Evaluation of the Efficiency and the Performance of a Variable-Rate Chemical Fertilizer Spreader Using a GPS-Based Control System

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Abstract

Finned centrifugal disc fertilizer spreaders are widely used worldwide for distributing granular mineral fertilizers due to their simple construction and high operational efficiency. The investigation studied the effect of three parameters forward speed 9,12, and 15 km h^{-1}, disc rotational speed 500, 550, and 600 rpm, and fin angle 0, +25, and -25 degree on the performance of a GPS-controlled variable-rate fertilizer spreader at two application rates 25% and 75%, representing low and high fertilizer levels, respectively. The image processing was used to quantify fertilizer amounts instead of conventional methods. The results showed that both theoretical and effective field capacities increased with forward speed. The best uniformity (CV = 15.6%) was achieved at the forward speed of 12 km h^{-1}, disc speed of 550 rpm, and fin angle of –25° at 25% the gate opening, while values exceeding 170% were observed at 75% of the gate opening. Correlation analysis revealed strong positive relationships between forward speed and both theoretical and effective field capacities (r = 0.99), and between disc speed and most performance traits (r > 0.99). Operating costs ranged between 1395 and 1498 ID ha^{-1}. Overall, operating at a moderate forward speed, high disc speed, and medium fin angle provided an optimal balance between uniformity, efficiency, and economy. It was concluded that adjusting the forward speed, disc speed, and blade angle plays a crucial role in improving spread uniformity and work efficiency, it also that variable rate technologies can increase fertilizer distribution accuracy and reduce costs.

Introduction

With the world's population increasing and to address the global food crisis, grain production in countries must be increased through the introduction of innovative sustainable agricultural technologies, this is aimed at increasing soil fertility and crop yields while reducing carbon dioxide emissions and limiting environmental pollution (Ma *et al.,* 2024; Vakal *et al.,* 2023),. Mineral fertilizers consist of mineral salts and inorganic materials containing essential elements in the plant life cycle, such as nitrogen, phosphate, and potassium. Therefore, they are among the most important methods used to enrich the soil and achieve high productivity.(Ali and Al-Dolaimi, 2023;

Amer *et al.,* 2025). Due to the ease of operation and simple construction of their components, centrifugal chemical fertilizer spreaders are used globally, primarily for distributing granular fertilizers at high production capacities (Barłóg *et al.,* 2022). Optimal fertilizer use through the integration of modern technologies and innovations in the agricultural sector leads to increased production efficiency and reduced initial costs. To achieve this, the correct fertilizer rates must be applied at precise locations using these machines (Fulton *et al.*, 2003). Variable Rate Technology (VRT) is an effective system for applying inputs at specific rates, times, and locations, ensuring that all plants, despite spatial variations in location and soil characteristics within the field, receive the same amount of nutrients (Pawase *et al.,* 2023). VRT technology operates using spectral or self-analyzing sensors, or it utilizes systems based on pre-prepared descriptive maps using GPS, GIS, or similar software that performs spatial analysis and comparison (Almahdi *et al.,* 2019; Ess *et al.,* 2001). To reduce stress and noise on agricultural tractors and transmission components during farming operations, and to minimize environmental pollution and additional maintenance, it improves overall performance by using direct-drive electric motors that replace mechanical parts with high precision (Cai *et al.,* 2022; Li *et al.,* 2025). One of the most important principles of sustainable agriculture is the use and development of environmentally friendly and efficient technologies, which ensures the achievement of the global ambition to increase the quantity and quality of agricultural yields (Hachim and Jebur, 2022; Kachel *et al.,* 2020). Considerations affecting the performance of fertilizer spreaders during fertilization include the direction of movement of the mechanical unit, the spreader disc settings, the prescribed dosage, and the manufacturing limitations of the equipment used in the fertilization process (Barłóg *et al.,* 2022; Mankhi and Jebur, 2022). Numerous studies have been conducted in previous research on the relationships between the design and operational components of chemical fertilizer spreaders. These studies include the relationship between flow rate and the rotation speed of the spreading disc, the relationship between the position of the discharge opening and the landing position of fertilizer granules relative to the surface of the spreading disc, and other related studies *(*Mundhe *et al.,* 2023; Sharipov *et al.,* 2021). In Iraq, the problem lies in the fact that farmers often apply fertilizers at fixed rates. This is due to the limited research conducted on these processes and the lack of equipment necessary for variable-rate fertilizer application, which has led to increased costs and pollution. Therefore, it is essential to keep pace with global developments and integrate precision agriculture into agricultural fields to achieve sustainable resource use. The machine's performance was evaluated using image processing technology and according to the standards set by the American Society of Agricultural and Bioengineering Engineers (ASAE-S341.6, 2024; Shearer *et al.,* 2005). This study aims to investigate the effect of three key operating parameters, namely forward speed, disc rotation speed rpm, and fin angle, on the performance of a variable rate fertilizer spreader, controlled by (GPS), at two application rates (25% and 75%), representing low and high fertilizer levels, respectively.

