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PRECISION FERTILIZATION REVOLUTION: PERFORMANCE EVALUATION OF AN ELECTRO-MECHANICAL VARIABLE RATE FERTILIZER APPLICATOR

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ABSTRACT

Efficient fertilizer management is critical for achieving sustainable agricultural productivity while minimizing environmental degradation. This study presents a comprehensive performance evaluation of an electro-mechanical variable rate fertilizer applicator (VRFA) engineered for site-specific nutrient management in precision agriculture. The developed system integrates an auger-type metering mechanism driven by a variable-speed DC motor, with rotational speed precisely controlled through a microcontroller (Arduino Uno) interfaced with a voltage regulator. Laboratory and field evaluations were conducted at the University of Agricultural Sciences, Raichur, systematically varying operational parameters including shaft speeds (20–50 rpm), forward speeds (3–5 km h^{-1}) and fertilizer fill levels (25, 50, 75 and 100%). Key performance parameters measured included fertilizer discharge rate, application uniformity and system response time. Calibration results revealed a strong linear relationship between shaft speed and fertilizer discharge ($R^2 \geq 0.98$), demonstrating excellent system consistency and precision. The fertilizer discharge rate F_d (kg ha^{-1}) was computed using $F_d = (W \times 60 \times 10^4) / (S \times W_i \times V)$, ensuring precise field application control. The coefficient of uniformity (CU) and auger discharge efficiency exceeded 90% and 95%, respectively, indicating highly uniform fertilizer distribution across the application swath. Field trials conducted with a Mahindra Yuvraj 215 high-clearance tractor in cotton fields demonstrated significant improvements in effective field capacity and substantial reductions in input losses compared to conventional uniform application methods. Real-time prescription map-based control was implemented through a custom mobile application developed in Flutter, enabling Bluetooth-based communication with the applicator's microcontroller and integration with GPS positioning for precise spatial control. Statistical analysis using Design Expert 11 software confirmed that shaft speed and forward speed interactions significantly influence fertilizer discharge performance ($p < 0.05$). The developed electro-mechanical VRFA demonstrates significant potential for optimizing fertilizer use efficiency, improving crop yield quality and promoting environmentally sustainable farming practices. The system's precision, adaptability, cost-effectiveness and technological integration make it a viable solution for small and medium-scale farmers seeking to implement precision nutrient management strategies in diverse agricultural contexts, contributing to both economic and environmental sustainability.

Keywords: Arduino-based control system, Electro-mechanical applicator, Fertilizer use efficiency, Site-specific nutrient management, and Variable rate fertilization.

Introduction

Agriculture plays a crucial role in ensuring food security for the growing global population and efficient nutrient management is central to sustainable agricultural productivity (Prasad, 2011). Variable rate fertilizer application (VRFA) technology has emerged as a key precision agriculture tool that optimizes fertilizer use by adjusting application rates according to spatial variability in soil fertility and crop requirements (Ning *et al.*, 2015; Wu and Ma, 2015). In India, where fertilizer consumption is among the highest globally, the adoption of site-specific nutrient management practices is essential to address issues of over-application, environmental degradation and escalating input costs (Prasad, 2011; Suman *et al*., 2016). Despite the proven benefits of precision agriculture, adoption remains limited in developing countries due to high costs and technological complexity (Takacsne, 2018).

The performance evaluation and calibration of fertilizer applicators are critical prerequisites for achieving accurate and uniform application rates in variable rate systems (Price *et al*., 2008; Singh *et al*., 2015). Proper calibration ensures that the applicator delivers the prescribed fertilizer dose consistently across varying field conditions and operational parameters (Dhanaraju *et al*., 2022). Several studies have emphasized the need for rigorous testing protocols to assess applicator performance under both laboratory and field conditions (RNAM, 1983; Segun and Ugochukwu, 2023). The development of standardized test procedures for farm machinery, including fertilizer applicators, provides a framework for comprehensive performance evaluation (RNAM, 1983).

Various metering mechanisms have been developed for granular fertilizer application, including auger-type, fluted roller and pneumatic systems (Srivastava *et al*., 2006; Talha *et al*., 2011). Auger-type metering mechanisms have demonstrated particular promise for consistent discharge performance due to their positive displacement characteristics (Wang *et al*., 2023; Zareiforoush *et al*., 2010). The uniformity of fertilizer application significantly influences crop response, with non-uniform distribution leading to yield variability and reduced nutrient use efficiency (Ndiaye and Yost, 1989). Performance evaluation of screw augers has shown that operational parameters such as shaft speed and feed rate critically affect discharge uniformity and accuracy. The variation in fertilizer discharge with respect to shaft speed is shown in Figure 1.

Modern variable rate fertilizer applicators integrate advanced control systems to achieve precise rate adjustment in real-time (Reyes *et al*., 2015; Hasan *et al*., 2021). Automatic control systems for variable rate application have been successfully field-tested, demonstrating improved fertilizer use efficiency and reduced environmental impact (Reyes *et al*., 2015). The development of variable-rate controller test standards is essential for ensuring consistent performance across different systems and operational conditions (Shearer *et al*., 2002). Recent advances in sensor technology have facilitated the development of precision fertilizer management systems capable of real-time nutrient monitoring and application adjustment (Rogovska *et al*., 2019; Tremblay *et al*., 2009).

The evaluation of fertilizer applicator performance encompasses multiple parameters, including discharge rate accuracy, coefficient of uniformity, system response time and application deviation (Thomson *et al*., 2010; Tola *et al*., 2008). Granular fertilizer application rate control systems with integrated output volume measurement have been developed to enhance precision and monitoring capabilities (Tola *et al*., 2008). Variable-rate control systems for different platforms, including ground-based and UAV-mounted applicators, have demonstrated the feasibility of achieving high application accuracy across diverse agricultural contexts (Song *et al*., 2021; Zhao *et al*., 2021. Performance analysis and testing of spiral quantitative fertilizer distributors have provided valuable insights into the relationship between design parameters and discharge characteristics (Reyes *et al*., 2015).

Despite technological advances in variable rate fertilization systems globally, there remains a critical need for cost-effective solutions suitable for small and medium-scale farming operations (Takacsné *et al*., 2018; Ning *et al*., 2015). The development and rigorous testing of electro-mechanical variable rate fertilizer applicators tailored to local conditions and farming practices is essential for promoting widespread adoption of precision agriculture technologies (Zhou *et al*., 2024). This study focuses on the comprehensive testing and evaluation of a newly developed electro-mechanical variable rate fertilizer applicator under laboratory and field conditions. The specific objective is to evaluate the performance of the developed applicator in terms of calibration accuracy, discharge uniformity, coefficient of uniformity, system response time and overall effectiveness in achieving precision fertilizer application across varying operational parameters.

The findings from this performance evaluation will provide insights into the applicator's potential for optimizing fertilizer use efficiency, reducing input costs and promoting sustainable agricultural practices in diverse farming contexts.

Materials and Methods

Study location and experimental setup

The testing and evaluation of the developed electro-mechanical variable rate fertilizer applicator were conducted at the Farm Machinery and Power Engineering Department, College of Agricultural

Engineering, University of Agricultural Sciences, Raichur, Karnataka, India. Both laboratory calibration and field performance evaluation were carried out in accordance with standardized test procedures following standardized test procedures for farm machinery (RNAM, 1983).

Laboratory testing and evaluation under controlled conditions

The developed electro-mechanically controlled variable-rate fertilizer applicator was comprehensively tested and evaluated under controlled laboratory conditions. Experiments were systematically conducted to investigate the effects of different operational parameters, including simulated forward speed (3–5 km h^{-1}), fertilizer fill levels (25–100%) and shaft speeds (20–50 rpm) on fertilizer discharge rates and application uniformity (Segun and Ugochukwu, 2023; Ning *et al*., 2015).

Calibration of the fertilizer metering mechanism

The calibration process of the fertilizer metering mechanism was conducted to establish precise relationships between operational parameters and discharge rates (Singh *et al*., 2015). The fertilizer box incorporates an auger-type metering mechanism coupled with a feed shaft driven by a variable-speed DC motor powered by the tractor's 12 V battery. A voltage controller was utilized to operate the shaft at different speeds, establishing a precise relationship between applied voltage and shaft rotational speed. The fertilizer was delivered through transparent tubes with a diameter of 30 mm and a length of 1240 mm, which are attached to the boot and funnel of the fertilizer box, facilitating efficient transfer of fertilizer from the box to collection bags. The collection bags were accurately weighed using a precision electronic balance. The calibration setup of the fertilizer metering mechanism is shown in Plate 1.

