14	2.25
		Within Group	16.13	40	0.40			
		Grand total	20.89	47				
II	5V	Inter-group	4.40	7	0.63	0.86	0.55	2.25
		Within Group	29.32	40	0.74			
		Grand total	33.71	47				
	7V	Inter-group	7.16	7	1.02	1.29	0.28	2.25
		Within Group	31.72	40	0.79			
		Grand total	38.88	47				
	9V	Inter-group	2.44	7	0.35	0.94	0.49	2.25
		Within Group	14.82	40	0.37			
		Grand total	17.26	47				

5.2.2 Establishment of Fertilization Amount Detection Model

According to the structure of the metering unit of the device and the principle of fertilizer application detection, determining the correspondence between the metering voltage of the metering unit and the mass of a single discharge of fertilizer in the storage box is the basis and key to establishing the fertilizer application detection model. Basically, the detection performance of the fertilizer amount of the device is not affected by the rotation speed of the external fertilizer applicator, so the test was conducted under the condition that the rotation speed of the fertilizer applicator is 40 r/min according to the requirements of the conventional operation. Before the test, the measurement voltage was set by the PWM voltage regulating module, and the working voltage of the electromagnetic sucker was set at a step of 0.5 V in the range of 4-10 V. During the test, for each metering voltage, the selected fertilizer was gradually poured into the testing device from small to large in the range of 10-90 g until the mass of the poured fertilizer is equal to the critical discharge volume of the fertilizer discharging board (i.e., thus triggering the fertilizer discharging board discharge action). This process was repeated 10 times, and the average value was taken as the test result. To avoid the error caused by the manufacturing difference between the electromagnetic sucker and the metering unit, two metering units were tested respectively. The test results are presented in Figure 9. Generally, the mathematical models between the metering voltage of the two metering units and the critical discharge amount of the fertilizer discharging board are the same, and only the coefficients are different.



(a) (b)

Figure 9. The relationship between critical fertilizer discharge and metering voltage for fertilizer discharging boards. (a)metering unit I(b) metering unit II

Based on the test results in Figure 9, Eq. (5), and the principle of fertilizer application detection, the fertilizer application detection model shown in Eqs. (6) ~ (8) can be obtained.

$$m_1 = (1.63u_1^2 - 12.64u_1 + 40.25)f_1 \quad (6)$$

$$m_2 = (1.1u_2^2 + 11.07u_2 + 42.75)f_2 \quad (7)$$

$$M = m_1 + m_2 \quad (8)$$

where m_1 and m_2 are the critical fertilizer discharge of the discharge plate of metering units I and II, respectively (unit: g); u_1 and u_2 are the metering voltage of metering units I and II, respectively, (unit: V); f_1 and f_2 are respectively the pulse number of discharge plate fertilizer action counting of metering units I and II; m is the amount of fertilizer detected by the device (unit: g).

5.2.3 Fertilization Detection Performance Verification

Following the design structure and the detection principle, based on the single detection amount of the two metering units (i.e., the critical fertilizer discharge amount of the fertilizer discharging board), the device realizes online detection of the fertilizer mass flow according to the pulse number of the fertilizer discharge action of the fertilizer discharging board, which does not affect the fertilizer discharge effect of the fertilizing machine. Therefore, the test was mainly conducted from two aspects: the amount of fertilizer online detection and fertilizer performance verification.

The fertilizer application amount online detection test includes a single detection amount of the metering unit and an online detection test of the fertilizer mass flow rate of the device. It is shown above that the fertilizer discharge speed of the external fertilizer applicator has no significant effect on the detection performance, and the detection of fertilizer amount is closely related to the metering voltage. Thus, in the verification test of single detection and online detection of fertilizer mass flow, the rotation speed of the fertilizer applicator was set to 40 r/min, and the test was conducted under three measurement voltages of 5 V, 7 V, and 9 V. For each metering voltage, each test was repeated 10 times, and the mean value was taken as the test result. The accuracy of fertilizer application detection was verified by the weighing method. The accuracy verification results of online detection of fertilization amount are listed in Tables. 2 and 3.