Materials and Methods

The research was conducted in March 2025 at the experimental farm in Dhi Qar Governorate, Shatrah city, affiliated with the Agricultural Extension Department (31°27'22.25"N,

46°11'42.20"E). Field trials were conducted involving three operating factors: three forward speeds (9, 12 and 15 km h^{-1}), three angular speeds of the sawing disc (500, 550 and 600 rpm) and three angles of fin mounting on the disc (0°, +25°, and -25°) Figure 1, Evaluate the effect of these factors on several operational characteristics of a variable-rate fertilizer spreader. During the tests, the wind speeds ranged between 3 and 5 km. h^{-1}, and the relative humidity was recorded at 22-31%.

In the laboratories of the Ministry of Industry's Research and Development Department, tests were conducted to determine the mechanical properties of granular materials and their resistance to mechanical damage under static loads, in accordance with the standards of the American Society of Agricultural and Biological Engineers (ASAE-S368.4, 2006) standard, which is based on Hertzian contact stress equations 1. Used in solid mechanics, these tests were performed using a fully automated universal testing machine (Tach Tab Systems Instron), Figure 2. It works by applying pressure on the grains between two surfaces, the lower one being fixed and the upper one moving downwards until the grains fail to resist breaking. Urea fertilizer particle size distribution was determined according to the ASAE S281 standard, while the fertilizer spread width and the coefficient of variation (CV %) were measured following the ASAE S341.6 standard (USA), (Figure 3). The collection trays were handcrafted from 20 mm thick industrial foam (polystyrene) panels, measuring 50 × 50 cm, and placed at a total height of 25 cm above the ground (15 cm above the container base and 10 cm from the base to the ground), to reduce the mechanical impact on the fertilizer particles upon impact. The trays contained internal compartments made of cardboard, measuring 10 × 10 cm and 10 cm above the base, to reduce the possibility of particles bouncing off the container, in accordance with the specifications set forth in the aforementioned standard, Figure 4.
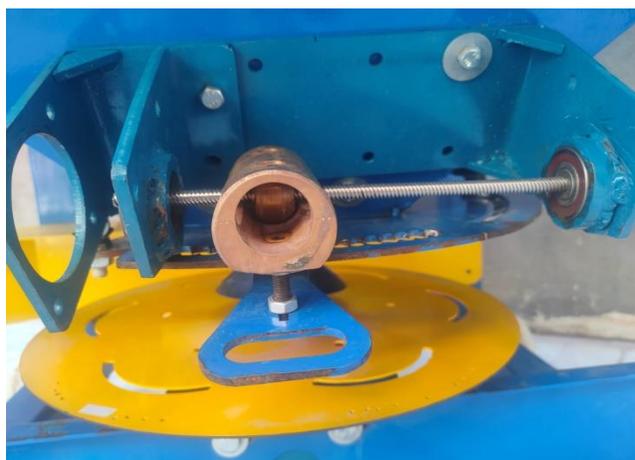

Figure 1. The disc of the spreader contains channels to move the wings at multiple angles

Figure 2. Testing machine (Tach Tab Systems Instron)

Figure 3. Arrange the bins to determine the fertilizer spread width behind the machine and the coefficient of variation according to ASAE S341.6

Figure 4. Boxes are designed according to ASAE S341.6

$$E = \frac{0.338F(1-\mu^2)}{D^{3/2}}\left[K_U\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{\frac{1}{3}} + K_L\left(\frac{1}{R_L}+\frac{1}{R'_U}\right)^{\frac{1}{3}}\right]^{\frac{3}{2}} \qquad (1)$$

Where:

E: Apparent modulus of elasticity.

F: Applied force.

D: Deformation or displacement.

μ: Poisson's ratio.

R_U, R'_U: Semicircular curvature of the upper surface at the point of contact.

R_L, R_L: Semicircular curvature of the lower surface at the point of contact.

K_U, K_L: Geometric constants that depend on the shape of surfaces

The Applied Machine

The equipment used is a Turkish-made centrifugal chemical fertilizer spreader, manufactured by AGRI SAGLAM Figure (5) (*Agrisaglam, n.d.*). The fertilizer spreader's control unit consists of two components: hardware Figure 6 and software required for machine operation. The control system includes a receiver (Node MCU CP2102) that communicates via Wi-Fi from Espressif Systems Co. to transmit essential data for the distributor's operation. This data includes the coordinates of the farm's outer boundaries, the size of the feed opening, and the distributor disc's rotational speed at each point-parameters pre-specified by the farm manager using an application accessed via a mobile communication device (phone, tablet, or computer) equipped with Wi-Fi. The communication device also receives and transmits coordinates from a GPS receiver type (GPS NEO-6M Module) (u-blox., 2025) to the control board (Arduino Mega 2560) (Ardunic, 2025), which controls the stepper motor via a stepper motor driver. The speed of the DC motor 180w *(*THT-Auto-Parts, 2025*)* is regulated using a high-power motor driver (BTS7960 IBT2 40A) (Ardunic, 2025), by varying the electrical current. The mixer operates continuously and is powered

directly from the main power source. A descriptive map was created using ArcGIS to represent the fertilizer spreading zones and to identify inflection points for feed rate and disc rotation speed. These points were determined using a Stonex GNSS 911 (Stonex., 2025) unit from the S9xx Professional series, which offers high precision with horizontal accuracy of approximately 0.0025 m and vertical accuracy of approximately 0.0035 m.