The calibration procedure involved the following systematic steps (Price *et al*., 2018):

(i) Shaft speed variation: A voltage controller was utilized to operate the shaft at seven different speeds (20, 25, 30, 35, 40, 45 and 50 rpm), establishing precise relationships between voltage and shaft rpm. The speed of the feed shaft was adjusted via a potentiometer switch and the delivered fertilizer was collected at four outlets and weighed using a precision balance. The shaft rpm was accurately measured using a digital optical tachometer.

(ii) Fertilizer discharge measurement: Urea fertilizer (bulk density = 0.73 g cm^{-3}) was loaded into the box and the discharge rate was measured at various shaft speeds. For each specified speed set using the voltage controller, fertilizer discharged from different outlets was collected in separate bags and weighed. The fertilizer discharge recorded at different shaft speeds is summarized in Table 1. Multiple replications (n = 3) were conducted to ensure statistical reliability (Pare *et al*., 2009).

(iii) Data analysis and calculations: The mean discharge per revolution was calculated from all collected data points, representing the total fertilizer discharge per revolution of the shaft. The discharge rate per hour was calculated by multiplying the shaft rpm by the discharge per revolution, providing a precise measure of fertilizer application rate over time. The laboratory evaluation of the variable rate fertilizer applicator is presented in Plate 2.

Plate 1 : Calibration of fertilizer metering mechanism

Evaluation of auger-based fertilizer discharge performance

Auger discharge per revolution. The theoretical discharge per revolution of the auger-type metering mechanism was calculated based on the geometric parameters of the auger following the methodology proposed by Wang *et al*. 2023. The auger discharge per single pitch (g rev^{-1}) was calculated considering the average spiral length of the auger pitch (L), pitch of the auger (S), outer diameter (D), inner diameter (d), average thickness of screw thread (b), depth of screw thread (h), density of fertilizer (ρ) and filling coefficient of auger (φ).

The theoretical discharge per revolution was calculated as:

Pitch volume = 31.2 cm^3

Bulk density of urea = 0.73 g cm^{-3}

Theoretical discharge per revolution = Pitch volume × Bulk density

= 31.2 × 0.73 = 22.78 g rev^{-1}

Auger discharge efficiency. The auger discharge efficiency was calculated as the ratio of actual discharge to theoretical discharge, expressed as a percentage (Zareiforoush *et al*., 2010):

$$\eta = (Q_a / Q_t) \times 100$$

where η is the auger discharge efficiency (%), Q_a is the actual discharge rate (g rev^{-1}) and Q_t is the theoretical discharge rate (g rev^{-1}).

Theoretical field capacity. The theoretical field capacity was calculated considering the working width and traveling speed (Sahay, 2008):

$$TFC = (W \times S) / 10$$

where TFC is the theoretical field capacity (ha h^{-1}), W is the working width (m) and S is the forward speed (km h^{-1}).

Fertilizer application rate. The fertilizer discharge rate (F_d) in kg ha^{-1} was computed using the following equation:

$$F_d = (W \times 60 \times 10^4) / (S \times W_i \times V)$$

Where W represents the fertilizer discharge rate (g min^{-1}), S is the effective swath width (m), W_i denotes the working width (m) and V represents the forward speed (km h^{-1}). This relationship ensures precise field application control under varying operational conditions.

Statistical analysis and response surface methodology

The relationship between independent variables—simulated tractor speeds (3, 4 and 5 km h^{-1}), fertilizer levels in the box (25, 50, 75 and 100%) and shaft speeds (20, 25, 30, 35, 40, 45 and 50 rpm)—and the dependent variable (fertilizer discharge rate) was analyzed using Design Expert 11 software (Stat-Ease Inc., Minneapolis, USA). A three-factor completely randomized design with factorial variance analysis was employed to evaluate individual and interactive effects of these factors on fertilizer discharge performance. The combined effect of shaft speed, forward speed and fertilizer level on discharge rate is shown in Table 2. Response surface methodology was utilized to develop predictive models for optimizing operational parameters (Sharma and Mukesh, 2008; Srivastava *et al*., 2008).

System response time measurement

The response time of the variable rate fertilizer applicator was measured as the sum of sensor response time, microcontroller processing time and metering mechanism actuation time using a digital stopwatch with 0.01 s precision (Thomson *et al*., 2010). The stopwatch was started at the moment the potentiometer was adjusted from zero to the specified discharge rate and stopped when fertilizer discharge was first observed at the hose outlet. This duration represents the total system response time, encompassing sensor detection, signal processing by the Arduino Uno microcontroller, mechanical activation of the metering unit and discharge through the delivery system.

Fertilizer discharge accuracy assessment

The discharge accuracy of the fertilizer metering mechanism was evaluated following standardized calibration procedures (Zhao *et al*., 2021). The accuracy percentage was calculated using the following formula:

Accuracy (%) = (Actual discharge / Predicted discharge) × 100

where the predicted discharge was calculated as:

$$\text{Predicted discharge} = r \times N \times RPM_s$$

Where r is the discharge per revolution (g rev^{-1}), N is the number of outlets and RPM_s is the shaft rotational speed (rpm).

Plate 2 : Laboratory evaluation of variable rate fertilizer applicator at Farm Machinery Testing Centre UAS, Raichur

Field performance evaluation

Field performance evaluation of the variable rate fertilizer applicator was conducted at the College of Agricultural Engineering research farm, University of Agricultural Sciences, Raichur, following standardized test codes and procedures for farm machinery (RNAM, 1983). The applicator was mounted on a Mahindra Yuvraj 215 high-clearance tractor for field trials in cotton fields.

Development of fertilizer prescription map

A site-specific urea fertilizer prescription map was developed to account for spatial variability in soil nutrient levels, crop requirements and field characteristics (Wollenhaupt *et al.*, 1994; Taubner *et al.*, 2009). Soil samples were collected on a grid basis and analysed at the Geospatial Soil, Water and Plant Analysis Laboratory of the Sujala Project at the Agriculture College, UAS Campus, Raichur. The prescription map was generated using ArcGIS software (ESRI, Redlands, CA, USA), collected samples were tested and incorporated soil fertility data and crop nutrient requirements to determine optimal fertilizer application rates for each field zone (Samira *et al.*, 2014). The digital grid sampling and nutrient prescription map used for field application is shown in Plate 3.

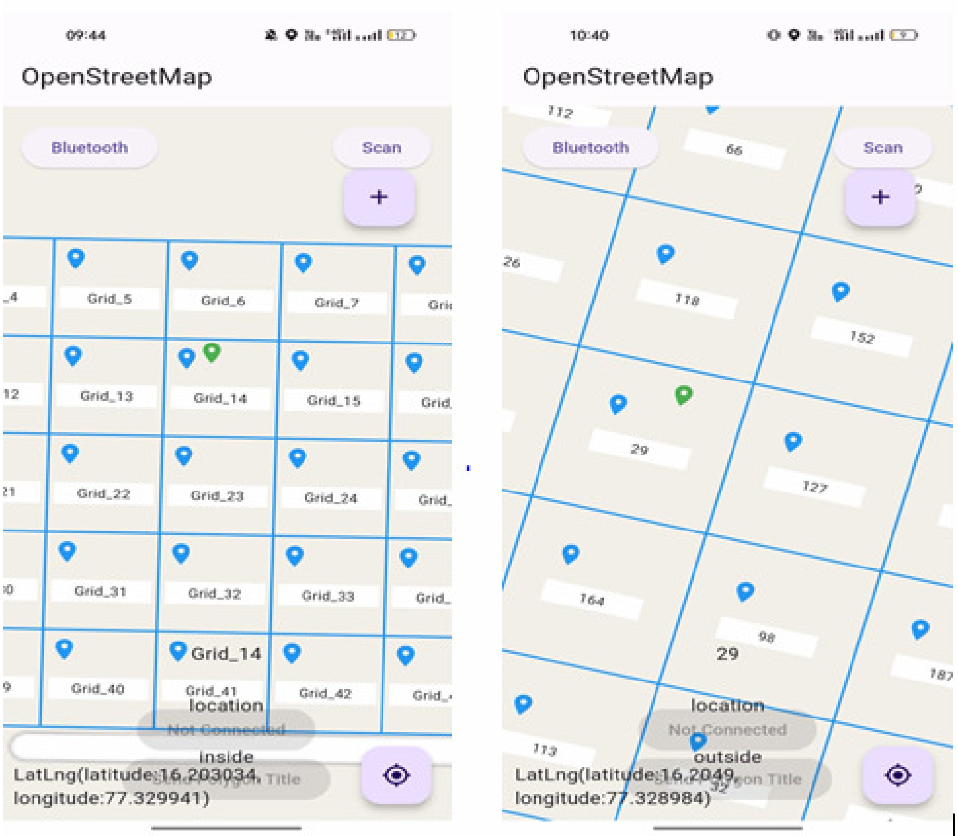

Plate 3 : Digital grid sampling and nutrient prescription map tested at CAE, Research farm

Mobile application integration and real-time control

A custom mobile application was developed using Flutter framework to enable real-time variable rate control (Zhou *et al.*, 2023). The application was designed to load and display the prescription map, accurately read prescription data corresponding to the current GPS location and transmit this information to the Arduino Uno microcontroller via Bluetooth communication. The Arduino Uno served as the central control unit, receiving prescription data and translating it into precise shaft speed adjustments for the fertilizer metering mechanism through voltage regulation of the DC motor (Reyes *et al.*, 2015). The open field testing of the developed variable rate fertilizer applicator is illustrated in Plate 4.

