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Experimental Study of Disc Fertilizer Spreader Performance

Artur Przywara [1], Francesco Santoro [2,*], Artur Kraszkiewicz [1], Anna Pecyna [3] and Simone Pascuzzi [2]

[1] Department of Machinery Exploitation and Management of Production Processes, University of Life Sciences in Lublin, 20-033 Lublin, Poland; artur.przywara@up.lublin.pl (A.P.); artur.kraszkiewicz@up.lublin.pl (A.K.)
[2] Department of Agricultural and Environmental Science, University of Bari Aldo Moro, Via Amendola 165/A, 70126 Bari, Italy; simone.pascuzzi@uniba.it
[3] Department of Technology Fundamentals, University of Life Sciences in Lublin, 20-033 Lublin, Poland; anna.pecyna@up.lublin.pl
* Correspondence: francesco.santoro@uniba.it; Tel.: +39-0805442474

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Abstract: We report the experimental results of tests aimed at assessing the effects of different settings on the mean radius of mineral fertilizer distribution using a disc fertilizer spreader. Our aim was to improve the performance of fertilizer distribution in sustainable agriculture. Three types of mineral fertilizers with different physical characteristics, commonly used in agriculture, were considered: urea, calcium ammonium nitrate and ammonium sulfate. A complete randomization method based on a four-factor experimental model was used to study the influence of the functional and operational parameters on the mean radius of fertilizer spread. Fixed model analysis of variance showed that fertilizer type, vane configuration and disc angular velocity explained 91.74% of the variance of the spread mean radius, while linear multiple regression analysis highlighted that the fertilizer dust fraction and disc angular velocity had an overall effect of 82.72%, the former showing an inverse correlation as high as 72.77%.

Keywords: mineral fertilizers; centrifugal spreading; spatial distribution

1. Introduction

The most common method for distributing dry mineral fertilizer is with a fertilizer spreader. In a sustainable framework, economic and political aspects also have to be considered in order to achieve the best possible maintenance of environmental and natural resources [1–3]. A sustainable economy requires the conservation and maintenance of the natural soil environment [4,5], in which the leading objective must be improvement of soil sorption properties and the maximum possible increase in humus content, which is influenced among other things by the soil cultivation method [6,7]. Many aspects of this issue depend on the plant cultivation technology, the subsequent processing phase [8–10] and how biomass used for energy production is stored [11–13]. In each of these areas, occupational safety is also important and requires farmers to specialize. This increases production quality, sustainability [14,15] and compliance with local and international regulations [16]. A major technical problem in agriculture, directly related to increasing production in sustainable agriculture, is optimization of the construction of agricultural machinery to increase its reliability and efficiency. Liquid [7] and granular fertilization are both greatly affected by the shape and uniformity of fertilizer distribution on the soil [17,18]. Fertilizing fields at the recommended doses, adjusted for soil nutrient content and plant requirements, is of paramount importance for obtaining high-quality crops without depleting the environment. Any error in the fertilization phase, such as excessive doses and wrong proportions of elements, can cause pollution and environmental degradation.

In this framework, mathematical models can be used to improve the performance of agrotechnical operations [19–22] by testing the different solutions for machinery with the given technical and operational characteristics. For mineral fertilizer spreaders, basic information on these characteristics is provided by tests of spread lateral and longitudinal unevenness. Research on uneven distribution of fertilizers is conducted around the world according to standardized methodological recommendations [23]. A quality assessment of mineral fertilization is first of all related to the transverse distribution of the fertilizer on the ground, in which the radius of the spreading field density plays an important role [24]. The distribution shape depends on three main factors: (i) the technical and operational characteristics of the machinery; (ii) the physical characteristics of the fertilizers; and (iii) the environmental conditions in which the process takes place. Regarding the machine construction characteristics and settings of the spreading discs, parameters like transverse and longitudinal absolute tilt of the machinery, vane angle and angular velocity are of paramount importance for machine performance and are hard to set because they depend on many factors, especially the physicochemical properties of fertilizers and the geometric and kinematic parameters of the discs. Mineral fertilizers used in agriculture have very different physical properties, which makes computer-aided numerical simulations necessary to develop accurate and reliable spreading tables. In turn, this numerical approach requires testing to determine the relationship between the specific parameters of fertilizer distribution and the factors affecting it.