Figure 5. The application equipment used (AGRI SAGLAM)
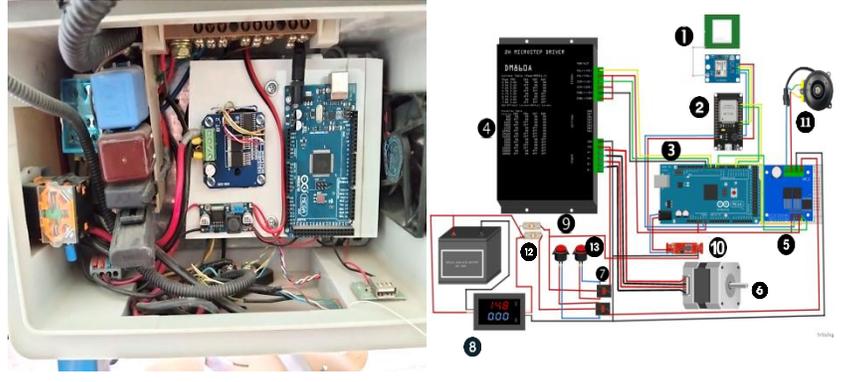

Figure 6. The hardware components of the control unit in the fertilizer spreader:
1. GPS sensor 2. Node MCU CP2102 board 3. Arduino Mega 2560 board 4. TB6600 Stepper Motor Driver 4A 5. BTS7960 IBT-2 Motor Driver 6. Stepper motor 7. Relay 8. DC voltmeter, current meter, and wattmeter 9. TB6600 Stepper Motor Driver 4A 10. Power transformer 11. Motor 12. Fuse 13. Electrical buttons.

Fertilizer spreader productivity (ha h⁻¹)

The theoretical field capacity for all treatments was calculated based on the specified forward speed and theoretical patch width of the machine equation 2. To determine the actual field capacity of the machine, the sawing operation was carried out in a field 83.33 m long and 120 m wide, equivalent to an area of 1 hectare equation 3. The rotation time at the end of each pass was estimated to be 17 seconds for all treatments. This time was added to the total operating time to obtain the actual field capacity of the machine equation 4, expressed in hectares per hour (ha h⁻¹), (Srivastava *et al.,* 1993b).

$$\text{TFC} = \frac{speed\,(\text{km h}^{-1}) \times width\,(\text{m})}{10} \quad (2)$$

Where: (TFC) is Theoretical Field Capacity (ha h⁻¹)

$$\text{EFC} = \frac{speed\,(\text{km h}^{-1}) \times widt\,(\text{m}) \times \eta_f}{10} \quad (3)$$

Where: (EFC) is Effective Field Capacity (ha hr⁻¹)

$$\eta_f = \frac{\tau_t}{\tau_e + \tau_h + \tau_a} \qquad (4)$$

Where: $\eta_f\%$: is Field efficiency. $\tau_e = \tau_t/Kw$: effective operating time (h). τ_t: theoretical time required to perform operation (h). Kw: fraction of implement width actually used. τ_a: time losses that are proportional to area (h). τ_h: time losses that are not proportional to area (h).

The parameters τ_a and τ_h represent two extremes of time losses, with some losses falling between them. τ_a **-type** losses include tasks like refilling or unclogging equipment, while τ_h **-type** losses relate to rest stops or adjustments during operation.

Fertilizer Spread Rate (kg m^{-2})

The test was conducted according to ASABE S341.6 standard, with the machine passing over bins arranged along the theoretical width, making a single pass over each bin during the composting process. The results were obtained using image processing technology, which photographed and analyzed the floor area within each bin's perimeter, calculated the amount of fertilizer within the bin's frame, and calculated the fertilizer application rate per square meter (ASAE-S341.6, 2024) .

The fertilizer application rate of a chemical fertilizer spreader can be simply defined as the amount of fertilizer distributed (kg) over the covered area (m²) equation 5, (Kweon and Grift, 2006).

Spreading Rate = Amount of fertilizer spread (kg) / Area covered (m²) $\qquad$ (5)

Or, in other words, depending on operating conditions, equation 6, (Segun and Ugochukwu, 2023):

$$\textbf{Spreading Rate} = \frac{Q}{W \times V} \qquad (6)$$

Where:
Q = Quantity of material dispersed (kg min^{-1}). W = Width of dispersion (m). V = Speed of movement (m min^{-1}).

Fertilizer Distribution Uniformity (%)

The coefficient of variation (CV) is defined as the percentage of the standard deviation to the arithmetic mean of the fertilizer quantity at the measurement points. The coefficient of variation is affected by several factors, including fertilizer type (density, particle size, uniformity), blade angle and disc speed (affecting the dispersal pattern), tractor forward speed (affecting the time and amount distributed), as well as wind and weather conditions (Kömekçi et al., 2024; Ou et al., 2025).