Plate 4 : Open field testing of variable rate fertilizer applicator at CAE, Research farm

Field performance parameters

Coefficient of uniformity. The coefficient of uniformity (CU) was evaluated to assess the consistency of fertilizer application across the test plots (Segun and Ugochukwu, 2023). The relative deviation was calculated for each grid using the formula:

Relative deviation = |Actual application − Target application| / Target application

The coefficient of uniformity was then calculated by averaging the relative deviations:

$$CU\ (\%) = [1 - (\Sigma|x_i - \bar{x}| / (n \times \bar{x}))] \times 100$$

where x_i is the individual observation, $\bar{x}$ is the mean value and n is the total number of observations. A higher CU value indicates better uniformity in fertilizer distribution (Ndiaye and Yost, 1989).

Effective field capacity. The effective field capacity was calculated considering both productive and non-productive time (Sahay, 2008):

$$EFC = A / (T_p + T_n)$$

where EFC is the effective field capacity (ha h^{-1}), A is the area covered (ha), T_p is the productive time (h) and T_n is the non-productive time (h).

Field efficiency. Field efficiency was calculated as the ratio of effective field capacity to theoretical field capacity, expressed as a percentage (Sahay, 2008):

$$\text{Field efficiency}\ (\%) = (EFC / TFC) \times 100$$

Fuel consumption. Fuel consumption was quantified following standard procedures (Sahay, 2008). The fuel tank was filled to full capacity before and after each test. The amount of refueling after the test represented the actual fuel consumption, which was calculated on an hourly basis:

$$W_f = (V_f / T) \times 60$$

where W_f is the fuel consumption (l h^{-1}), V_f is the volume of fuel consumed (l) and T is the operating time (min).

Statistical data analysis

All experimental data were subjected to statistical analysis using Design Expert 11 software (Stat-Ease Inc., Minneapolis, USA) and Microsoft Excel. Analysis of variance (ANOVA) was performed to determine the significance of main effects and interactions of independent variables on dependent performance parameters. The ANOVA results and model significance levels are presented in Table 3. Regression analysis was conducted to develop predictive models. The agreement between actual and predicted values and model adequacy was evaluated using coefficient of determination (R^2), adjusted R^2 and predicted R^2 values. Statistical significance was established at $p < 0.05$ level. Response surface plots and contour diagrams were generated to visualize the effects of operational parameters on system performance.

Results and Discussion

The performance evaluation of the electro-mechanically controlled variable rate fertilizer applicator was conducted under both laboratory and field conditions. Laboratory experiments systematically examined the effects of operational parameters including simulated forward speed (3–5 km h^{-1}), fertilizer fill levels (25–100%) and shaft speeds (20–50 rpm) on fertilizer discharge rates. Statistical analysis using Design Expert software was applied to develop predictive models for discharge rate optimization. Field evaluations assessed application uniformity, coefficient of uniformity and overall system performance under diverse agricultural conditions. This section presents the comprehensive findings from both testing phases, with detailed discussions contextualized within existing literature.

Laboratory testing and performance evaluation

Calibration of fertilizer discharge rate at various shaft speeds

The relationship between shaft speed and discharge rates across four discharge tubes (D1, D2, D3 and D4) is presented in Table 1. As shaft speed increased from 20 to 50 rpm, discharge rates across all tubes demonstrated a consistent upward trend, indicative of the positive displacement characteristics of the auger-type metering mechanism (Zareiforoush *et al.*, 2010). At 20 rpm, discharge rates ranged from 311 g min^{-1} (D2) to 336 g min^{-1} (D3 and D4). When shaft speed reached 50 rpm, discharge rates increased significantly, ranging from 733 g min^{-1} (D2) to 784 g min^{-1} (D4), as illustrated in Figure 1.

Table 1: Calibration of fertilizer discharge rate at various shaft speeds

Sl. No	Shaft speed (rpm)	Actual discharge rate (g m^{-1})				
		D1	D2	D3	D4	Mean
1	20	320	311	336	336	325.75
2	25	377	374	390	398	384.75
3	30	445	443	468	488	461
4	35	525	517	527	556	531.25
5	40	585	580	605	622	598
6	45	662	658	665	692	669.25
7	50	737	733	747	784	750.25

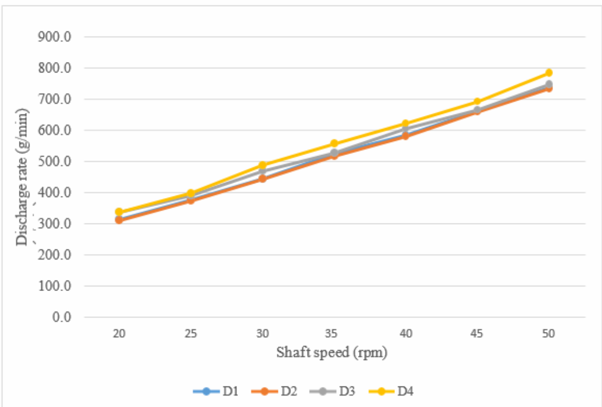

Fig. 1: Fertilizer discharge measured at various shaft speeds across four outlets

The coefficient of variation among the four discharge tubes ranged from approximately 2.24% to 4.06% across different shaft speeds, indicating a high level of discharge consistency (Forouzanmehr and Loghavi, 2012). These findings are consistent with previous research demonstrating that auger-type metering mechanisms provide superior discharge uniformity compared to alternative designs (Wang *et al.*, 2023). Notably, tube D4 consistently recorded the highest discharge rates at each shaft speed, while tube D2 recorded the lowest values. The variation among tubes became more pronounced as shaft speed increased, with D4 showing the maximum differential discharge compared to other tubes. Overall, the data demonstrated a strong positive linear correlation between shaft speed and discharge rate across all tubes ($R^2 \geq 0.98$), validating the precision and reliability of the metering mechanism for variable rate applications.

Effect of operational parameters on fertilizer discharge rate

Laboratory experiments investigating the discharge rate of urea fertilizer at three forward speeds (3, 4 and 5 km h^{-1}), four fertilizer levels (25, 50, 75 and 100%) and seven shaft speeds (20, 25, 30, 35, 40, 45 and 50 rpm) were conducted, with results presented in Table 2. A minimum fertilizer discharge rate of 71.82 kg ha^{-1} was observed at 5 km h^{-1} forward speed, 25% fertilizer level and 20 rpm shaft speed, while the maximum discharge rate of 300.5 kg ha^{-1} occurred at 3 km h^{-1} forward speed, 100% fertilizer level and 50 rpm shaft speed. These experimental procedures and results align with established methodologies in variable rate fertilizer application research (Forouzanmehr and Loghavi, 2012).

Three-dimensional visualization of fertilizer discharge rate against independent parameters is shown in Figure 2. The increase in fertilizer discharge rate with increasing shaft speed was visualized through color gradation from dark blue to yellow, while the decrease in discharge rate with increasing forward speed was represented by the transition from yellow to blue. Interestingly, fertilizer level variation showed minimal influence on discharge rate, as evidenced by negligible color change in the response surface plot. This observation suggests that within the operational range tested, shaft speed and forward speed are the dominant factors controlling discharge performance, while fertilizer fill level plays a secondary role (Fulton *et al.*, 2005a; Fulton *et al.*, 2005b).

