UDC 631.347.4:519.876.5
DOI: 10.37128/2520-6168-2025-3-2

MODELING OF A CENTRIFUGAL SPREADER FOR MINERAL FERTILIZER APPLICATION

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The efficiency of mineral fertilizer application largely depends on the uniformity of its distribution over the soil surface. Uneven spreading leads to reduced crop yields, fertilizer overuse, deterioration of soil ecological conditions, and inefficient use of resources. One of the most common technical means for surface application of granular fertilizers is the centrifugal spreader, the operation of which is based on complex dynamic processes of particle interaction with the distribution disc. The aim of the numerical simulation was to study the kinematics of mineral fertilizer particle motion during the operation of the centrifugal disc spreading mechanism, to determine the regularities of the formation of the spreading zone, and to assess the influence of design and operational parameters on the uniformity of fertilizer distribution. The paper presents the results of numerical modeling of the fertilizer spreading process by a centrifugal disc spreader. A physico-mathematical model of particle motion in a non-inertial reference frame was developed, taking into account the effects of centrifugal force, Coriolis force, gravity, and friction. A differential equation of particle motion along the vane of the distribution disc was obtained, allowing the determination of the particle exit velocity and angle depending on the geometric and kinematic parameters of the working body. Based on simulations in Simcenter Star-CCM+ and Wolfram Cloud, a three-dimensional analysis of granule trajectories and the distribution of particles on the field surface was carried out, and the influence of the machine travel speed, disc rotational speed, and outlet diameter on fertilizer spreading uniformity was determined. The obtained regression equations enabled optimization of the process parameters, determination of rational operating modes of the spreader, and the development of a table of optimal factor values. The research results can be used to improve the design of centrifugal spreaders, increase dosing accuracy, and ensure uniform fertilizer distribution under field conditions.

***Key words**: fertilizers, application, field, centrifugal spreader, modeling, physico-mathematical model, disc working body, DEM, Simcenter Star-CCM+, distribution uniformity, parameter optimization.*
Eq. 10. Fig. 8. Table. 1. Ref. 20.

1. Problem formulation

The efficiency of mineral fertilizer application largely depends on the uniformity of its distribution over the soil surface [1]. Uneven spreading leads to reduced crop yields, fertilizer overuse, deterioration of soil ecological conditions, and inefficient use of resources [2]. One of the most common technical means for surface application of granular fertilizers is the centrifugal spreader, the operation of which is based on complex dynamic processes of particle interaction with the distribution disc [3]. Insufficient dosing accuracy, uneven transverse distribution of fertilizers, and the influence of disc rotational speed, vane geometry, material properties, and meteorological factors complicate the achievement of optimal agrotechnical performance [4]. To improve spreading quality, it is necessary to study in greater detail the regularities of particle motion in the centrifugal force field and to determine the influence of structural and technological parameters on the pattern of their distribution [5]. Therefore, a relevant scientific and technical challenge is the development and improvement of a physico-mathematical model of a centrifugal fertilizer spreader, which would allow

Article received 24.10.2025. Article accepted 08.12.2025. Article published 25.12.2025.

simulation of particle motion, determination of their trajectories, assessment of distribution uniformity, and optimization of the spreader's design parameters to achieve high fertilizer application efficiency.

2. Analysis of recent research and publications

In recent years, the issue of improving the efficiency of mineral fertilizer application and ensuring uniform distribution has gained particular importance due to the development of precision agriculture technologies. A significant number of studies by domestic and foreign researchers have been devoted to improving the design of centrifugal spreaders, investigating the regularities of fertilizer particle motion on the distribution disc, and optimizing their structural and technological parameters [6–10]. Among modern approaches, numerical modeling methods hold a special place, particularly the Discrete Element Method (DEM), which makes it possible to study the interaction of individual fertilizer granules with the disc surface and vanes, as well as to evaluate the influence of geometric and kinematic parameters of the spreader on particle trajectories [11–12]. For a more accurate assessment of the spreading process, a combination of DEM with Computational Fluid Dynamics (CFD) methods is increasingly used, allowing for the consideration of the influence of the air medium, turbulence, and aerodynamic forces on particle motion after ejection from the disc [14]. Experimental studies employing high-speed cameras, laser systems, and visualization tools allow verification of the adequacy of numerical models and identification of key parameters for their calibration. Numerous studies have shown that the uniformity of fertilizer distribution largely depends on the shape and installation angle of the vanes, disc rotational speed, physical and mechanical properties of the granules, and the height of the distribution unit [15–16]. At the same time, unresolved issues remain regarding the scaling of laboratory results to real field conditions, consideration of changes in material properties during operation, and the effects of disc wear and fluctuations in fertilizer feed rate [18]. Moreover, further development is needed in DEM model calibration techniques for various types of fertilizers differing in density, size, and particle shape. The analysis of scientific publications [6–18] indicates that integrating numerical modeling with experimental research is the most promising approach toward creating a universal model of a centrifugal fertilizer spreader capable of providing high accuracy in material distribution prediction and improving fertilizer application efficiency under real field conditions.