To calculate the mean equation 7, the standard deviation equation 8, and the coefficient of variation equation 9, (ASAE-S341.6, 2024):

$$\textbf{Mean} = \text{X} = \frac{\sum X_i}{N} \qquad (7)$$

$$\text{Standard deviation} = \left\{\frac{\sum[(X_i - X)^2]^{\frac{1}{2}}}{(N-1)}\right\} \quad (8)$$

$$\text{CV} = (\text{standard deviation})\frac{100}{X} \quad (9)$$

Where: X: is the arithmetic mean. Xi: is the accumulated sample weight for each collector location for the overlapped swaths. N: is the number of collector locations used.

Total Mechanical Unit Costs

Studying the total cost of agricultural equipment is a very important tool in effective financial planning in various agricultural projects, in terms of making decisions related to purchase, rental and replacement time. It is a critical instrument for obtaining greater economic efficiency, decreasing waste, and enhancing the profitability of agricultural operations (Vinayak *et al.,* 2022). The total cost study of agricultural equipment is intended to help farmers, farm managers, and decision makers make well-informed decisions on a number of topics, including assessing comprehensive costs, analyzing fixed costs (owning) like depreciation, interest (cost of capital), taxes, insurance, and fixed equipment like storage or shelter, and analysing operating costs (operating) like labour wages, fuel, oil, and lubrication, and maintenance and repair equation 10, (Akram *et al.,* 2024; Tajuddin *et al.,* 2023). According to the statistics in the ASABE standard, these statistics reflect typical values for tractor performance, equipment power requirements, and fixed and variable costs (ASAE-D497.7, 2011):

$$C = \frac{p}{h}\left(\frac{1}{a} + \frac{i}{2} + r + t\right) + (w \times e) + \frac{m}{144} \quad (10)$$

Where:
C: Machine operating cost (pounds per hour). p: Machine price. h: Number of annual operating hours. a: Machine productive life (years). i: Capital interest rate. t: Tax rate. r: Insurance rate. w: Horsepower or electrical power. e: Electricity or fuel consumption rate (pounds per horsepower. hour or kWh). m: Technical worker's monthly wage.

In addition to the above costs, there are expenses related to fuel and oil consumption. Field fuel consumption has been estimated to account for these costs and their relationship to the actual productivity of the machine, (Lotfy *et al.,* 2008):

Fuel consumption cost = Amount of fuel consumed (L h⁻¹) × Price per liter (Di L⁻¹)

Where the amount of fuel consumed was estimated in the field:

Oil consumption cost = Amount of oil consumed (L h⁻¹) × Price per liter (Di L⁻¹)

Where the amount of oil consumed (L h⁻¹) was calculated according to the equation, (Vinayak *et al.,* 2022):

Oil consumed cost = Fuel consumed cost (L h^{-1}) × 0.05

Image Analysis Algorithm for Fertilizer Particle Detection

A novel image processing approach was used to detect and count fertilizer granules, based on a "split and invade" strategy with adaptive optimization. Algorithms were designed to increase the accuracy of calculating the number of granules in areas with high fertilizer density, as well as to increase the calculation speed in areas with low density. A method was employed to divide the image into smaller sections after removing the outer edges of the captured images, providing greater flexibility than scanning the entire image. An algorithm was also used to identify the number of each bin and input the corresponding quantity of fertilizer into the final algorithm result. This combination of algorithms leads to more balanced and efficient performance. To enhance this method, a Nikon 5600 camera mounted on a 1-meter tripod, vertically positioned on the ground, was used. To increase the resolution of the captured images, an 18-55 mm lens was used. The purpose of employing image processing in this research is to reduce the effort required by traditional methods for calculating the weights of collected fertilizers in the collection device (Figure 7), which are involved in calculating most of the studied characteristics, such as the fertilizer dispersion rate, the applied quantity, and the coefficient of variation for homogeneity of distribution.
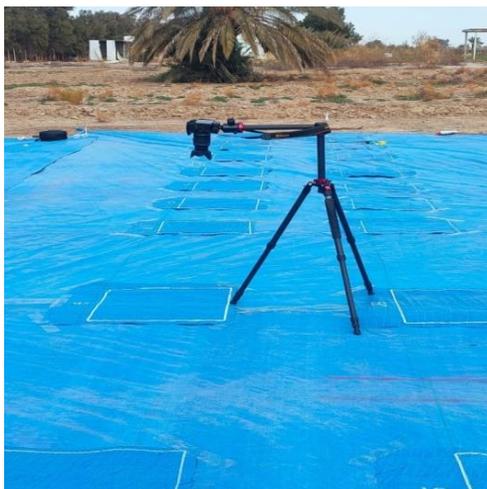

Figure 7. A Nikon 5600 camera positioned vertically at the location of the collection trays

Statistical Analysis

The experimental data were analyzed using GenStat 23.1 software according to a randomized complete block design (RCBD). Analysis of variance (ANOVA) was carried out to evaluate the effects of the studied factors and their interactions. Mean comparisons were performed using the Least Significant Difference (LSD) test at the 5% significance level ($p \leq 0.05$).