The aim of the present study was to analyze the theoretical kinematic and dynamic aspects of the spreading process and to assess the role of disc settings that affect the radius of distribution for mineral fertilizers with different physical properties.

2. Materials and Methods

2.1. Theoretical Considerations

A spinning disc spreader consists of one or two rotating discs with two or more vanes mounted on them. The spreader has a hopper, usually cone shaped, above the disc(s) and the fertilizer is fed in a stream by gravity or by means of a conveyor mechanism to the disc(s). The disc distributes the fertilizer by throwing it away with velocities normally in the range 15–50 m·s^{-1}; for some spreaders the velocity may be up to 70 m·s^{-1}. These high velocities are required to obtain large effective working widths.

The important design factors of the spinning disc are disc radius (r_d), feed radius (r_0), pitch angle (β_0) of the vane, cone angle of the disc (a) and the shape of the vane (straight in the present case). The radius of the disc of most spreaders is 0.30–0.45 m. The angular velocity of most discs is 42–105 rad·s^{-1}. The feed radius determines the starting position of particles on the disc. The pitch angle is the angle between vane and the radial line. This angle has a large influence on particle motion. The cone angle is the angle between the disk surface and the horizontal plane. A positive cone angle (6° in the present case) means the particles are discharged with a vertical velocity component that usually projects the particles a longer distance.

The motion of a particle on a spinning disc can be described by a differential equation derived from the forces acting on the particle according to D'Alembert's Principle.

If m_p is the particle mass (kg) and g the acceleration due to gravity (m s^{-2}), we consider the following forces (Figure 1):

- weight $\left(F_g = m_p \cdot g\right)$; N
- centrifugal force $\left(F_{ce} = m_p \cdot \omega_d^2 \cdot r\right)$; N
- inertial force $\left(F_i = m_p \cdot \frac{d^2 x_v}{dt^2}\right)$; N
- Coriolis force $\left(F_{co} = 2 \cdot m_p \cdot \omega_d \cdot \frac{dx_v}{dt}\right)$; N

- friction $\left(F_f\right)$; N (Friction occurs when one of the above forces has a component perpendicular to the direction of motion).

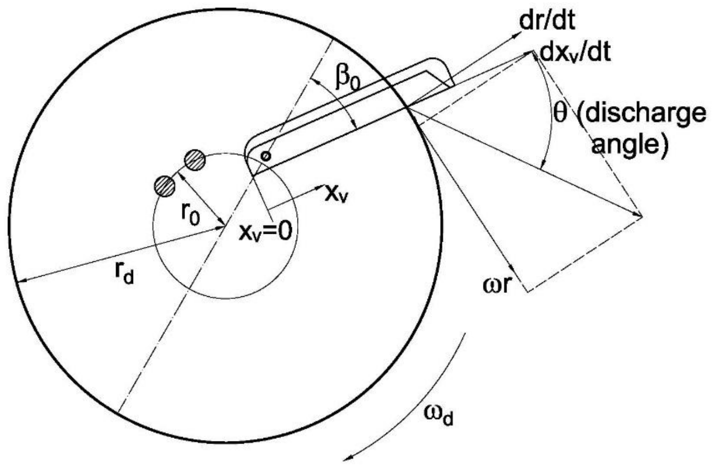


Figure 1. Geometry, kinematics and dynamics of a spinning disc fertilizer.

Depending on the following variables:

- Residence time: the time elapsing between the moment the particle begins to move on the disc and the moment the particle leaves the disc;
- Rotation angle of the disc: the angular rotation of the disc during the residence time;
- Tangential velocity: the circumferential velocity of the tip of the vane;
- Velocity along the vane $\left(\frac{dx_v}{dt}\right)$;
- Radial velocity: the velocity of the particle in a radial direction $\left(\frac{dr}{dt}\right)$.

The final result of the acceleration of particles along the vane of a spinning disc can be summarized by two main parameters:

- Discharge velocity: the absolute velocity at which the particle is discharged, equal to the vector addition of the velocity along the vane and the tangential velocity;
- Discharge angle: the angle between the radial direction and the discharge direction.