3. The purpose of the article

The purpose of the numerical modeling was to study the kinematics of mineral fertilizer particle motion during the operation of the centrifugal disc spreading mechanism, to determine the regularities of spreading zone formation, and to evaluate the influence of structural and operational parameters on the uniformity of material application.

4. Results and discussion

The numerical simulation of fertilizer particle motion on the spreading disk is based on a physico-mathematical model derived from Newton's second law of motion. The model is formulated in a non-inertial reference frame rotating with the disk, taking into account both the centrifugal and Coriolis forces. It is developed to determine the velocity and direction of fertilizer particle ejection depending on the geometric and kinematic parameters of the disk. A flat disk with blades inclined in the direction of rotation is considered, as this configuration provides the maximum ejection velocity at a constant rotational speed.

The particle motion analysis was carried out by obtaining a differential equation of dynamics that accounts for the main acting forces (Fig. 1): mg – gravitational force; $F_{cf} = m \cdot r \cdot \omega_d^2$ – centrifugal force; $\vec{F}_{co} = 2m \cdot \dot{\xi} \cdot \omega_d$ – Coriolis force; $F_{p_{cf}} = \mu_f \cdot m \cdot r \cdot \omega_d^2 \cdot \sin\psi$, $F_{p_{co}} = \mu_f \cdot 2m \cdot \dot{\xi} \cdot \omega_d$, $F_{p_g} = \mu_{fd} \cdot m \cdot g$ – friction forces between the particle, the blade, and the disk.

By applying Newton's second law in the non-inertial frame, the differential equation of motion of a particle along the blade is obtained:

$$mr\omega_d^2 \cos\psi - \mu_f mg - \mu_f mr\omega_d^2 \sin\psi - 2\mu_f m\omega_d \frac{d\xi}{dt} = m\frac{d^2\xi}{dt^2}. \quad (1)$$

This is a linear non-homogeneous second-order differential equation. Its general solution has the form:

$$\xi = \left[\frac{\mu_f g}{\omega_d^2} - r_0 \frac{\cos(\pi - \psi_0 - \phi_f)}{\cos(\phi_f)}\right]\left[\frac{1}{\lambda_2 - \lambda_1}(\lambda_2 e^{\lambda 1t} + \lambda_1 e^{\lambda 2t} - 1)\right], \quad (2)$$

$$\lambda_1 = \omega_d(-\mu_f + \sqrt{1+\mu_f^2}),\ \lambda_2 = -\omega_d(-\mu_f + \sqrt{1+\mu_f^2}).$$

which describes the particle displacement along the blade.

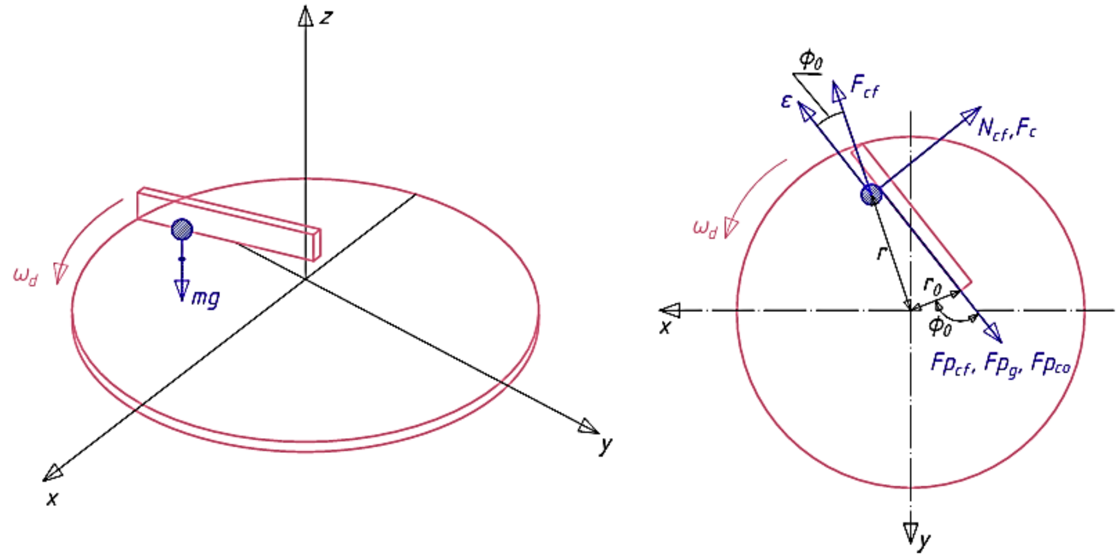
The absolute velocity of a particle at the disk outlet is determined by the vector sum of the disk's rotational velocity and the particle's relative velocity::