Results and Discussion

Fertilizer Spreader Productivity Rate (hr h^{-1})

The results of the analysis of variance (Table 1) showed that both forward speed and disc rotation speed had a significant effect (P < 0.01) on both the theoretical field capacity (TFC) and the effective field capacity (EFC). The highest theoretical productivity was recorded at the highest forward speed in the test, reaching 18.0 ha h^{-1} at 15 km h^{-1}, followed by 114.4 ha h^{-1} at 12 km h^{-1}, and then 10.8 ha h^{-1} at 9 km h^{-1}. The average theoretical productivity in the test was 14.4 ha h^{-1}. The same pattern was observed regarding the disc rotation speed. The highest average was recorded at 16.8 ha h^{-1} at 600 rpm, 14.4 ha h^{-1} at 550 rpm, and 12.0 ha h^{-1} at 500 rpm. This is attributed to the increased effective spread width with increasing disc rotation speed per minute. LSD testing indicated significant differences across all levels.

For effective field capacity, the overall average was 12.96 ha h^{-1}, with the highest value occurring at 15 km h^{-1} (15.78 ha h^{-1}), followed by 12 km h^{-1} (13.2 ha h^{-1}) and then 9 km h^{-1} (9.9 ha h^{-1}). Similarly, the 600 rpm (15.36 ha h^{-1}) disc speed outperformed 550 rpm (12.96 ha h^{-1}) and 500 rpm (10.56 ha h^{-1}), with significant differences observed across all levels. Blade mounting angle showed no significant effect, with P=0.99 values, indicating that blade angle did not affect the actual working width of the spreader (Srivastava *et al.,* 1993a).

Table 1. Effect of the forward Speed and disc rotational speed on the theoretical and actual capacity rate

Theoretical Field Capacity (ha h^{-1})			
Forward Speed (Km h^{-1})		Disc Rotational Speed (rpm)	
15	18.00 a*	600	16.80 a
12	14.40 b	550	14.40 b
9	10.80 c	500	12.00 c
LSD	1.36	LSD	1.36
Effective Field Capacity (ha h^{-1})			
Forward Speed (Km h^{-1})		Disc Rotational Speed (rpm)	
15	15.78 a	600	15.36 a
12	13.20 b	550	12.96 b
9	9.90 c	500	10.56 c
LSD	1.35	LSD	1.35

*Different letters (a, b, and c) within the same column indicate significant differences according to LSD at the 0.05 significance level.
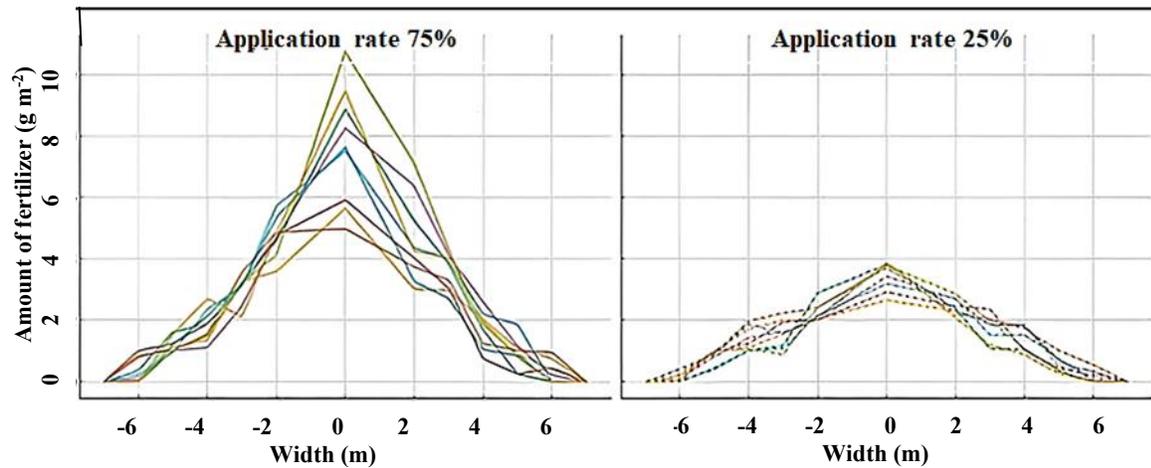
Figure 8. Fertilizer concentrations spread over the width of the work according to ASABE 341.6 standard by using image processing

Fertilizer Spread Rate (g m⁻²)

As shown in Figure 8, two graphs illustrate the distribution of fertilizer quantity in (g m⁻²) over the spread width (width in meters) at two different application rates: 75% (left) and 25% (right). At 75% of the application rate, the maximum fertilizer quantity was approximately 10.5 g m⁻² at the center of the spread (at zero on the horizontal axis). The distribution starts at approximately 0 g m⁻² at ±6.5 meters and gradually increases until it reaches 8-10.5 g m⁻² at the center (0 m). The curve tends to have a steep peak (fertilizer concentration is higher in the center, lower at the edges).