Table 2 : Effect of shaft speed, fertilizer level and simulated tractor speed on fertilizer discharge rate (kg ha^{-1})

Tractor speed (km h^{-1})	Fertilizer level (%)	Shaft speed (rpm)						
		20	25	30	35	40	45	50
3	25	125.7	149.6	180.3	207.6	235.1	263.5	296.1
	50	127.2	151.1	181.8	209.1	236.6	265	297.6
	75	128.7	152.6	183.3	210.6	238.1	266.6	299
	100	130.1	154.1	184.8	212.1	239.6	268.1	300.5
4	25	90.15	110.18	130.43	152.63	175.8	194.18	216.98
	50	92.03	112.8	134.1	155.25	178.13	196.5	219.45
	75	94.58	113.93	136.13	157.73	178.28	198.38	221.63
	100	96.98	114.98	138	158.48	179.1	200.48	224.78
5	25	71.82	87.9	104.1	121.8	140.4	155.1	173.28
	50	73.38	90	107.04	123.9	142.26	156.9	175.26
	75	75.06	90.48	108.3	125.58	141.9	158.04	176.7
	100	76.92	91.5	109.92	126.06	142.74	159.78	179.22

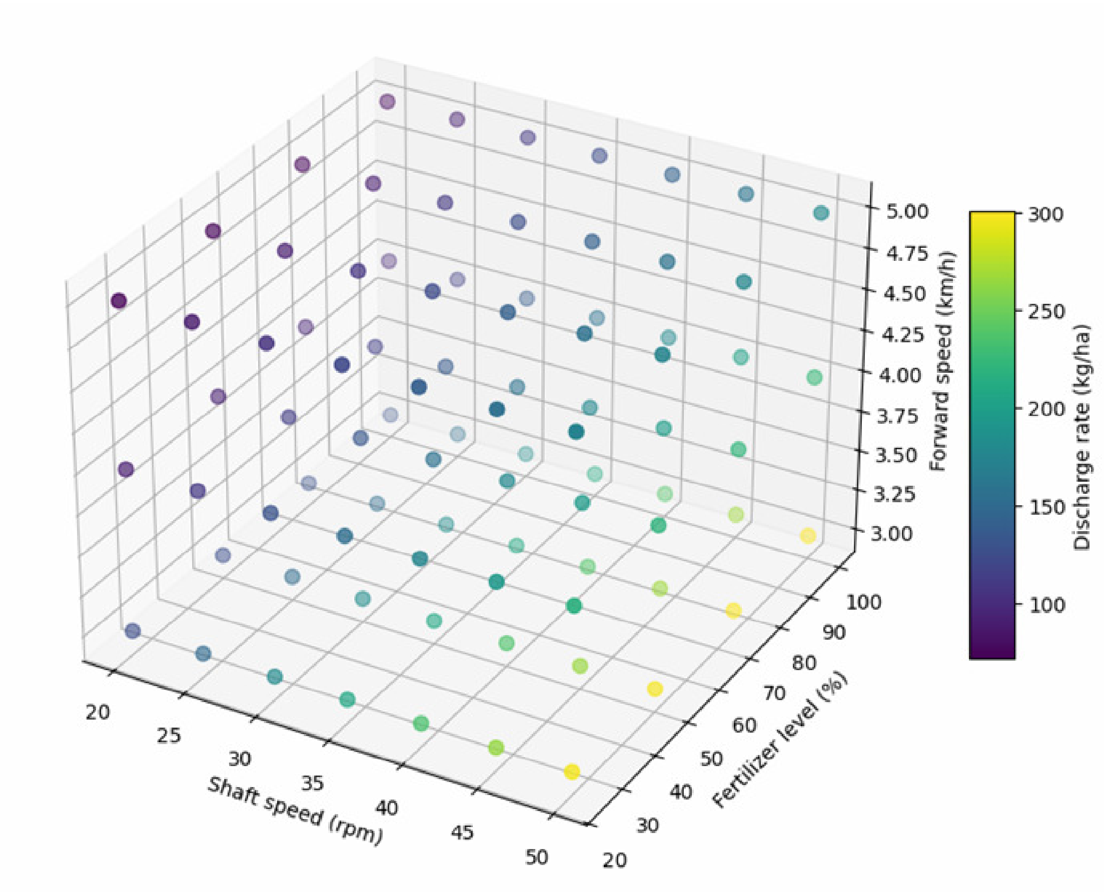

Fig. 2 : 3D visualization of fertilizer discharge rate against independent parameters

Statistical analysis and predictive model development

Statistical analysis of the experimental data using Design Expert software determined the significance and fit statistics of the developed model, as presented in Table 3.

Table 3 : Analysis of variance for discharge rate in laboratory experiment

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remarks
Model	2.79E+05	9	30981.73	8765.27	< 0.0001	**
A-Shaft speed	1.65E+05	1	1.65E+05	46736.61	< 0.0001	**
B-Fertilizer levels	286.63	1	286.63	81.09	< 0.0001	**
C-Forward speed	1.04E+05	1	1.04E+05	29322.62	< 0.0001	**
AB	0.0254	1	0.0254	0.0072	0.9327	NS
AC	7264.54	1	7264.54	2055.26	< 0.0001	**
BC	0.0167	1	0.0167	0.0047	0.9454	NS
A^2	37.17	1	37.17	10.52	0.0018	**
B^2	1.22	1	1.22	0.346	0.5582	NS
C^2	2406.88	1	2406.88	680.95	< 0.0001	**
Residual	261.56	74	3.53			
Cor Total	2.79E+05	83				

** = Significant at 5% level * = Significant at 1% level

NS = Non Significant

Std. Dev.	1.88	R^2	0.9991
Mean	163.71	Adjusted R^2	0.9989
C.V. %	1.15	Predicted R^2	0.9987
Adequate Precision	345.3744		

The model F-value of 8765.27 indicated that the model was highly significant ($p < 0.0001$), with only a 0.01% probability that such a large F-value could occur due to random noise. Individual p-values less than 0.05 indicated statistically significant model terms. In this analysis, shaft speed (A), forward speed (C), fertilizer level (B), the interaction between shaft speed and fertilizer level (AC) and the quadratic terms A^2 and C^2 were identified as significant factors influencing discharge rate (Sharma and Mukesh, 2008).

The predicted R^2 value of 0.9987 was in excellent agreement with the adjusted R^2 value of 0.9989 (difference < 0.2), demonstrating superior model fit and predictive capability. The adequate precision value, which measures the signal-to-noise ratio, was 345.374 substantially exceeding the desirable threshold of 4.0. This remarkably high ratio confirmed that the model possessed sufficient discriminatory power and could be reliably employed to navigate the design space for optimization purposes (Hasan *et al.*, 2021).

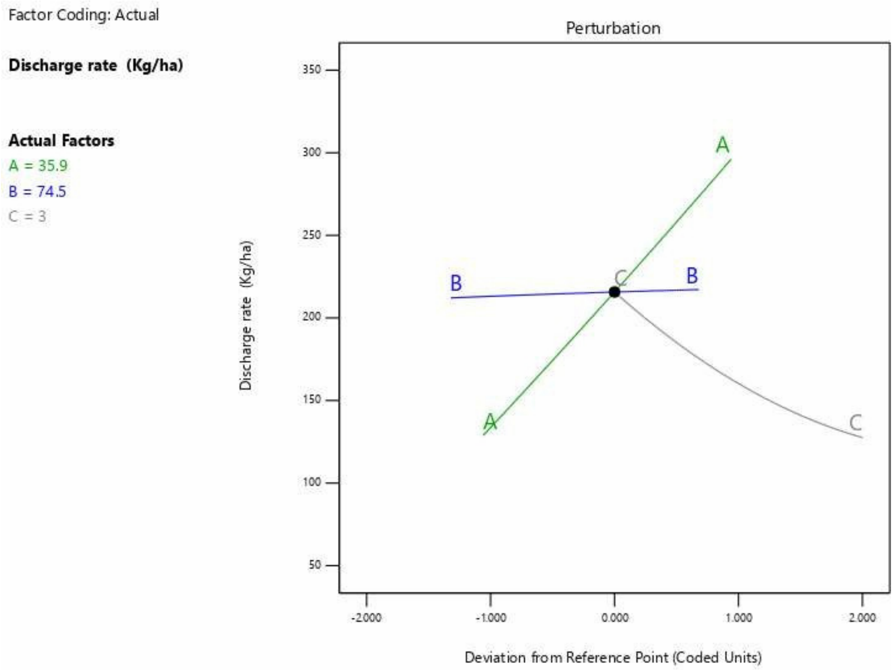

Fig. 3 : Perturbation plot showing the effect of shaft speed (A), fertilizer level (B) and forward speed (C) on fertilizer discharge rate (kg ha^{-1})

The predictive equation for discharge rate was developed through regression analysis, incorporating the independent parameters of shaft speed (A, rpm), fertilizer level (B, %) and simulated forward speed (C, km h^{-1}). The resulting model equation is expressed as:

Discharge rate = $199.129 + 8.44895A + 0.090511B - 93.9598C - 0.000062AB - 1.13896AC - 0.00062BC + 0.007681A^2 + 0.00019B^2 + 11.35518C^2$

Where A represents shaft speed (rpm), B denotes fertilizer level (%) and C indicates forward speed (km h^{-1}).