The coefficient of friction, a major physical property of fertilizer that affects the motion of particles on a disc, significantly influences the value of these parameters. An increase in the coefficient of friction results in an increase in residence time and a decrease in velocity along the vane. A lower velocity along the vane decreases the radial velocity, the discharge velocity and consequently the discharge angle. The magnitude of these effects is also greatly influenced by other parameters, such as the rotational velocity of the disc.

2.2. Esperimental Tests

Fertilizer spreading was studied in relation to the mean radius of spread. We developed a bench testing method for a single-disc spreader based on the literature and relevant compulsory standards. In particular, in line with EN 13739-2:2011 recommendations [25], the experiment was conducted in a suitably equipped indoor laboratory. Wind direction and speed were therefore not recorded. Relative humidity was 52.0–57.7% and temperature 13–17 °C in compliance with the said recommendations [25].

The test area, measuring 167.4 m^2, consisted of an array of 176 collection trays, each measuring 0.5 m × 0.5 m × 0.15 m (length × width × height), arranged in 11 rows and 16 columns, separated from each other by 0.5 m (2 in Figure 2). The spreader (Sipma RN 410-Antek, Lublin, Poland) was located almost in the middle of the first row, 0.7 m from the right lower edge of the first tray in Column 9 (1 in Figure 2). The center of the rotating disc was taken as the origin from which the fertilizer range was measured.