The three-way revealed a highly significant effect of forward speed on the mean fertilizer spread rate (F = 52.30, p < 0.001). Mean comparison showed that the low speed (9 km h⁻¹) achieved the highest value (1.051), followed by the medium speed (12 km h⁻¹) with 1.005, and the high speed (15 km h⁻¹) with 0.990. This indicates that reducing forward speed increases the spread rate due to the longer exposure time per unit area. Conversely, the differences within the scope of the study were not sufficient to produce measurable differences for both the number of disk rotations (F=0.66, P=0.199) and the blade fixation angle (F=1.67, P=0.167), therefore they did not have statistically significant effects. The interaction effects among factors were also insignificant, except for a marginal trend between forward speed and disc rotation (p = 0.089). Correlation analysis confirmed these trends: forward speed correlated negatively with spread rate at the 25% gate opening (r = –0.86 to –0.94) Figure 9, while the correlation was negligible at 75% (r = 0), indicating stable system performance under higher discharge rates. At the 75% gate opening, all main factors and interactions were statistically non-significant, with an overall mean of = 3.0 and minor deviations (< 0.1).
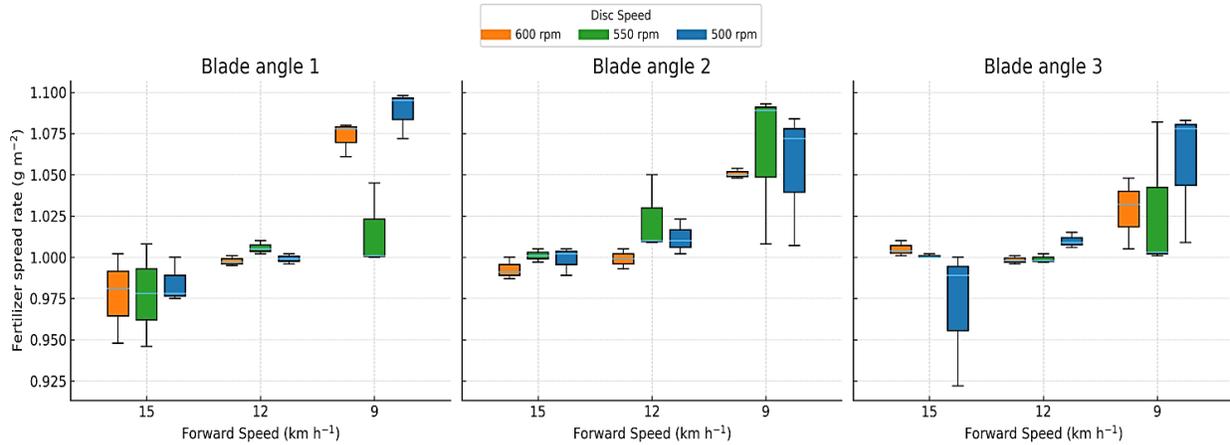
Blad angle 1 = 0, Blad angle 2= +25, Blad angle 3= -25

Figure 9. Interaction between Forward speed and Disc rotation speed at each blade angle on spreader rate (25%) Gate opening

Fertilizer Distribution Uniformity (%)

The results obtained are summarized in Table 2 and Figure 10, which shows the CV% values obtained when each of the studied factors was affected. The results of the statistical analysis confirmed the significant effect of all factors on the coefficient of variation, as values of $p < 0.05$ were recorded. At the 25% gate opening, the overall coefficient of variation (CV) averaged 28.3%. The lowest forward speed (9 km h^{-1}) produced the highest variability (36.75-40.32%), whereas increasing the speed to 15 km h^{-1} markedly improved uniformity, reducing CV to 16.50-23.97%. Disc rotational speed strongly influenced spread pattern uniformity; 600 rpm achieved the best results (19.18–26.58%, mean = 22.76%), while 500 rpm caused a significant increase in variation (30.97-41.57%, mean = 35.52%). We also observe that angle 0 recorded a CV% variance of 26.3, the highest achieved by the blade clamping factor. On the other hand, we note that opening the feed port to 75% resulted in an overall average CV%=74.2, a significant increase compared to 25% of the feed port. We observe that the disc rotations achieved average CV%= 35.6%, 62.8%, and 124% at speeds of 600, 550, and 500 rpm, respectively. However, angle 0 maintained the lowest CV%=61.1%, while angle -25° continued to record the highest CV%=86.6%. The results also revealed that the CV% was lowest when combining high forward speeds with an increased disc rotation across all blade clamping angles in the tests. Conversely, combining the lowest forward speeds with the fewest disc rotations across all clamping angles resulted in the highest CV%. An exceptional interaction was observed between the studied factors, where the combined effect of (12 km h^{-1}, 550 rpm, and -25°) resulted in a power variation coefficient (CV%=15.6), but it demonstrated high sensitivity to minor operational fluctuations.

