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DEVELOPMENT AND LABORATORY TEST OF AN INJECTION SYSTEM FOR THE TRACTOR OPERATED LIQUID UREA APPLICATOR

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ABSTRACT

This study investigates the development of an injection system incorporating an electronic metering mechanism for a tractor-operated applicator, designed to inject liquid urea beneath straw mulch. The primary objective of the system is to achieve continuous, uniform, and precise injection of liquid urea, optimizing fertilizer application in agricultural fields. The injection process is independently controlled by the speed of the rotary wheel, while the flow rate of the fertilizer is regulated by the system's pump pressure. A laboratory testbed was developed to monitor and evaluate the liquid flow, with a focus on flow characteristics and uniformity. Three experimental factors were considered: wheel revolution speed, injector outlet diameter, and system pressure. Experimental results indicated that the system's performance was highly consistent, with a homogeneity index of 5.53% at an injector outlet diameter of 5 mm and a system pressure of 330 psi. These findings demonstrate that the injection system is capable of maintaining uniform flow and consistent fertilizer application, suggesting its suitability for efficient use in agricultural practices where precision and consistency are critical for maximizing crop yield and minimizing waste.

Keywords: Electronic metering, Injection system, Liquid urea

India, the world's second-most populous country, is home to 17.7% of the global population (Anonymous, 2011; 2021). The country's agriculture sector occupies approximately 43% of its total geographical area (Mor *et al.*, 2022; Jaideep *et al.*, 2018). Over the years, India has emphasized self-sufficiency and self-reliance in food grain production, a goal that has been consistently highlighted in successive Five-Year Plans. These concerted efforts have led to substantial increases in agricultural production and productivity, with fertilizers playing a pivotal role in boosting foodgrain output (Chunfeng *et al.*, 2015). For instance, food grain production in India rose dramatically from just 52 million tonnes in 1951-52 to an estimated 328.8 million tonnes in 2023-24 (Anonymous, 2024). Among the various agricultural regions in India, Punjab has become a important contributor to the nation's food security, with the state accounting for more than half of the grain in the central food grain pool (Parveen *et al.*, 2020; Dhanger *et al.*, 2021). However, the region's focus on rice and wheat cultivation has led to significant residue management challenges, including issues related to the incorporation, removal, and mulching of crop residues (Singh *et al.*, 2008; Dhanger *et al.*; 2022, Kumar *et al.*, 2023). The introduction of the Happy Seeder technology has alleviated some of these challenges by facilitating the sowing of wheat on surface-applied rice straw, thereby minimizing the need for burning and residue incorporation (Sidhu *et al.*, 2007; Kumar *et al.* 2013).

The timely and accurate application of fertilizers is crucial for optimal crop growth. Incorrect fertilizer application, whether in excess or insufficient amounts, can have detrimental effects on crop yields and environmental sustainability (Cheng *et al.*, 2017). The task of fertilizing crops has become increasingly challenging, particularly with the rising complexity of agricultural practices (Dhanger *et al.*, 2023a). Surface application of urea, for instance, leads to significant nutrient losses and high ammonia volatilization rates, further reducing its effectiveness (Ismail *et al.*, 1991). Moreover, the broadcasting method of urea often results in lower yields, especially in no-till fields with substantial rice straw residue, due to the limited nitrogen availability (Tian *et al.*, 2001; Singh *et al.*, 2013; Dixit and Mahal, 2016; Dixit *et al.*, 2016). One promising solution to these challenges is the application of liquid fertilizers, which offer several advantages over solid fertilizers. While solid fertilizers are typically absorbed by plants at rates of approximately 30%, liquid fertilizers can be absorbed at rates exceeding 80%, significantly improving nutrient uptake. Furthermore, liquid fertilizers are associated with higher absorption efficiency, reduced volatilization losses, and lower environmental pollution (Salah, 2006; Spangberg *et al.*, 2011). Keeping in view the ecological and economic benefits of liquid fertilizer use (Dhanger

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et al., 2023b), there is strong practical value in further research to optimize and refine liquid urea injection technologies (Chunfeng *et al.*, 2015).