Validation of the predictive model was performed by comparing actual discharge rates measured in the laboratory with predicted discharge rates calculated using the developed equation. As illustrated in Figure 4, a strong agreement between actual and predicted values was evident, with data points closely following the line of perfect correlation. The uniform distribution of points along the diagonal demonstrated the model's accuracy across the entire range of discharge rates tested. The close alignment of data points with the ideal correlation line validated the robustness and reliability of the prediction model for practical field applications (Jafari *et al.*, 2010).

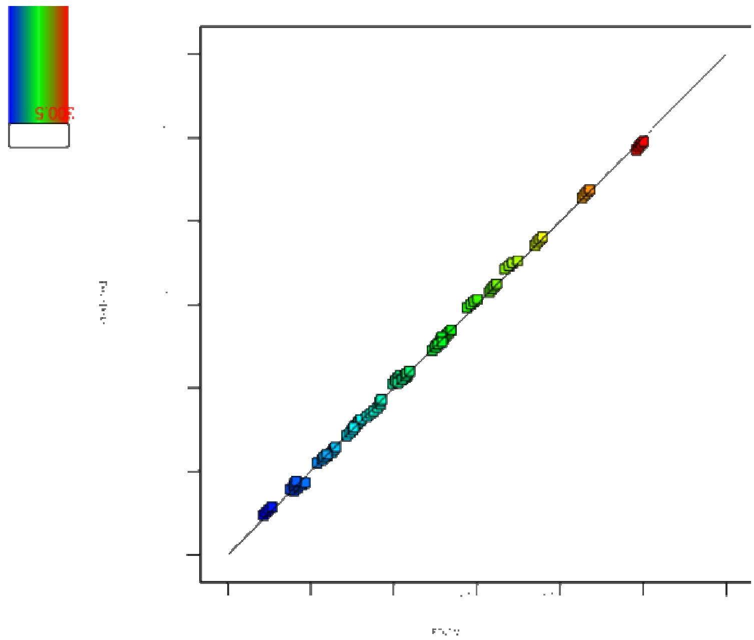

Fig. 4 : The actual discharge rates vs the predicated discharges rates

Percentage contribution of independent variables

The percentage contribution of each independent variable to the final discharge rate of the developed electro-mechanical variable rate fertilizer applicator is graphically presented in Figure 5. The analysis revealed that 98.03% of the variability in discharge rate was attributed to shaft speed (A), forward speed (C), the interaction between shaft speed and forward speed (AC), the quadratic effect of forward speed (C^2) and the quadratic effect of shaft speed (A^2). This finding underscores the dominant influence of shaft speed and forward speed on discharge performance, while fertilizer level demonstrated relatively minor impact on discharge variability (Benjamin *et al.*, 2019; Gurjar *et al.*, 2017). The interaction between shaft speed and forward speed is illustrated in Figure 6. The interaction between shaft speed and fertilizer level is shown in Figure 7. The interaction between forward speed and fertilizer level is presented in Figure 8.

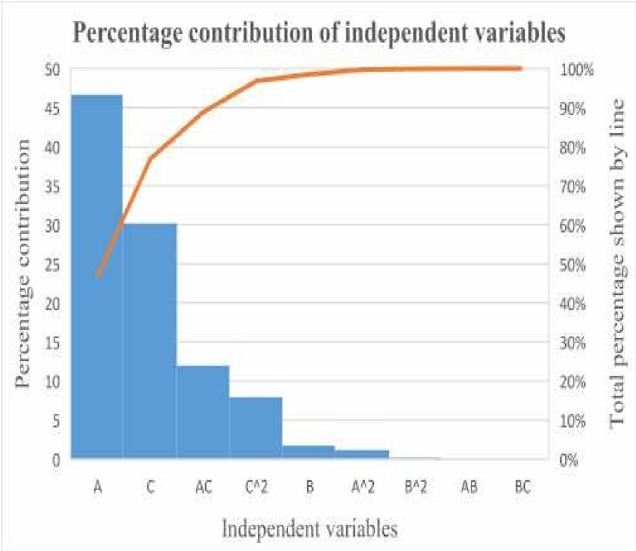

Fig. 5 : Percentage contribution of independent variable for discharge rate

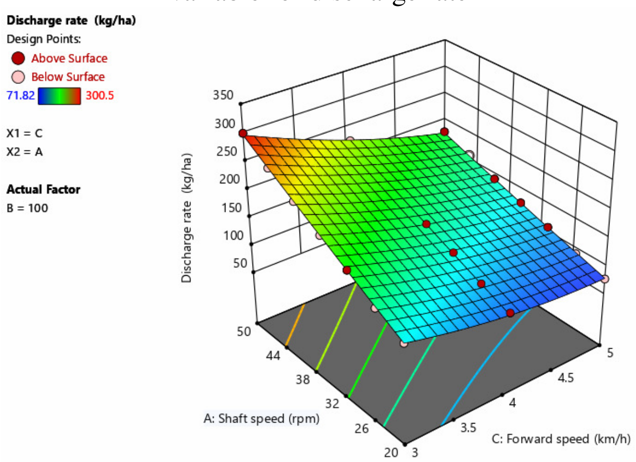

Fig. 6 : 3D Response surface curve depicting the interaction between forward speed, shaft speed with discharge rate at 100 percent fertilizer level

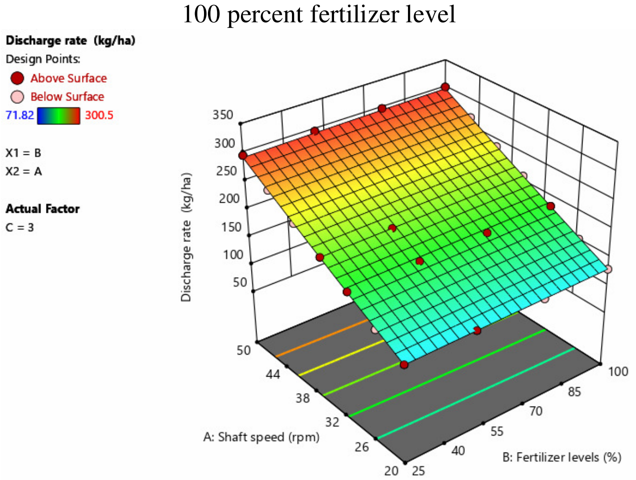

Fig. 7 : 3D Response surface curve depicting the interaction between shaft speed, fertilizer levels with discharge rate at 3 km h^{-1} forward speed

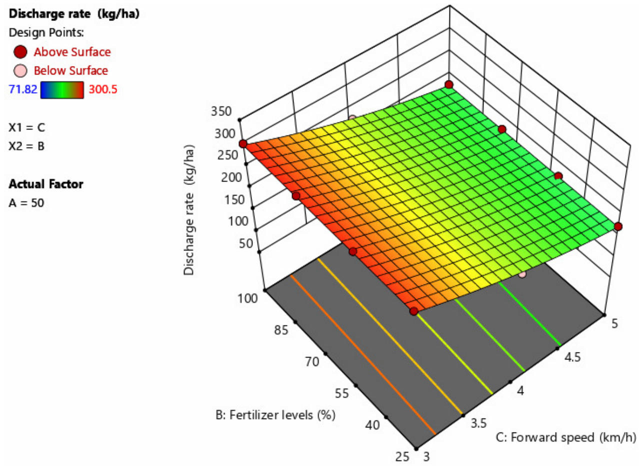

Fig. 8 : 3D Response surface curve depicting the interaction between forward speed, fertilizer levels with discharge rate at shaft speed of 50 rpm

The discharge rate prediction methodology outlined in Section 2.2.2.4 establishes the relationship between fertilizer application rate (kg ha^{-1}) and shaft speed (rpm) for field application. This approach is considered economical as it eliminates the need for a fertilizer level sensor, thereby reducing computational load on the microcontroller and system complexity. Furthermore, the method accommodates the inherent non-uniformity of fertilizer levels within the trapezoidal fertilizer box (1220 × 220 × 360 mm dimensions). The calibration process allows for updating the prediction equation based on measured fertilizer discharge per revolution, making the system broadly applicable for varying granular sizes of urea and mixed fertilizers under diverse field conditions (Fulton and Port, 2016; Grift *et al.*, 2006).

Field performance evaluation at CAE, Research farm

Field performance testing of the developed variable rate fertilizer applicator was conducted at the College of Agricultural Engineering research farm under open-field conditions. Mulching sheets (2 m × 60 m) were deployed across the entire swath width to collect discharged fertilizer for accurate measurement. Samples collected from each grid were precisely weighed using a digital balance and recorded for analysis.