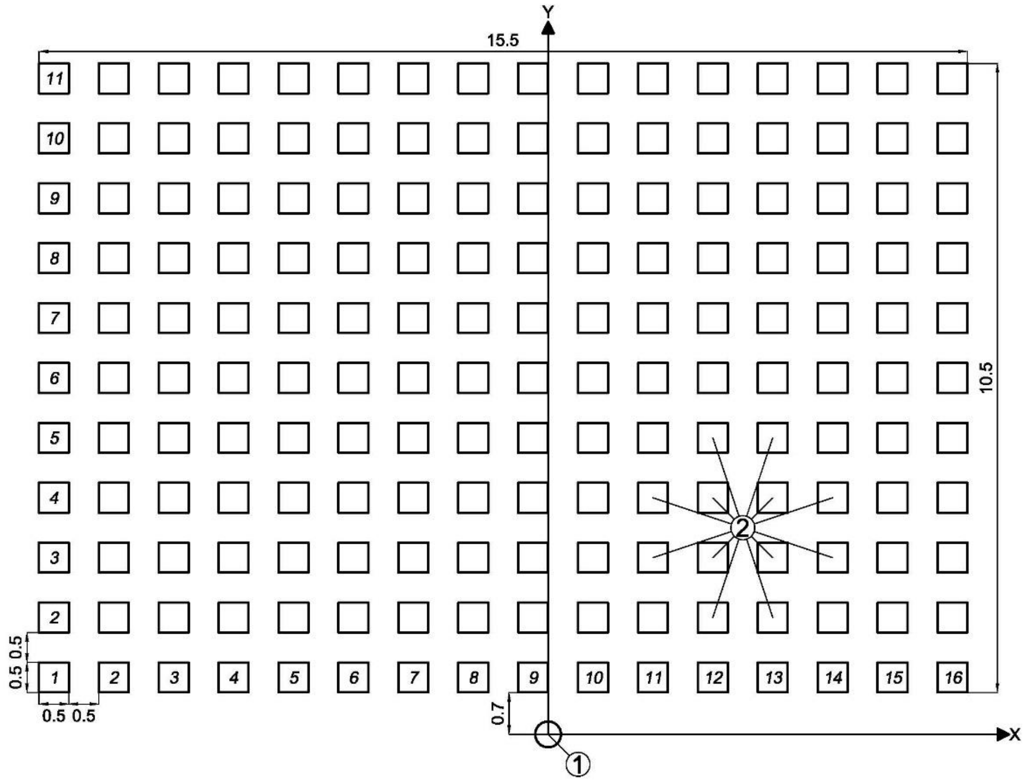


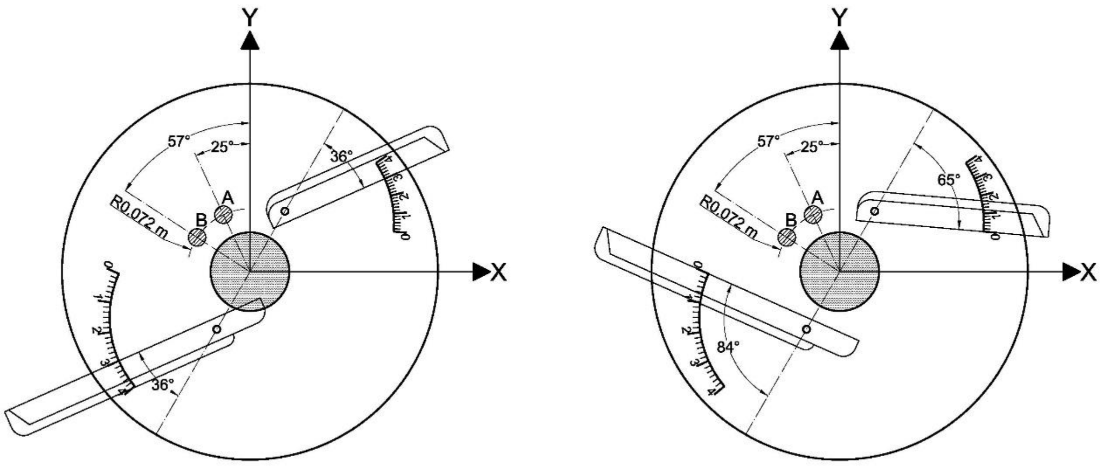
Figure 2. Scheme of experimental test site: (**1**) disc spreader; (**2**) collection trays.

The spreader was mounted on an experimental test stand (Figure 3) consisting of a frame, a hopper (capacity about 0.09 m^3) with a dosing outlet and a stirrer, a disc (diameter 0.43 m, concavity angle 6°) mounted 0.67 m from the ground, two electric motors (to drive the disc and the stirrer) and controls. The design allowed the parameters, such as the fertilizer feed point on the disc, the angular velocity of the disc and the pitch of the vanes, to be readily modified.

Figure 3. Disc spreader experimental test stand.

A complete randomization method based on a four-factor experimental model was used, in which the independent variables were disc angular velocity, vane settings on the disc, fertilizer feed point on the disc and types of mineral fertilizers. We tested two disc angular velocities of 42 rad·s^{-1} and 63 rad·s^{-1}, which are the most frequent in practice.

Two vanes, 0.32 m and 0.22 m long, were tested in two configurations: L3 and L0, respectively. In the L3 configuration, the angles between the two vanes and the imaginary line connecting the fixing point of each vane was 36° in both cases, whereas in L0 the angle was 65° for the shorter and 84° for the longer vane (Figure 4).



(**a**) (**b**)

Figure 4. Spreading disc showing the location of the fertilizer feed points A and B: (**a**) the L3 vane configuration; (**b**) the L0 vane configuration.

Technical solutions used in commercial spreaders conditioned our choice of the point where the fertilizer was fed onto the rotating disc. We tested two different feed points, both circular with a diameter of 0.02 m and located 0.1 m above the disc surface. Assuming a polar coordinate system with the origin at the disc center and the axis coinciding with the Oy axis in a Cartesian coordinate system, the centers of the projections of the two feed points on the disc had polar coordinates A(0.072 m, 25°) and B(0.072 m, 57°), as shown in Figure 4.

Three mineral fertilizers commonly used in agriculture were tested: (i) urea; (ii) calcium ammonium nitrate (CAN) and (iii) ammonium sulfate (AS). To assess the influence of the basic physical properties of the fertilizers on the multiple regression analysis used to evaluate the radius of spread, we determined the loose bulk density, bulk density after sieving and specific density with an Ultrapyc 1200e automatic gas pycnometer (Quantachrome- Boynton Beach, FL, USA), as well as the granulometric composition and the mass of the dusty fractions with an LPzE-2e sieve shaker (MULTISERW-Morek, Brzeźnica, Poland) in each case (Table 1).

Table 1. Physical properties of the mineral fertilizers.

Property	Fertilizer		
	Urea	**CAN**	**AS**
Bulk density (loose), kg·m^3	758	1029	1018
Bulk density (sieved), kg·m^3	789	1062	1104
Specific density, kg·m^3	1340	1800	1780
Mass powdery fraction (<1·10^{-3} m) , %	10.350	0.030	52.500
Median diameter d_{50}, 10^{-3} m	0.830	2.100	0.490

Considering all variables, including the three types of fertilizers, eight different combinations were tested. Each test was replicated three times to improve the statistical significance.