To address the challenges associated with urea application in high-residue fields under no-till wheat cultivation, a self-propelled liquid urea applicator with a mechanical metering and cut-off mechanism was designed and developed at the Department of Farm Machinery and Power Engineering (FMPE), Punjab Agricultural University (PAU), Ludhiana, during 2012-13 (Dixit and Mahal, 2016; Dixit *et al.*, 2016). However, this system had limitations, including imprecise cut-off due to component wear and clogging of the injection nozzles. Hence, the present study focuses on the development of an electronic metering and cut-off injection system for tractor-operated machines. This system is capable of injecting liquid urea beneath the straw mulch into the soil, offering significant advantages in terms of application efficiency, nutrient absorption, placement accuracy, and operational reliability (Dhanger *et al.*, 2024). The development process, along with laboratory testing, demonstrated that this new injection system is well-suited for uniform and precise distribution of liquid fertilizer, overcoming the limitations of previous models.

MATERIALS AND METHODS

Structure and working principle of the rotary wheel

The proposed liquid urea injection machine was designed to inject fertilizer directly into the soil through paddy straw mulch. To achieve this, the machine required specially designed ground wheels with injector nozzles distributed around their periphery. These nozzles were intended to apply liquid fertilizer through the surface mulch and into the soil. The earlier self-propelled machine, which had injector holes located on the front face of the nozzles, faced the disadvantage of clogging and inconsistent fertilizer injection. In contrast, the newly developed system incorporates a more efficient wheel design, where liquid urea is fed through the hub, carried along the hollow spokes, and then ejected via nozzles positioned around the circumference of the wheel. Since the machine is tractor-mounted, five such wheels were proposed for optimal functionality. The rotary wheel assembly consists of several key components: injector nozzles, hollow spoke pipes, a mild steel (MS) frame, springs, and U-clamps for secure mounting. The central shaft ensures axial alignment for accurate positioning of the liquid urea injectors. The hub of the rotary wheel contains bearings, seal rings, and O-rings to prevent leakage and ensure efficient operation. The liquid urea is ejected through the hollow spokes of the wheel, allowing for consistent distribution into the soil. To facilitate smooth, friction-free movement, the interface between the central hub and the circular shaft is constructed from hardened chrome steel. This material was selected for its exceptional mechanical strength, heat resistance, wear resistance, self-lubricating properties, and corrosion resistance, making it ideal for the demanding conditions of the machine. To meet sealing requirements, an internal O-ring rubber seal is employed between the bearings and the distribution hub. This sealing system is designed to perform reliably under high temperatures and pressures, ensuring that the system remains airtight and free from leakage. The bearings are positioned at both ends of the rotor shaft to support the wheel's rotation and enhance durability. The rotary wheel itself is manufactured from mild steel, known for its high strength, good toughness, and long-term durability. Mild steel was chosen for its reliability, which ensures the system's long-term performance across various fertilizer types. Additionally, to prevent the wheel from skidding during operation, lugs are evenly spaced around the circular ring, providing stability and preventing malfunctions.

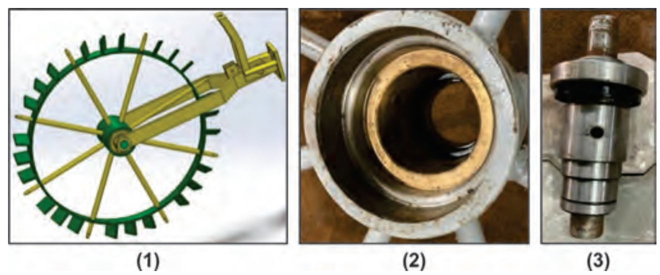

Fig. 1. Structure of rotary wheel. (1) Rotary wheel, (2) Distribution hub (3) Circular shaft

Development of pipeline structure

As illustrated in Figure 2, the liquid urea flow path within the system begins at the fertilizer tank, progressing through the distribution pipe, central shaft, distribution hub, hollow spoke pipe, and ultimately to the injectors. To ensure efficient and continuous liquid flow, a high-pressure PVC pipe was used to connect the water pump to the fertilizer tank. The primary function of the distribution system is to maintain a steady and uniform distribution of the liquid fertilizer. The distribution pipe, which is connected to the water pump, is made of a 12 mm PVC pipe, while the connection to the wheels is facilitated by 10 mm Reverse Osmosis (RO) pipes. To monitor the pressure within the system, a brass pressure gauge (0-300 psi/ kPa, ½") is installed on the distribution pipe, allowing real-time monitoring of pipeline pressure. The pump pressurizes the liquid fertilizer, and its flow rate is regulated via a speed controller and a flowmeter. This allows for precise adjustment to meet the fertilization requirements of the system, ensuring accurate and effective application of the liquid urea.