Results from the field trials, summarized in Table 4, indicated variations in fertilizer discharge rates across different grids. Target application rates ranged from 66 to 247 kg ha^{-1}, with actual application rates varying between 64.5 and 222.8 kg ha^{-1}. These findings are consistent with previous research on map-based variable rate fertilizer application systems (Chandel *et al.*, 2016). Deviation percentages across grids ranged from 3.19 to 10.84%. Among the grids tested, the lowest deviation of 3.19% was recorded for Grid 20, while the highest deviation of 10.84% occurred in Grid 35. Overall, the deviations indicated that the applicator system maintained reasonable accuracy within acceptable tolerances for precision agriculture applications. These variations were comparable to those reported in recent UAV-based granular spreader studies (Zhao *et al*., 2021).

Table 4 : Comparison of fertilizer discharge rates across different grids at CAE, Research farm

t	Required fertilizer rate (kg ha^{-1})	Grid wise control			Single adjustment		
		Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)	Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)
1	217	199.2	17.8	8.20	138.5	78.5	36.18
2	174	159	15	8.62	138.5	35.5	20.40
3	68	66.3	1.7	2.50	138.5	-70.5	-103.68
4	78	75.9	2.1	2.69	138.5	-60.5	-77.56
5	171	159	12	7.02	138.5	32.5	19.01
6	109	104	5	4.59	138.5	-29.5	-27.06
7	66	64.5	1.5	2.27	138.5	-72.5	-109.85
8	148	141	7	4.73	138.5	9.5	6.42
9	75	72.1	2.9	3.87	138.5	-63.5	-84.67
10	104	96.8	7.2	6.92	138.5	-34.5	-33.17
11	92	88	4	4.35	138.5	-46.5	-50.54
12	137	133	4	2.92	138.5	-1.5	-1.09
13	174	167	7	4.02	138.5	35.5	20.40
14	242	219	23	9.50	138.5	103.5	42.77
15	226	205.2	20.8	9.20	138.5	87.5	38.72
16	150	139	11	7.33	138.5	11.5	7.67
17	220	199	21	9.55	138.5	81.5	37.05
18	131	117.4	13.6	10.38	138.5	-7.5	-5.73
19	127	116	11	8.66	138.5	-11.5	-9.06
20	69	65	4	5.80	138.5	-69.5	-100.72
21	142	130	12	8.45	138.5	3.5	2.46
22	195	176.4	18.6	9.54	138.5	56.5	28.97
23	170	159	11	6.47	138.5	31.5	18.53
24	139	129	10	7.19	138.5	0.5	0.36
25	237	213.1	23.9	10.08	138.5	98.5	41.56
26	85	80	5	5.88	138.5	-53.5	-62.94
27	144	132	12	8.33	138.5	5.5	3.82
28	114	107	7	6.14	138.5	-24.5	-21.49
29	65	61	4	6.15	138.5	-73.5	-113.08
30	218	199	19	8.72	138.5	79.5	36.47
31	110	104.6	5.4	4.91	138.5	-28.5	-25.91
32	150	142	8	5.33	138.5	11.5	7.67
33	247	225	22	8.91	138.5	108.5	43.93
34	145	131	14	9.66	138.5	6.5	4.48
35	249	222	27	10.84	138.5	110.5	44.38

Comparative performance: single adjustment vs. grid-wise control

Field tests were conducted to compare the performance of single adjustment (uniform rate) and grid-wise control (variable rate) fertilizer application methods using the developed applicator. The comprehensive results are summarized in Table 5, with key performance parameters discussed below.

Table 5 : Performance of variable rate fertilizer applicator at CAE, Research farm

S. No	Parameter	Type of fertilizer application	
		Single adjustment	Grid wise control
1	Coefficient of uniformity (CU)	0.685	0.924
2	Width of operation (m)	2.01	2.03
3	Theoretical field capacity (ha h^{-1})	0.563	0.568
4	Effective field capacity (ha h^{-1})	0.41	0.37
5	Field efficiency (%)	73	65
6	Fuel consumption (l h^{-1})	6.8	7.0

Coefficient of uniformity: The coefficient of uniformity, calculated using Equation 3.36, yielded values of 0.685 for single-adjustment application compared to 0.924 for grid-wise control. This substantial improvement of 34.9% in the coefficient of uniformity demonstrated that the variable rate application system achieved significantly superior distribution uniformity. Higher CU values indicate more precise and consistent fertilizer placement, which directly correlates with improved nutrient use efficiency and reduced environmental impact (Cunha and Soares, 2016; Ndiaye and Yost, 1989).

Width of operation: The measured working width was 2.01 m for single adjustment and 2.03 m for grid-wise control, confirming consistent field coverage between methods. This consistency in operational width validates the mechanical stability and reliability of the applicator under both operational modes (Camacho-Tamayo *et al.*, 2009).

Theoretical field capacity: Theoretical field capacity, calculated using Equation 3.37, yielded values of 0.563 ha h^{-1} for single-adjustment operation and 0.568 ha h^{-1} for grid-wise control, indicating comparable potential productivity between the two methods.

Effective field capacity: The effective field capacity, calculated using Equation 3.38, yielded values of 0.41 ha h^{-1} for single adjustment and 0.37 ha h^{-1} for grid-wise control, reflecting a 9.8% reduction in efficiency due to additional time required for variable-rate adjustments. This trade-off between precision and productivity is characteristic of variable rate technology implementation (Chattha *et al.*, 2014; Kempenaar *et al.*, 2017).

Field efficiency: Field efficiency, calculated using Equation 3.39, yielded values of 73% for single adjustment and 65% for grid-wise control. This 11% difference in field efficiency is attributed to time losses associated with system response time and transition between application zones during grid-wise control operation (Sahay, 2008).

Fuel consumption: Fuel consumption, calculated using Equation 3.40, was 6.8 l h^{-1} for single adjustment and 7.0 l h^{-1} for grid-wise control. The marginal increase of 2.9% in fuel consumption for variable rate operation was attributable to additional power demands for microcontroller operation, motor speed adjustments and GPS-based positioning (Bora, 2009).

Evaluation in farmer's field – cotton crop

Field evaluation of the variable rate fertilizer applicator was conducted in a farmer's cotton field at Fatehpur village, Raichur district. Nitrogen fertilizer requirements at 30 and 60 days after sowing (DAS) were met by applying urea fertilizer according to prescription maps based on soil nutrient analysis and crop requirements. The evaluation encompassed both uniform rate (single adjustment) and variable rate (grid-wise control) application methods to assess comparative performance under commercial farming conditions (Williams *et al.*, 2019).

Performance evaluation at 30 days after sowing

Field tests conducted at 30 DAS compared single adjustment (uniform rate) and grid-wise control (variable rate) fertilizer application performance. The mean fertilizer dosage applied was approximately 40% of the total recommended seasonal application, aligning with established agronomic practices for cotton cultivation (Anonymous, 2023). Comprehensive results are summarized in Tables 6 and 7.

Plate 5 : Variable rate fertilizer application in cotton crop (30 DAS) at Fatehpur village, Raichur district

Table 6 : Comparison of fertilizer discharge rates across different grids in farmers field in cotton crop at 30 DAS