Table 2. The verification results of metering unit single test accuracy

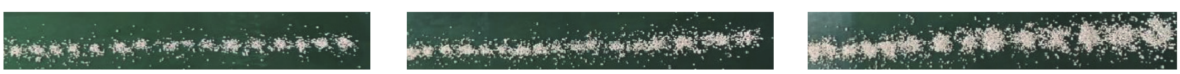
Metering unit	Metering voltage/v	Measuring mass/g	Real mass/g	Relative error/%
I	5V	18.93	19.58	3.32
	7V	33.24	33.95	2.09
	9V	54.45	55.58	2.03
II	5V	16.68	16.1	3.60
	7V	25.57	24.78	3.19
	9V	38.75	37.4	3.61

Table 3. Fertilizer mass flow online testing accuracy verification results

Metering voltage/v	Experiment serial number	Measuring mass/g	Real mass/g	Relative error/%
5V	1	163.24	169.58	3.73
	2	276.04	283.36	2.58
	3	341.34	330.25	3.35
7V	1	285.02	275.15	3.58
	2	386.38	374.72	3.11
	3	456.1	470.28	3.01
9V	1	271.56	279.36	2.79
	2	452.6	462.82	2.2
	3	511.1	518.72	1.46

Table 2 presents the verification result of the single detection accuracy of the two metering units, and the detection error is less than 3.61 %. Table 3 presents the verification results of the online detection accuracy of the fertilizer mass flow rate of the device, and the detection error is less than 3.73 %. These results indicate that the device has high detection accuracy and can be well applied to online detection of fertilizer mass flow of fertilization machinery.

The fertilizer discharge performance test includes the fertilizer discharge effect test of the device, and the fertilizer application amount detection accuracy analysis test. In the first test, the height of the falling fertilizer point and the drive belt was set to 30 mm; meanwhile, the fertilizer applicator discharge speed was set to 40 r/min, and the drive belt speed was set to 0.37 m/s so that the two speed paces are consistent. Besides, the fertilizer metering values were set to 20 g, 25 g, and 35 g, and the unit metering voltage values corresponding to the two metering units were set to 5.5 V, 6.3 V, 7.3 V, and 7.2 V, 8.1 V, 9.3 V respectively. Let the fertilizer applicator and the drive belt work in a unit of 1 m and a normal cumulative travel of 10 m, and then the test section of the broken strips was observed and recorded.



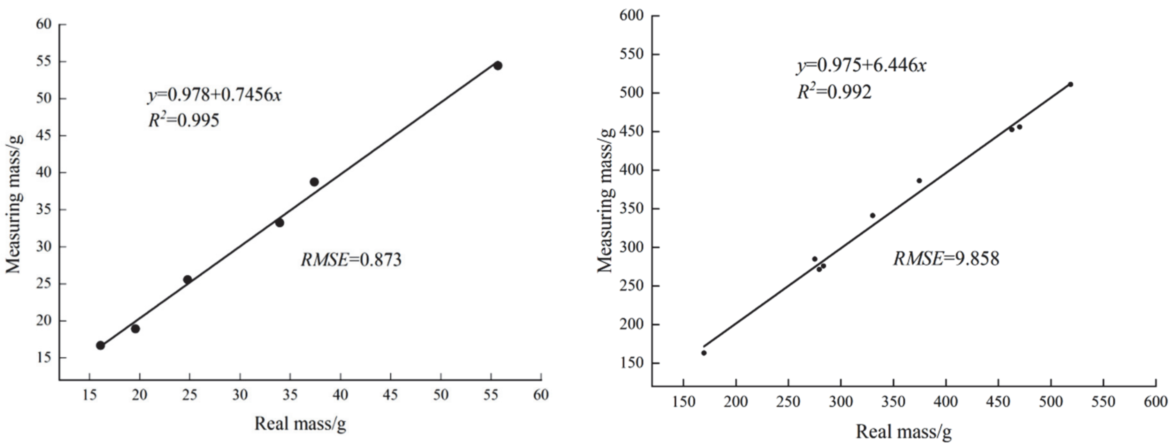
(a) (b) (c)