So that the results could be compared, a constant weight (13 kg) of fertilizer was used in the tests. The fertilizer flow rate through the dosing outlet depended on its properties (urea: 0.054 $kg{\cdot}s^{-1}$, test duration 241 s; CAN: 0.048 $kg{\cdot}s^{-1}$, test duration 271 s; and AS: 0.075 $kg{\cdot}s^{-1}$, test duration 173 s). At the end of each replicate, the mass of fertilizer collected in each tray was weighed with a PX3202/1 OHAUS Pioneer analytical balance. To evaluate the density of the fertilizer within the spreading field, we considered the mean radius of spread defined below. It should not be confused with the machine working width, which in the present case was at least as wide as the testing field.

To evaluate the mean radius of spread ($\overline{R}$), the following relationship was used [24]:

$$\overline{R} = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{m_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} m_{ij}} r_{ij}, \tag{1}$$

where,

n: number of testing field rows;
m: number of testing field columns;
m_{ij}: mass of fertilizer collected by tray at row i column j of testing field, kg;
r_{ij}: distance between center of tray at row i column j of the testing field and center of disc, m.

A significance level α = 0.05 was set for the multivariate analysis of variance of the fertilizer spreading mean radius constant model. The coefficient of determination R^2 was used to explain the variability of the dependent variable in the model. A multiple regression analysis with R version 4.0.2 software (R Foundation for Statistical Computing) was used to assess the relationships between the different variables.

We used a quadruple orthogonal cross classification model (m = 3) with observations in all subclasses to obtain an overall picture of the effects of the factors on the fertilizer distribution shape parameters, based on the following expression:

$$\left(\overline{R}\right)_{ijklm} = \mu + FT_i + DS_j + FP_k + VC_l + (FT.DS)_{ij} + (FT.FP)_{ik} + (FT.VC)_{il} + (DS.FP)_{jk} + (FP.VC)_{jl} + +(FP.VC)_{kl} + e_{ijklm} \\ (i = 1,2,3;\ j = 1,2; k = 1,2; l = 1,2; m = 1,2,3) \tag{2}$$

where,

$\left(\overline{R}\right)_{ijklm}$: m-th result of calculations of the mean fertilizer spread radius for the i-th fertilizer, the j-th angular velocity of disc, the k-th point of fertilizer feed onto the disc and the l-th vane configuration, m;
μ: general average of the population of fertilizer spread radius measurements, m;
FT: main effect of the i-th fertilizer;
DS: main effect of the j-th angular velocity of the disc;
FP: main effect of the k-th fertilizer feed point on the disc;
VC: main effect of the l-th vane configuration on the disc;
Ij: interaction effect of the i-th fertilizer with the j-th angular velocity of the disc;
ik: interaction effect of the i-th fertilizer with the k-th fertilizer feed point;
il: interaction effect of the i-th fertilizer with the l-th vane configuration;
jk: interaction effect of the j-th angular velocity of the disc with the k-th fertilizer feed point;
jl: interaction effect of the j-th angular velocity of the disc with the l-th vane configuration;
kl: interaction effect of the k-th fertilizer feed point with the l-th vane configuration;
e_{ijklm}: random experimental error, m.

Coefficient R^2 was used to explain the variability of the dependent variables by a constant model; T-Tukey confidence intervals were used to assess the significance of the differences in individual parameters. The relationships between the dependent variables (parameters of the average fertilizer distribution field) and independent variables were described by first-degree multiple regression equations. Model parameters were estimated using the least squares method [26]. Statistical verification of the model was carried out by the Fisher–Snedecor F test.

3. Results and Discussion

Mean spread radii are reported as a radar plot in Figure 5. The highest mean radius, 6.76 m, was obtained with CAN fertilizer, feed point B, angular velocity of disc 63 rad·s^{-1} and vane configuration L3. The smallest radius, 2.56 m, was recorded with the AS fertilizer, feed point A, angular velocity of the disc of 42 rad·s^{-1} and vane configuration L0. A general increase in mean spread radius was observed with vane configuration L3 and, as expected, increasing disc angular velocity.