The correlation coefficient between the CV and the studied factors (forward speed, disc rotation count, and blade clamping angle) was ($r = 0.94$, $r = 0.97$, and $r = 0.99$), respectively, indicating that disc rotation count is the strongest factor affecting the CV, and that blade clamping angle has a

significant impact even with minor adjustments. Overall, the CV more than doubled from 28.3% to 74.2% when the feed opening was changed from 25% to 75%. These results are consistent with those found in previous studies (Przywara *et al.,* 2020*;* Shi *et al., 2018*), emphasizing the need for precise control of disc dynamics in variable-rate fertilizer spreading systems.
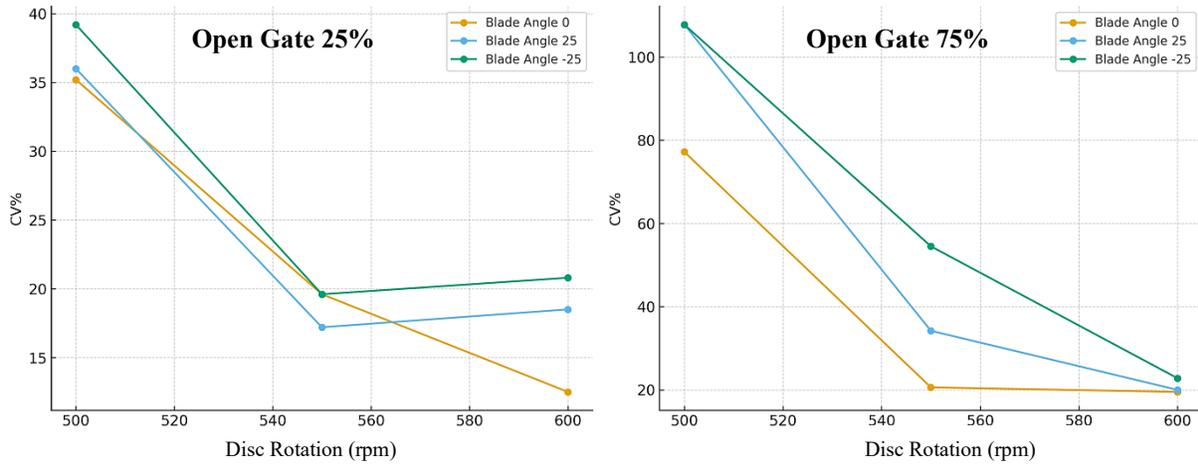

Figure 10. The relationship in the same forward speed (15 km h⁻¹) between Disc rotation speed and Blade Angle in Coefficient of Variation (CV) for both 25% and 75% Gate opening

Table 2. Summary of the Effect of Operational Factors on the Coefficient of Variation (CV) at 25% and 75% Fertilizer Application Rates

Factor	Gate Opening (%)	Observation
Forward Speed	25	(9 km h⁻¹) recorded the highest CV (36.75-40.32%), while (15 km h⁻¹) achieved the lowest CV (16.50–23.97%).
	75	The highest CV values (>150%) occurred mostly with (9 km h⁻¹) at low disc speeds, while (15 km h⁻¹) combined with (600 rpm) reduced CV to 18-37%.
Disc Rotation Speed	25	(600 rpm) produced the lowest CV (19.18-26.58%), whereas (500 rpm) showed the highest (30.97-41.57%).
	75	(600 rpm) remained most stable (mean 35.9%), followed by (550 rpm, 62.8%), while (500 rpm) resulted in extremely high variation (mean 124%, up to 214%).
Blade Angle	25	(0°) showed the lowest CV (≈26.3%), while (–25°) had the highest (=30-41%).
	75	(0°) maintained the lowest mean CV (61.1%), and (-25°) the highest (86.6%)

Total Mechanical Unit Costs

Table 3 shows the average total operating cost of a mechanized spreading unit, expressed in ID hr^{-1}. Statistical analysis revealed a significant effect ($p < 0.05$) of the tractor's forward speed on the total cost. Increasing the forward speed from 9 to 12 km h^{-1} resulted in a significant decrease in operating cost from 1477.68 to 1395.21 ID hr^{-1}, reflecting an improvement in economic efficiency due to an increase in effective field capacity (EFC) from 9.9 to 13.2 hr h^{-1}. However, the continuous increase in forward speed up to 15 km h^{-1} had the opposite effect, as operating costs rose again to 1498.15 ID ha^{-1} Figure 11, even though the actual field capacity reached its highest level of 15.77 ha h^{-1}. This indicates that the increased downtime in the field, coupled with increased fuel consumption and inconsistent spreading, led to higher expenses relative to production gains. Therefore, the results suggest that an average speed of 12 km h^{-1} is the optimal choice for achieving the lowest possible cost and the highest operational efficiency.

The statistical analysis also showed that operating costs were significantly affected by the number of disc revolutions. The results showed that operating costs increased considerably from 1202 to 1424 ID ha^{-1} when the number of revolutions was reduced from 600 to 550 rpm, and then reached 1746 ID ha^{-1} at 500 rpm. These results indicate that the decrease in the machine's actual production capacity led to increased operating costs. The results also indicated that the angle of blade assembly did not significantly affect the results ($p=0.99$).