Figure10. Fertilizer discharge effect of the fertilizer application detection device. (a) 20 g (b) 25 g (c) 35 g

By observing the measuring area of the fertilizer discharge uniformity test with fertilizer metering values of 20 g, 25 g, and 35 g, the continuity of fertilizer discharge was obtained according to the broken strips of the fertilizer.

The field fertilization standards indicate that there is no fertilizer during normal operations of the machine section length greater than 10cm above identified as broken bars. The fertilizer discharge effect of the device is illustrated in Figure 10. The test results show that the fertilization broken strips rate is 0, indicating that the detection device does not affect the fertilizer discharge performance of the external fertilization machine when the fertilizer mass flow is carried out.

In the accuracy analysis test of fertilizer application amount detection, the parameters were set the same as the above, and the online detection results of single detection amount and fertilizer mass flow rate were analyzed. Then, the fertilizer application amount detection results of the detection device shown in Figure 11 were compared with the mass obtained by the weighing method.



(a) (b)

Figure 11. Comparison of the actual quality and detection quality. (a) Comparison of the actual quality and single detection quality (b) Comparison of the actual quality and detection quality of alternating discharge fertilizer quantity by a measurement unit

It can be seen from Figure 11 that the amount of fertilizer detected by the device is consistent with the actual amount of fertilizer. For the single detection amount, the determination coefficient R^2 and the root mean square error RMSE are 0.995 and 0.873, respectively; for the fertilizer mass flow rate detection, the determination coefficient R^2 and root mean square error RMSE reached 0.992 and 9.858 g/g, respectively, indicating that the device has high detection accuracy.

6. Conclusion

(1) Based on the moment balance principle, this paper designs an online detection device for fertilizer application rate, which has a simple structure and no need for pre-installation. It can be installed on the fertilizer discharge port of fertilization machinery to realize online detection of fertilizer mass flow, and the single detection amount of the metering unit can be adjusted according to the actual operation requirements to ensure the continuity of its fertilization.

(2) The fertilizer guide mechanism has a good buffering effect on the fertilizer falling at different speeds. For the commonly used fertilizer discharge speed (10~60 r/min) of the fertilizer applicator, the metering units I and II were measured at 5 V, 7 V, and 9 V, respectively. The P values between the groups of the rotation speed of the fertilizer are 0.13, 0.76, 0.14, 0.55, 0.28, and 0.49 respectively, which are greater than 0.05, indicating that the rotation speed of the external fertilizer applicator has no significant effect on the detection performance of the fertilizer application rate of the device. Thus, the device has good applicability and consistency of detection performance.

(3) The fertilizer detection model ($R^2 > 0.98$) was established, and the detection performance of the device was verified through experiments. The test results showed that the single detection error of the two metering units is less than 3.61 %, and the detection error of fertilizer mass flow is less than 3.73 %. The determination coefficient (R^2) and the root mean square error (RMSE) reached 0.992 and 9.858, respectively. When the fertilizer measurement value of the metering unit was less than 35 g, the fertilization broken strips rate was 0, indicating

that the fertilizer discharge effect of the external fertilization machinery was not affected. Therefore, the device can be well applied to the online detection of fertilizer mass flow of fertilization machinery.

In this paper, the principle of moment balance is adopted to realize the online detection of fertilizer. At present, the uneven field in the mechanical fertilization process will lead to the bump and jitter of the fertilizer applicator. In the previous test, the influence of the bump and jitter of the working fertilizer applicator on the detection device is not considered. Therefore, in the follow-up study, we will investigate the anti-shake of the detection device to improve the detection device's adaptability.

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