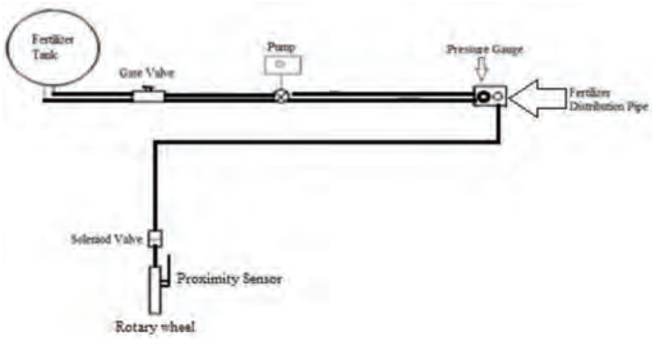

Fig. 2. Pipeline structure for injection system

Cut-off mechanism

This section outlines the selection and operation of the key control components of the electronic metering mechanism, in alignment with the design requirements. All control system components for the electronic metering mechanism were selected to operate on a 12V DC battery, ensuring compatibility and efficiency in the system's power supply. The cut-off mechanism comprises several critical components: a diaphragm pump (12V DC, double motor, 9 L/min flow rate, 6.8 bar pressure), a 2-way solenoid valve (1/2", brass, 12V DC), an inductive sensor (12V DC, M18, 8 mm, NPN-NO type), and an electro-mechanical relay (MSP-2 Pole, 12V). These components work in conjunction to control the flow of liquid urea through the system. The diaphragm pump provides the necessary pressure for the injection system, with the pump selected for its ability to withstand a maximum pressure of 300 psi, which is critical for the effective operation of the system. Sensors are positioned on the mild steel (MS) frames of each wheel, located near the distribution hub, to monitor the speed of the rotary wheel. The cut-off mechanism operates independently based on the speed of the wheel, ensuring that liquid urea is injected only when required. The flow of fertilizer in the system is regulated by both the speed of the rotary wheel and the pressure generated by the pump. A specially designed control circuit governs the entire cut-off mechanism, providing precise and efficient operation. This circuit is essential for maintaining the high efficiency and accuracy of liquid urea application, ensuring the system meets the fertilization requirements with optimal precision.

Construction and principle of lab test bed

The test-bed developed for evaluating the performance of the liquid urea injection system comprises several key components, including the rotary wheel, a variable frequency drive (VFD) motor with a display, a power transmission system, a mounting frame for the rotary wheel, and liquid collection trays (Fig. 4). To mitigate environmental pollution and protect the operator from exposure to liquid fertilizer, clean water

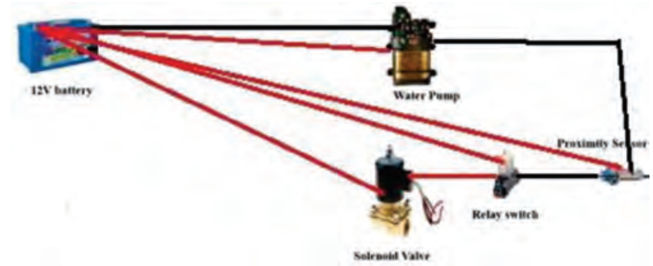

Fig. 3. Components integration of system for cut-off mechanism

was used as a substitute for the fertilizer during the tests. The primary objective of the test was to assess the continuity and uniformity of the liquid flow, as well as to evaluate the influence of three experimental factors: rotational speed, injector outlet diameter, and operating pressure. These factors were varied independently in the test-bed design. The developed rotary wheel was mounted on the machine frame in the laboratory for evaluation of discharge performance and testing of the cut-off mechanism. In the experimental setup, rotational speed, injector outlet diameter, and system pressure were treated as independent variables, while the liquid discharge was measured as the dependent response variable. Data analysis was performed using the Statistical Package for the Social Sciences (SPSS), and a Factorial Completely Randomized Design (CRD) was employed to analyze the data. The test involved varying the motor speed on the VFD at three different settings, with the rotary wheel mounted on a fixed frame. The rotation of the wheel was facilitated by a drive belt, and the liquid discharge rate was measured over a one-minute interval. A rectangular tray was used to collect the discharged liquid, allowing for precise measurement of the amount of liquid urea applied during each test.