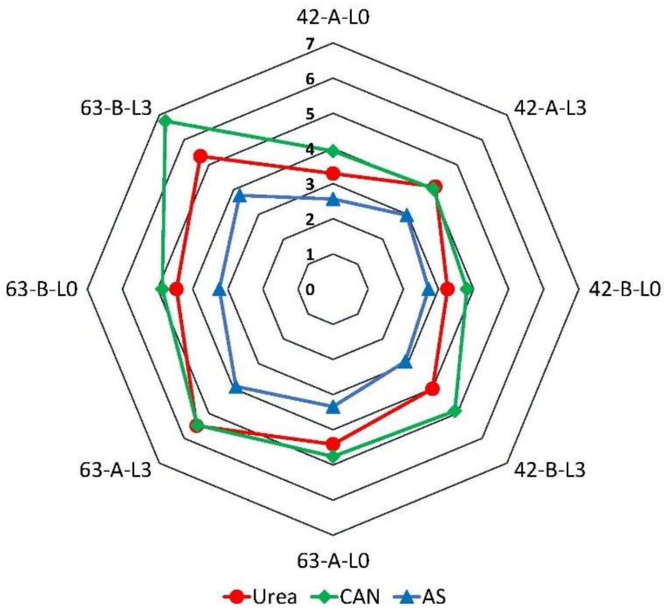


Figure 5. Mean spread radius for the different fertilizers (axes: DS–FP–VC).

Figure 5 also shows an amplifying effect of changing the feed point from A to B for urea and CAN, due to their lower coefficient of friction [27] with respect to AS. A lower friction increased the fertilizer velocity along the vane, increasing the radial velocity and consequently discharge velocity and discharge angle (Figure 1).

Tables 2–5 show the results of the different analyses. Table 2 reports the results of the analysis of variance of the mean fertilizer spread radius fixed model based on quadruple classification (fertilizer type (FT) × disc angular velocity (DS) × fertilizer feed point (FP) × vane configuration (VC)), in which three replicates were done in each subclass. The independent variables explained 99.48% of the variance of the dependent variable. In particular, the FP was substantially irrelevant compared to the other variables (FT, VC and DS), which together explained as much as 91.74% of the variability of the dependent variable. Likewise, among the two-factor interaction effects, including feed point (FP), only fertilizer type (FT) × feed point (FP) contributed, albeit very little, to explaining the variability of the mean radius of fertilizer spread.

Table 2. Fixed model analysis of variance for the mean radius of fertilizer spread.

Variation	DoF	Sum of Squares	Mean of Squares	F Function Value	Pr > F
Model	14	123.82	8.84	783.26	<0.0001
Error	57	0.64	0.01		
Total	71	124.46			
$R^2 = 0.9948$					
Average mean radius of fertilizer spread = 4.10 m					
Standard Estimation Error = 0.103 m					
Coefficient of Variation = 0.0248					
FT	2	63.44	31.72	2809.03	<0.0001
DS	1	34.24	34.24	3032.2	<0.0001
FP	1	0.01	0.01	0.94	0.337
VC	1	15.92	15.92	1409.65	<0.0001
FT × DS	2	6.16	3.08	272.55	<0.0001
FT × FP	2	0.05	0.025	2.16	0.1241
FT × VC	2	3.02	1.51	133.76	<0.0001
DS × FP	1	0.05	0.05	4.21	0.0448
DS × VC	1	0.89	0.89	79.54	<0.0001
FP × VC	1	0.05	0.05	4.12	0.0471

FT: fertilizer type; DS: disc angular velocity; FP feed point position; VC: vane configuration.

Table 3 shows the T-Tukey confidence intervals for differences in the means based on the same number of observations and mean square error. All differences in the mean radius of fertilizer spread proved to be significant.

Table 3. T-Tukey's multiple confidence intervals comparing the average mean radius of fertilizer spread.