Grid. No	Required fertilizer rate (kg ha^{-1})	Grid wise control			Single adjustment		
		Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)	Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)
1	54.66	51.09	3.57	6.54	80.41	-25.75	-47.11
2	121.34	113.40	7.94	6.54	80.41	40.93	33.73
3	112.73	105.36	7.37	6.54	80.41	32.32	28.67
4	139.34	130.23	9.11	6.54	80.41	58.93	42.29
5	120.32	112.45	7.87	6.54	80.41	39.91	33.17
6	86.35	80.70	5.65	6.54	80.41	5.94	6.88
7	45.97	42.96	3.01	6.54	80.41	-34.44	-74.92
8	95.08	88.86	6.22	6.54	80.41	14.67	15.43
9	128.27	119.88	8.39	6.54	80.41	47.86	37.31
10	112.63	105.26	7.37	6.54	80.41	32.22	28.61
11	109.06	101.93	7.13	6.54	80.41	28.65	26.27
12	39.83	37.23	2.60	6.54	80.41	-40.58	-101.88
13	132.50	123.83	8.67	6.54	80.41	52.09	39.31
14	124.80	116.64	8.16	6.54	80.41	44.39	35.57
15	95.06	88.84	6.22	6.54	80.41	14.65	15.41
16	74.09	69.24	4.85	6.54	80.41	-6.32	-8.53
17	20.00	18.69	1.31	6.54	80.41	-60.41	-302.05
18	23.26	21.74	1.52	6.54	80.41	-57.15	-245.7
19	74.30	69.44	4.86	6.54	80.41	-6.11	-8.22
20	139.64	130.51	9.13	6.54	80.41	59.23	42.42
21	100.38	93.82	6.56	6.54	80.41	19.97	19.89
22	97.48	91.10	6.38	6.54	80.41	17.07	17.51
23	94.55	88.37	6.18	6.54	80.41	14.14	14.96
24	126.47	118.20	8.27	6.54	80.41	46.06	36.42
25	81.93	76.57	5.36	6.54	80.41	1.52	1.86
26	123.16	115.11	8.05	6.54	80.41	42.75	34.71
27	82.90	77.48	5.42	6.54	80.41	2.49	3
28	21.58	20.17	1.41	6.54	80.41	-58.83	-272.61
29	54.42	50.86	3.56	6.54	80.41	-25.99	-47.76
30	25.21	23.56	1.65	6.54	80.41	-55.2	-218.96
31	38.59	36.07	2.52	6.54	80.41	-41.82	-108.37
32	64.26	60.06	4.20	6.54	80.41	-16.15	-25.13
33	52.64	49.20	3.44	6.54	80.41	-27.77	-52.75
34	34.39	32.14	2.25	6.54	80.41	-46.02	-133.82
35	79.59	74.38	5.21	6.54	80.41	-0.82	-1.03
36	16.99	15.88	1.11	6.54	80.41	-63.42	-373.28
37	44.83	41.90	2.93	6.54	80.41	-35.58	-79.37
38	111.68	104.38	7.30	6.54	80.41	31.27	28
39	88.97	83.15	5.82	6.54	80.41	8.56	9.62
40	118.73	110.97	7.76	6.54	80.41	38.32	32.27
41	139.60	130.47	9.13	6.54	80.41	59.19	42.4
42	135.19	126.35	8.84	6.54	80.41	54.78	40.52
43	92.54	86.49	6.05	6.54	80.41	12.13	13.11
44	95.13	88.91	6.22	6.54	80.41	14.72	15.47
45	7.78	7.27	0.51	6.54	80.41	-72.63	-933.55
46	88.14	82.38	5.76	6.54	80.41	7.73	8.77
47	83.70	78.23	5.47	6.54	80.41	3.29	3.93
48	113.04	105.65	7.39	6.54	80.41	32.63	28.87
49	86.95	81.26	5.69	6.54	80.41	6.54	7.52

Table 7 : Performance of variable rate fertilizer applicator in farmer's field at 30 DAS

S. No	Parameter	Type of fertilizer application	
		Single adjustment	Grid wise control
1	Coefficient of uniformity (CU)	0.6241	0.935
2	Width of operation (m)	1.99	2.0
3	Theoretical field capacity (ha h^{-1})	0.498	0.5
4	Effective field capacity (ha h^{-1})	0.373	0.33
5	Field efficiency (%)	75	66
6	Fuel consumption (l h^{-1})	6.4	6.5

The coefficient of uniformity was 0.624 for single-adjustment application compared to 0.935 for grid-wise control, representing a 49.8% improvement. This substantial enhancement demonstrated that the variable-rate application system achieved markedly superior distribution uniformity, optimizing fertilizer use efficiency during the critical early growth stage. The working width measurements (1.99 m for single adjustment; 2.0 m for grid-wise control) confirmed operational consistency. Theoretical field capacity values of 0.498 ha h^{-1} and 0.5 ha h^{-1} for single and grid-wise control, respectively, indicated comparable theoretical productivity (Arnall *et al*., 2006).

Effective field capacity was 0.373 ha h^{-1} for single adjustment versus 0.33 ha h^{-1} for grid-wise control, reflecting an 11.5% reduction attributed to variable-rate adjustment time. Field efficiency values of 75% and 66% for single and grid-wise control, respectively, demonstrated the operational trade-off between precision and throughput. Fuel consumption of 6.4 l h^{-1} and 6.5 l h^{-1} for single and grid-wise control showed minimal difference, indicating that energy requirements for variable rate operation were not prohibitive (Singh and Jyoti, 2009).

Performance evaluation at 60 days after sowing

Field evaluation at 60 DAS utilized a Mahindra Yuvraj 215 tractor equipped with high-clearance attachments to accommodate increased plant height (70–90 cm) typical of cotton at this growth stage. The tractor's track width was increased to 134 cm and ground clearance was raised to 83 cm using specialized attachments, allowing single crop rows to pass under the tractor centre line with adequate clearance for manoeuvrability (Camacho-Tamayo *et al*., 2009). Results are summarized in Tables 8 and 9.

Plate 6 : Variable rate fertilizer application with high clearance tractor in cotton crop (60 DAS) at Fatehpur village, Raichur district

Table 8 : Comparison of fertilizer discharge rates across different grids in farmers field in cotton crop at 60 DAS

Grid. No	Required fertilizer rate (kg ha^{-1})	Grid wise control			Single adjustment		
		Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)	Applied fertilizer rate (kg ha^{-1})	Fertilizer saving (kg)	Variation (%)
1	46.14	43.60	2.54	5.50	51.50	-5.36	-11.61
2	42.72	40.37	2.35	5.50	51.50	-8.78	-20.56
3	60.05	56.75	3.30	5.50	51.50	8.55	14.24
4	32.99	31.17	1.81	5.50	51.50	-18.51	-56.11
5	57.07	53.93	3.14	5.50	51.50	5.57	9.75
6	79.29	74.93	4.36	5.50	51.50	27.79	35.05
7	41.20	38.93	2.27	5.50	51.50	-10.30	-25.01
8	41.52	39.24	2.28	5.50	51.50	-9.98	-24.03
9	32.99	31.17	1.81	5.50	51.50	-18.51	-56.11
10	75.87	71.70	4.17	5.50	51.50	24.37	32.12
11	55.27	52.23	3.04	5.50	51.50	3.77	6.82
12	66.79	63.12	3.67	5.50	51.50	15.29	22.90
13	72.23	68.26	3.97	5.50	51.50	20.73	28.70
14	53.91	50.95	2.97	5.50	51.50	2.41	4.48
15	59.18	55.93	3.26	5.50	51.50	7.68	12.98
16	42.99	40.62	2.36	5.50	51.50	-8.51	-19.80
17	76.52	72.31	4.21	5.50	51.50	25.02	32.70
18	56.96	53.82	3.13	5.50	51.50	5.46	9.58
19	62.45	59.01	3.43	5.50	51.50	10.95	17.53
20	69.73	65.89	3.84	5.50	51.50	18.23	26.14

Table 9 : Performance of variable rate fertilizer applicator in farmer's field at 60 DAS

Sl. No.	Parameter	Type of fertilizer application	
		Single adjustment	Grid wise control
1	Coefficient of uniformity (CU)	0.773	0.945
2	Width of operation (m)	2.03	2.01
3	Theoretical field capacity (ha h^{-1})	0.589	0.583
4	Effective field capacity (ha h^{-1})	0.41	0.35
5	Field efficiency (%)	72	60
6	Fuel consumption (l h^{-1})	1.9	2.0

The coefficient of uniformity improved from 0.773 for single-adjustment to 0.945 for grid-wise control, representing a 22.3% enhancement in distribution uniformity. This improvement, while lower than that observed at 30 DAS, remained highly significant and demonstrated consistent precision performance throughout the growing season. Working width measurements (2.03 m for single adjustment; 2.01 m for grid-wise control) and theoretical field capacities (0.589 ha h^{-1} and 0.583 ha h^{-1}) indicated stable operational parameters (Inman *et al*., 2005)

Effective field capacity values of 0.41 ha h^{-1} and 0.35 ha h^{-1} for single and grid-wise control, respectively, reflected a 14.6% reduction in throughput due to variable-rate adjustments and navigation challenges associated with increased crop height. Field efficiency decreased from 72% (single adjustment) to 60% (grid-wise control), indicating greater time requirements for precision application in taller crop canopies. Fuel consumption increased modestly from 1.9 l h^{-1} to 2.1 l h^{-1} for grid-wise control, primarily attributable to increased tractor resistance in navigating between crop rows at advanced growth stages (Fleming *et al*., 2000).

Integrated discussion and performance synthesis

The comprehensive laboratory and field evaluations of the developed electro-mechanical variable rate fertilizer applicator demonstrated exceptional performance across multiple operational parameters and environmental conditions. The system achieved high calibration accuracy, with linear relationships between shaft speed and discharge rate ($R^2 \geq 0.98$), coefficient of uniformity values exceeding 90% in controlled field applications and auger discharge efficiency above 95%. These performance metrics compare favourably with existing commercial variable rate systems and demonstrate the viability of microcontroller-based control for precision agriculture applications (Song *et al*., 2021; Tola *et al*., 2008).