Fig. 4. Lab test-bed system for liquid flow experiments

RESULTS AND DISCUSSION

Effect of speed of wheel rotation and injector outlet diameter on liquid flow

The maximum liquid flow of 35 mL was observed at the lowest rotational speed (7 rpm) with a 6 mm outlet diameter of the injector, while the minimum liquid flow of 6 mL was recorded at the highest rotational speed (25 rpm) with a 4 mm outlet diameter. As shown in Fig. 5, a linear decrease in the liquid flow rate was observed as the wheel rotation speed increased for each injector. However, the liquid flow rate increased when the system pressure was set to 330 psi compared to the two lower pressure settings. Similar trends were reported by previous studies (Baker *et al.*, 1989; Chunfeng, 2015). Wang *et al.* (2012) also observed a liquid flow of approximately 20 mL with a 3 mm diameter core hole at similar rotational speeds. Almost similar findings were reported by other researchers under similar experimental conditions (Singh *et al.*, 2013; Dixit *et al.*, 2015). Silva and Magalhães (2019) also reported liquid doses ranging from 5 to 18 mL per cycle at pressures between 50 and 100 mm. These lab results clearly demonstrate that wheel rotation has a significant impact on the injector flow rate. The observed differences in flow rates can likely be attributed to variations in the rotational speed of the wheel, as higher rotational speeds reduce the injection time, thereby affecting the volume of liquid delivered.

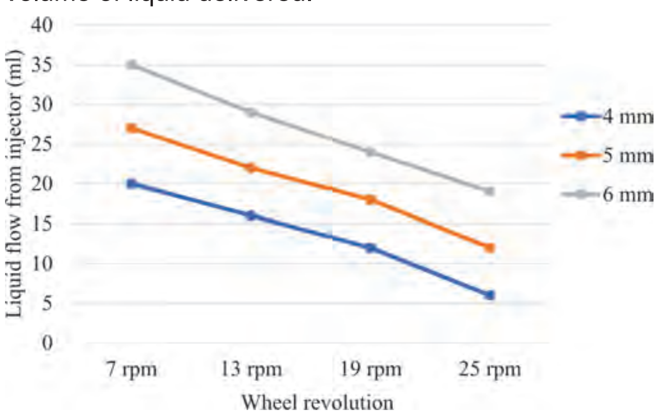

Fig. 5. Different wheel rotation and injector outlet diameter on liquid flow (at pressure of 330 psi)

Effect of injector outlet diameter and pressure on the liquid flow

The maximum liquid flow (29 mL) was observed at a pressure of 330 psi with a 6 mm injector outlet diameter, while the minimum liquid flow (5 mL) was recorded at a pressure of 110 psi with a 4 mm injector outlet diameter. As illustrated in Fig. 6, a linear increase in liquid flow was noted with both an increase in injector outlet diameter and system pressure, which ranged from 110 to 330 psi, while the wheel revolution was maintained at 13 rpm. The lower liquid flow rate at 110 psi can be attributed to the system pressure being insufficient to meet the operational requirements, a finding that aligns with similar observations in previous studies (Singh *et al.*, 2013; Dixit *et al.*, 2015; Chungfeng, 2015; Silva and Magalhães, 2019). Wang *et al.* (2012) also reported that with a distributor valve core hole diameter of 3 mm, a spraying-fertilizer nozzle diameter of 2 mm, a rotational speed of 110 rpm, and a pressure of 0.3 MPa, similar trends were observed.

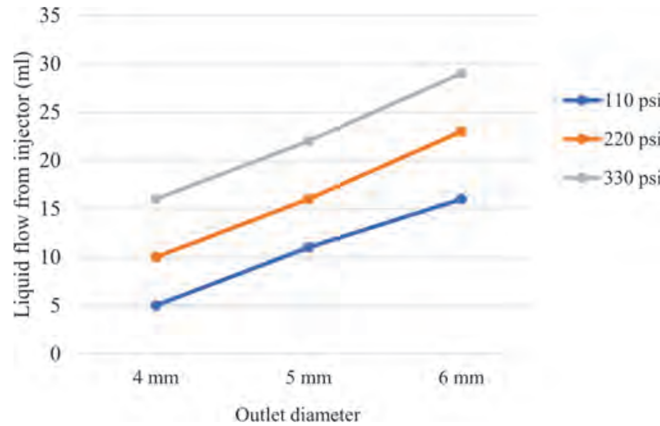

Fig. 6. Different injector outlet diameter and pressure on liquid flow (wheel revolution 13 rpm)