Compared Averages for	Average Value	Number of Observations	Mean Square Error	Limit Value (α = 0.05)	Least Significant Difference
Fertilizer type (FT): Urea	4.23	24	0.011	3.40	
Fertilizer type (FT): CAN	5.45	24	0.011	3.40	0.074
Fertilizer type (FT): AS	3.15	24	0.011	3.40	
angular velocity of disc (DS): 42 rad·s^{-1}	3.59	36	0.011	2.83	0.05
angular velocity of disc (DS): 63 rad·s^{-1}	4.97	36	0.011	2.83	
Fertilizer feed point (FP): A	4.26	36	0.011	2.83	0.05
Fertilizer feed point (FP): B	4.29	36	0.011	2.83	
Vane configuration (VC): L0	3.81	36	0.011	2.83	1.86
Vane configuration (VC): L3	4.75	36	0.011	2.83	

Since the fixed model analysis of variance for mean radius of fertilizer spread clearly showed that the feed point did not have a significant influence on the mean radius of fertilizer spread, a linear multiple regression was performed excluding that parameter. The results are reported in Tables 4 and 5, which give the following regression equation where the estimation errors for each parameter are reported in brackets. We see that the estimated values of the dependent variable, the mean radius of fertilizer spread, differ from the empirical ones by an average of 0.103 m.

$$\overline{R} = 0.80798 - 0.03483 \cdot VC + 0.00690 \cdot DS + 1.65821 \cdot SD - 0.04357 \cdot DF \pm 0.103 \quad (3)$$
$$(0.47985)\ (0.00352)\ (0.00047)\ (0.23382)\ (0.00221)$$

In Table 4, we observe a considerable difference in average estimation errors in relation to the different coefficients: while the estimation error of the parameters never exceeded 14%, the corresponding error for the constant was close to 60%.

Table 4. Model parameter assessment of the linear multiple regression of the mean radius of fertilizer spread.

Variation	Parameter	SE	F Function Value	Pr > F	Partial Correlations
Constant	0.80798	0.47985	2.84	0.0969	-
VC	−0.03483	0.00352	98.1	<0.0001	0.12789
DS	0.00690	0.00047	211.01	<0.0001	0.31543
SD	1.65821	0.23382	50.29	<0.0001	0.00421
DF	−0.04357	0.00221	389.04	<0.0001	0.85308

VC: vane configuration; DS: disc angular velocity; SD: specific density; DF: dusty fraction.

Table 5. Analysis of variance for the linear multiple regression model of the relationship between the mean radius of fertilizer spread and the considered parameters.

Variation	DoF	Sum of Squares	Mean of Squares	F Function Value	Pr > F
Model	4	113.59512	28.39878	175.02	<0.0001
Error	67	10.87144	0.16226		
Total	71	124.46656			
		$R^2 = 0.9127$			
		Coefficient of Variation = 0.0942			

We also see that the dusty fraction of fertilizer has a partial correlation coefficient of 0.85, which is the highest of all the estimated partial correlation coefficients. This value is so high that the dusty fraction DF alone is responsible for 72.77% ($0.85308^2 \cdot 100$) of the variance in mean radius of fertilizer spread. The second most influential variable was disc angular velocity, DS, which explained 9.95% ($0.31543^2 \cdot 100$) of the variance in mean radius of fertilizer spread. Likewise, if we consider the remaining two variables (specific density (SD) and vane configuration (VC)), we find that their overall contribution to the variance in mean radius of fertilizer spread was only 1.64%, to which specific density SD makes a negligible contribution (0.00177%).

In line with the instructions provided with the disc spreader, the coefficient of the dust fraction (DF) is negative in the regression (Equation (3)), resulting in a decrease in the dependent variable as the independent variable increases. From a practical point of view, this means that the average radius of spread decreases considerably with increasing fertilizer dust fraction.

4. Conclusions

The present study shows, by the fertilizer spread mean radius fixed model analysis of variance, that the feed point on the disc has a very marginal role in the mineral fertilizer spreading process while the other functional and operational parameters (fertilizer type, vane configuration and disc angular velocity) together explain 91.74% of the variance of the dependent variable.

Furthermore, on the basis of linear multiple regression analysis, the main parameters that determine the mean radius of fertilizer spread are the fertilizer dust fraction and the disc angular velocity with an overall influence of 82.72%. The dust fraction determines 72.77% of the variance, confirming its inverse correlation with the mean radius of spread possible with the machine. This could be a practical indication for farmers, enabling them to focus on the angular velocity setting, once the fertilizer type has been chosen.

Further tests are underway to acquire better insights into the relationships affecting the mean radius of fertilizer spread and to evaluate which of the same parameters affect angular spread, from the point of view of improving the effectiveness of fertilization procedures for precision and sustainable agriculture.

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