Table 3. Effect of the studied factors and Average cost (ID hr^{-1})

Forward Speed (km h^{-1})	Blade Angle			EFC	Average cost (ID hr^{-1})
9	0	+25	-25	9.9	1477.68 b
12	0	+25	-25	13.2	1395.21 a
15	0	+25	-25	15.77	1498.15 c
Disc Rotation Speed (rpm)	**Blade Angle**			**EFC**	**Average cost (ID hr^{-1})**
500	0	+25	-25	10.56	1746.24 c
550	0	+25	-25	12.96	1423.75 b
600	0	+25	-25	15.35	1202.06 a

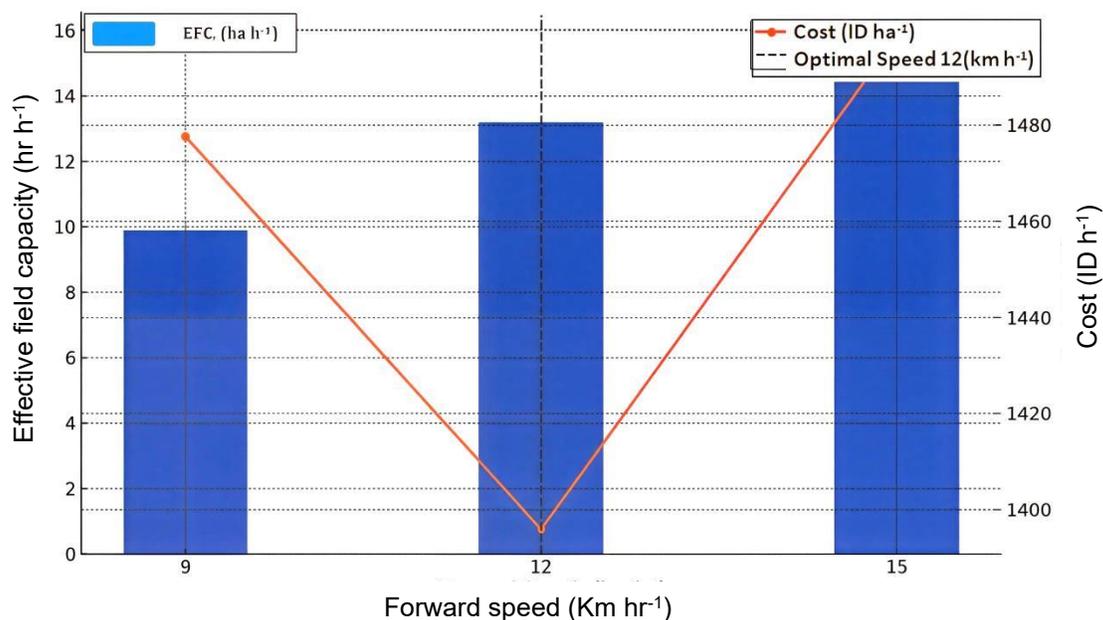**EFC:** Effective field capacity.

Figure 11. The relationship between forward speed, effective field capacity (EFC) and operating cost per hectare (ID hr⁻¹)

GPS data and image analysis

To determine the accuracy of fertilizer spreaders, the procedures of the ASABE S573 standard, "Test Procedures for Variable Rate Fertilizer Spreaders," were used. A descriptive application map was created using a STONEX GNSS precision positioning device to define the perimeter of a one-hectare field by marking eight points: four corner points and four midpoints. The field was divided into several panels of approximately equal dimensions, some representing high-rate and others low-rate zones. Twenty-one reference points, as shown in Figure 12, were identified using the precision positioning device to represent transition points between application rates. To demonstrate application accuracy, seven bins were placed on each panel, perpendicular to the machine's movement direction, to collect fertilizer granules during the fertilization process. This test determined the actual productivity and time losses of the machine within the field. The machine's application rate ranged between 96% and 98% of the target rate. The image processing system achieved an average accuracy of 97%.

Figure 12. GPS data and image analysis using geographic coordinates to identify points representing slabs located within the field boundaries. 21 internal points and 8 points representing the external boundaries of the field were identified

Conclusions

The results showed that the performance of the variable-rate fertilizer spreader is significantly affected by both the forward speed and the disc rotation speed, while the blade mounting angle did not have a significant impact on most of the measured operational characteristics. However, this factor played a significant role in improving the uniformity and consistency of fertilizer granule distribution behind the machine, which was clearly reflected in the coefficient of variation (CV%). The highest values for theoretical and effective field capacity were recorded at a forward speed of 15 km h^{-1} with a disc speed of 600 rpm, but this with low field efficiency (87%). Conversely, the best balance between actual productivity and field efficiency was recorded at an average speed of 12 km h^{-1}, reaching 13.2% for productivity and 0.91% for efficiency. The results also showed that the CV% variance factor was significantly affected by all studied factors, especially when the feed gate was open at a high percentage (75%). A high disc rotation speed of 600 rpm achieved the best uniformity when combined with a high forward speed of 15 km h^{-1}. At the high feed rate. Overall, confirm that the highest disc rotation speed (600 rpm) is the most important factor in fertilizer distribution uniformity. The average forward speed of the machine exemplifies a balance between accuracy, efficiency, and cost-effectiveness. These results highlight the potential of variable rate test (VRT) systems to enhance fertilizer application accuracy and operational efficiency.

Author Contribution

The first author conducted the experimental work, prepared the manuscript, and analyzed the data. The second author designed the study, supported the interpretation of the results, and reviewed the final manuscript.

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