Effect of pressure and speed of wheel rotation on liquid flow

The maximum liquid flow (25 mL) was observed at a wheel speed of 7 rpm and a system pressure of 330 psi, while the minimum liquid flow (7 mL) occurred at a pressure of 11 psi with a wheel speed of 25 rpm. As shown in Fig. 7, a linear decrease in liquid flow was observed as the wheel revolution increased from 7 to 25 rpm, with the injector outlet diameter fixed at 5 mm. At higher rotational speeds, the injector has less time to inject the liquid, resulting in a reduced flow rate. Similar findings have been reported in other studies under comparable conditions (Singh *et al.*, 2013; Dixit *et al.*,

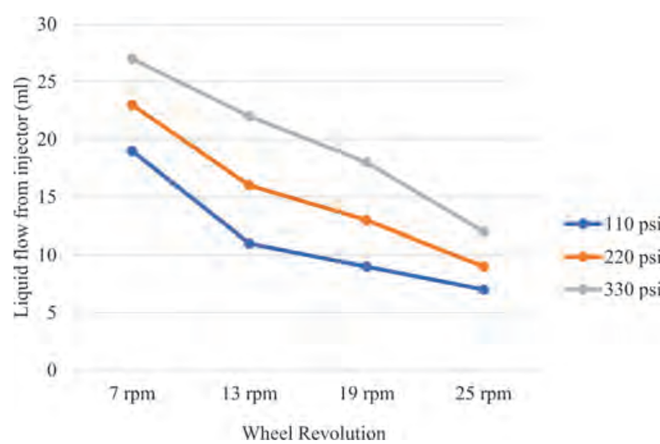

Fig. 7. Different pressure and speed of wheel rotation on liquid flow (injector outlet diameter 5 mm)

Table 1. ANOVA for effect of operational parameter of flowrate

Source	Type III Sum of Squares	*df*	Mean Square	*F*
Corrected Model	2233.194[a]	7	319.028	184.409*
Intercept	8311.361	1	8311.361	4804.255*
RPM	764.750	3	254.917	147.350*
DIA	926.722	2	463.361	267.839*
PRESSURE	541.722	2	270.861	156.567*
RPM * DIA	34.167	6	5.694	3.291**
RPM * PRESSURE	40.500	6	6.750	3.901**
DIA * PRESSURE	10.944	4	2.736	1.581**
RPM * DIA * PRESSURE	12.833	12	1.069	0.618**
Error	48.444	28	1.73	
Total	10643.000	36		

*Significant at $p \leq 0.01$ & **Significant at $p \leq 0.05$

2015). Silva and Magalhães (2019) also observed that liquid doses ranging from 5 to 18 mL per cycle were delivered at pressures between 50 and 100 mm. Almost similar results were reported by several researchers (Baker *et al*., 1989; Singh *et al*., 2013; Chungfeng, 2015; Dixit *et al*., 2015; Silva and Magalhães, 2019).

From the below table 1 it is observed that effect of the Diameter, Pressure and RPM on flowrate was significant. Their respective interaction of parameter also found significant.

Effect of system pressure on homogeneity of liquid flow

As shown in Fig. 8, the liquid flow from the wheel was examined under conditions where the wheel revolution was fixed at 13 rpm, the injector outlet diameter was set to 5 mm (based on the desired discharge rate range), and the system pressures were selected as 110 psi, 220 psi, and 330 psi, respectively. At lower pressures, the uniformity of liquid flow was irregular. However, as

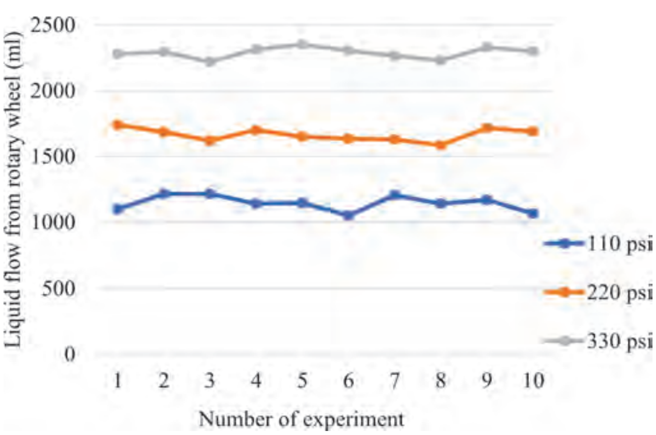

Fig. 8. The influence of liquid flow of rotary wheel at different pressure (at wheel revolution 13 rpm and injector outlet diameter 5 mm)

the system pressure increased, the uniformity of liquid flow improved. A working pressure greater than 2.0 MPa (290 psi) is required for the high-pressure technique to be effective in practice, as noted by Nyord *et al.* (2008). The selected control system showed a range of 2.97 to 6.39 mL/s² for carrier pressures between 140 and 414 kPa, which facilitated the desired rate change. Significant variations in the desired flow rate of the nozzle were compensated as the operating pressure increased, as reported by Luck *et al.* (2015).