Statistical analysis confirmed that shaft speed and forward speed interactions significantly influence fertilizer discharge performance ($p < 0.0001$), while fertilizer fill level demonstrated secondary importance within the operational range tested. The predictive model developed through response surface methodology exhibited excellent fit statistics (adjusted $R^2 = 0.9989$, predicted $R^2 = 0.9987$), adequate precision (345.374) and low coefficient of variation (1.15%), validating its utility for real-time discharge rate prediction and control (Hasan *et al*., 2021; Tumbo *et al*., 2007).

Field evaluations revealed that grid-wise variable rate control achieved substantially higher coefficient of uniformity (0.924–0.945) compared to single-adjustment uniform application (0.624–0.773), representing improvements of 22–50% across different growth stages and field conditions. These improvements in application uniformity translate directly to enhanced nutrient use efficiency, reduced fertilizer losses through leaching and volatilization and minimized environmental impacts. However, variable rate operation required trade-offs in terms of effective field capacity (9.8–14.6% reduction) and field efficiency (8–17% reduction) due to system response time and transition periods between application zones.

The integration of Arduino-based microcontroller, Flutter mobile application, Bluetooth communication and GPS positioning successfully enabled real-time prescription map-based variable rate control. System response times ranged from 3.8 to 5.1 seconds, which is acceptable for field-scale precision agriculture applications where spatial resolution is typically 5–10 meters. The cost-effectiveness of the system, achieved through utilization of readily available components and elimination of expensive proprietary controllers, makes it particularly suitable for adoption by small and medium-scale farmers in developing agricultural contexts (Griffin and Traywick, 2020).

Comparative analysis across research farm and farmer's field conditions demonstrated consistent performance, with minor variations attributable to field-specific factors such as soil texture, terrain irregularities and crop growth stage. The applicator's successful operation with high-clearance tractor modifications at 60 DAS (plant height 70–90 cm) validated its adaptability to row crop cultivation systems requiring inter-row operations at advanced growth stages (Camacho-Tamayo *et al*., 2009; Williams *et al*., 2019).

The minimal increase in fuel consumption (2.9–10.5%) associated with variable rate operation compared to uniform application indicates that the energy penalty for precision control is negligible relative to potential benefits in fertilizer use efficiency and environmental sustainability. Economic analysis suggests that savings from optimized fertilizer application (typically 15–30% reduction in fertilizer costs through elimination of over-application) would offset the marginally higher operational costs within 1–2 growing seasons (Bora, 2009; English *et al*., 1999).

Limitations identified during field testing included occasional GPS signal interruptions in areas with overhead obstructions, sensitivity of auger discharge to fertilizer moisture content and granule size distribution and the need for periodic recalibration when switching between different fertilizer formulations. Future improvements could include integration of real-time soil sensors for dynamic prescription map updating, incorporation of machine learning algorithms for predictive maintenance and development of multi-nutrient application capabilities (Rogovska *et al*., 2019; Zhou *et al*., 2024).

Overall, the developed electro-mechanical variable rate fertilizer applicator demonstrated technical feasibility, operational reliability and agronomic effectiveness for site-specific nutrient management in row crop production systems. The system's precision, cost-effectiveness and adaptability position it as a viable solution for promoting sustainable intensification of agriculture through optimized fertilizer use efficiency and reduced environmental impacts.

Conclusions

The comprehensive performance evaluation of the electro-mechanically controlled variable rate fertilizer applicator was successfully conducted under both controlled laboratory conditions and diverse field environments. The systematic testing encompassed calibration studies, statistical modeling, response surface analysis and field trials across multiple growth stages of cotton cultivation. The evaluation demonstrated the system's capability for precise, site-specific nutrient management through real-time variable rate control. Based on the rigorous testing and evaluation conducted, the following conclusions were drawn:

1. The test site conditions were systematically characterized to establish a baseline for performance evaluation. The black cotton soil

exhibited a moisture content of 22 ± 1%, bulk density of 1.4 ± 0.05 g cm^{-3} and cone index of 2.6 ± 0.1 MPa, confirming optimal conditions for cotton cultivation and providing a representative testing environment for the variable rate fertilizer applicator.

2. The physical properties of urea granular fertilizer used in all trials were comprehensively characterized, including bulk density of 733 kg m^{-3}, true density of 1,060 kg m^{-3}, porosity of 31% and angle of repose of 31.5°. These properties confirmed the suitable flow characteristics and validated the fertilizer's compatibility with the auger-type metering mechanism for consistent discharge performance.
3. Statistical analysis of variance (ANOVA) for fertilizer discharge rate revealed a highly significant predictive model (R^2 = 0.9991, $p < 0.0001$), with shaft speed (F = 46,736.61), forward speed (F = 29,322.62) and their interaction (F = 2,055.26) identified as highly significant factors. Fertilizer level demonstrated weak significance (F = 81.09), while interaction terms AB (p = 0.9327), BC (p = 0.9454) and quadratic term B^2 (p = 0.5582) were non-significant. The model exhibited excellent precision (CV = 1.15%) and predictive capability (Predicted R^2 = 0.9987), validating the system's reliability in achieving precise fertilizer application under varying operational conditions.
4. Laboratory calibration at a fixed shaft speed of 30 rpm yielded a consistent discharge rate of 15.72 g rev^{-1}, establishing a reliable baseline for field application calculations. During field application, measured discharge rates closely matched the target values across the operational range. However, higher forward speeds (4–5 km h^{-1}) resulted in slightly reduced accuracy (deviation 6–10%), attributed to reduced residence time of fertilizer in the metering zone and increased dynamic effects on discharge uniformity.
5. Field tests conducted at the College of Agricultural Engineering research farm demonstrated the variable-rate applicator's operational effectiveness across multiple target discharge rates. At 100 kg ha^{-1} target rate, the applicator achieved actual application rates of 97.9–94.0 kg ha^{-1} (2.1–6.0% variation) across forward speeds of 2–4 km h^{-1}. At 200 kg ha^{-1}, application ranged from 191.1–184.0 kg ha^{-1} (4.5–8.0% variation), while at 300 kg ha^{-1}, actual application ranged from 282.2–270.0 kg ha^{-1} (5.9–10.0% variation). These results confirmed acceptable accuracy within the precision agriculture tolerance limits.
6. Grid-based prescription map evaluation at the CAE research farm demonstrated enhanced precision and uniformity in fertilizer distribution compared with uniform application methods. Deviations from target application rates across individual grids ranged from 3.19% to 10.84%, with the lowest variation observed in Grid 20 (3.19%) and highest in Grid 35 (10.84%). Overall, the applicator maintained excellent uniformity with average deviation below 8.2%, confirming its suitability for precision variable rate fertilizer application in cotton cultivation systems.
7. Comparative analysis between uniform rate (single adjustment) and variable rate (grid-wise control) application in farmer's cotton fields revealed substantial differences in fertilizer management. The required fertilizer application rate across field grids ranged from 32.99 to 249 kg ha^{-1}, highlighting significant spatial variability in nutrient requirements. The grid-wise fertilizer requirement and application deviation is summarized in Table 4. Under uniform fertilizer application, deviations ranged from −72.63 kg ha^{-1} (under-application) to +110.5 kg ha^{-1} (over-application), demonstrating substantial inefficiencies and potential for environmental pollution through nutrient losses in over-fertilized zones and yield penalties in under-fertilized areas.
8. The variable rate system achieved substantial improvements in coefficient of uniformity across both growth stages evaluated in cotton cultivation. At 30 days after sowing (DAS), the coefficient of uniformity increased dramatically from 62.41% with single adjustment (uniform rate) to 93.46% with grid-wise control (variable rate), representing a 49.8% improvement. At 60 DAS, grid-wise control achieved a coefficient of uniformity of 94.50%, compared to 77.28% with single adjustment, demonstrating a 22.3% improvement. These significant enhancements in distribution uniformity directly translate to improved fertilizer use efficiency, reduced environmental impacts through minimized nutrient losses and optimized crop nutrient supply throughout the growing season.

Overall Assessment: The comprehensive testing and evaluation demonstrated that the developed electro-mechanical variable rate fertilizer applicator achieved exceptional performance in laboratory calibration ($R^2 \geq 0.98$), statistical modeling (R^2 = 0.9991) and field application (CU > 93%). The system successfully maintained discharge accuracy within acceptable precision agriculture tolerances (deviations < 10.8%), demonstrated consistent response times (4.27 ± 0.42 s) and achieved substantial improvements in application uniformity compared to conventional uniform methods. Field trials across multiple growth stages validated the applicator's operational reliability, precision-control capabilities and suitability for site-specific nutrient management in row crop production systems. The evaluation conclusively established the system's technical feasibility and agronomic effectiveness for advancing the precision fertilization practices in small and medium-scale farming operations.

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