In general, the test results demonstrated reliable uniformity. The experiments were conducted for one minute under the fixed parameters mentioned above. The liquid discharged during this period was collected on a plate and measured. To ensure greater uniformity, each experiment was repeated ten times, with the resulting data presented in Table 2.

$$C\ (\%) = \frac{(Fmax-Fmin)}{(Fmax)} \times 100 \qquad (1)$$

C: degree of homogeneity (%); F_{max}: Maximum flow (ml); $F_{min:}$ Minimum flow (ml)

The degree of homogeneity was highest (13.58%) at the lowest system pressure, but it decreased as the system pressure increased. Therefore, uniformity was lowest at 110 psi and improved with higher system pressures, reaching a homogeneity coefficient of 5.53% at 330 psi. These results indicate that the uniformity of the injection system was most reliable at 330 psi of operating pressure. Chungfeng (2015) reported a homogeneity coefficient of approximately 4% at pressures of 0.2-0.3 MPa for liquid fertilizer application. Schrock *et al.* (2001) tested valve duty cycles ranging from 3% to 90% and found that when the duty cycle of the PWM valve was 10% or greater, the lateral coefficients of variation were less than 10%. Johann *et al.* (2006) developed a low-cost servo valve,

Table 2. Statistical table of liquid flow

Pressure (psi)	Amount of liquid flow (F) (ml)										Mean (ml)	Standard Deviation
110	1100	1215	1215	1140	1145	1050	1205	1140	1170	1065	1144	56.14
220	1740	1685	1620	1700	1650	1635	1630	1585	1715	1690	1665	45.99
330	2280	2295	2220	2315	2350	2305	2265	2230	2330	2300	2289	39.23

which operates on an electronic signal for variable-rate liquid input applications. The servo valve demonstrated good repeatability, reasonable hysteresis, and a typical quadratic response curve. These results were promising, as non-linearity and hysteresis could be easily corrected using software. Luck *et al.* (2015) observed that the maximum absolute error (+2σ) did not exceed 10% of the desired flow, and the average absolute error was less than 5%, indicating that the nozzle operated within specifications 95% of the time, which was considered a successful operation. Field tests showed that the machine exhibited 92.5% subsoiling stability, a 61.1% soil breaking rate, a maximum positioning relative error of 2.68%, and a maximum variable-rate fertilization error of 3.89%. These indices met both the standards and design requirements (Qi *et al.*, 2020). Furthermore, a lag time detection system designed for variable-rate fertilization, incorporating the lag distance compensation method (LDCM), effectively reduced lag distances in variable-rate fertilizer applicators, ensuring precision fertilization in precision agriculture (Zhang *et al.*, 2021). The test results revealed that the control accuracy of the variable fertilization system exceeded 95%, meeting the requirements for quick automatic formula adjustments and precise variable fertilization, while remaining practical and cost-effective (Niu *et al.*, 2022).

CONCLUSION

In conclusion, the experiments clearly demonstrated the significant influence of wheel revolution, injector outlet diameter, and system pressure on liquid flow. The optimal operating parameters for consistent performance were identified as a 5 mm injector outlet diameter and a system pressure of 330 psi. The uniformity test on the rotary wheel revealed a high degree of homogeneity (5.53%) at 330 psi, indicating reliable and stable performance. The injection system was found to be suitable for use in a tractor-operated liquid urea applicator, meeting the requirements for precision application of liquid fertilizer into the soil. These results suggest that the system can effectively support the needs of precision agriculture, ensuring efficient and accurate fertilizer distribution.

Authors' contribution

Conceptualization of research work and designing of experiments (PD, RK, MS, KS); Execution of field/lab experiments and data collection (PD, RK, AKD); Analysis of data and interpretation (PD, AKD); Preparation of manuscript (PD, RK).

Conflicts of interest

Authors declare that they have no conflicts of interest.

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