$$v_{ab} = \sqrt{v_a^2 + (v_r \cos\psi_e)^2},$$

$$v_r = \frac{d\xi}{dt} = \left[\frac{\mu_f g}{\omega_d^2} - r_0 \frac{\cos(\pi - \psi_0 - \phi_f)}{\cos(\phi_f)}\right]\left[\frac{1}{\lambda_2 - \lambda_1}(\lambda_2 e^{\lambda 1t} + \lambda_1 e^{\lambda 2t} - 1)\right]. \tag{3}$$

and the spreading angle is:

$$\theta_s = \theta_{s1} - \theta_{s2} - \alpha_2 + \alpha_1,\ \alpha_1 = \tan^{-1}\frac{\omega_d r_e}{v_{r1}\cos\psi_e};\alpha_2 = \tan^{-1}\frac{\omega_d r_e}{v_{r2}\cos\psi_e}. \tag{4}$$



a) *b)*

Fig. 1. Forces acting on a particle in a centrifugal disk spreader with blades

Based on the analytical solution, a graphical dependence was obtained that made it possible to determine the fertilizer feeding zone on the disk. Under the conditions: disk rotational speed n_d = 540 rpm, outer disk radius r_e = 25 cm, angle between the blade and the terminal radius vector ψ_e = 20°, and friction coefficient of fertilizer against the disk and blades μ_f = 0.6, the resulting feeding zone was b_f = 7.94 cm, and the spreading angle was $\theta_s \approx 90°\pm2°$. The implementation of the model in Wolfram Cloud confirmed the correctness of theoretical calculations: the particle spreading angle was approximately 90°, and the feeding zone width was about 50–100 mm.

The centrifugal disk spreading of mineral fertilizers is a complex multifactor phenomenon that combines the interaction of a large number of granular particles with each other and with machine components, as well as the effects of centrifugal, gravitational, and aerodynamic forces, and stochastic effects leading to uneven field distribution. Analytical methods are practically unsuitable for quantitative analysis of such processes, therefore, numerical modeling using computational mechanics methods is an appropriate approach. The Simcenter Star-CCM+ software package [18–20] was used, as it belongs to integrated engineering analysis systems designed for 3D modeling of multiphase processes, including discrete element method (DEM) simulations of bulk materials.

To achieve the objective, a 3D geometric model of the working unit was created; the physical and mechanical properties of the particles were defined; the computational domain, boundary conditions, and contact interaction models were configured.

The geometric model of the disk spreader was created in Siemens NX and then imported into Simcenter Star-CCM+ for mesh discretization and computational setup (Fig. 2). The model included a 0.45 m diameter disk with four radial blades of throw-off type, a granule feed hopper, and a housing enclosing the particle rotation zone. To reduce computational costs, the model was confined within a cylindrical domain 50 m in diameter and 2 m in height, sufficient to capture particle flight trajectories after leaving the blades. The mesh was generated using a polyhedral mesh, providing higher accuracy with fewer elements than a tetrahedral mesh. Local mesh refinement was applied near the blades to capture detailed velocity and motion fields. For the granular phase, a mesh-free DEM method was used, which computes particle trajectories based on Newton's motion equations without constructing control volumes for each particle.

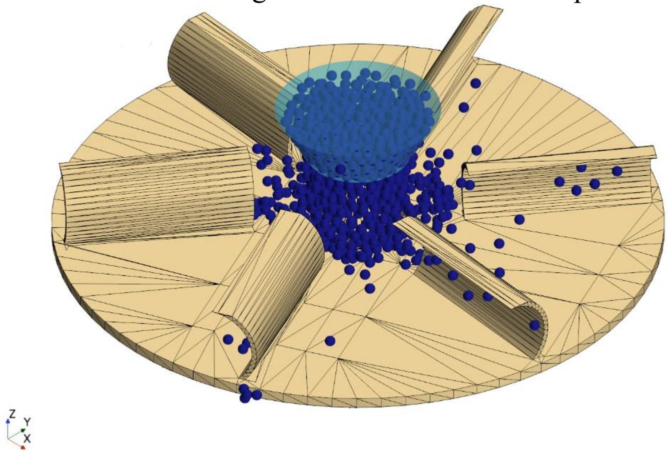


Fig. 2. Geometric model of the centrifugal disk fertilizer spreader

During numerical simulation of fertilizer distribution by the centrifugal disk unit in Simcenter Star-CCM+, a set of physical models was used to accurately describe particle motion, collisions with blades, and ejection into the air. The core is a Discrete Element Model (DEM) in a mesh-free formulation, treating each granule as an individual particle with its own physico-mechanical properties. This approach provides high accuracy in representing complex trajectories and allows for the consideration of bouncing, sliding, and accumulation phenomena.

Particle motion was described using a Lagrangian approach, which tracks each granule from its feed point on the disk to its ejection. The model assumes constant particle density and spherical shape, with a defined lifespan to ensure correct residence-time computation within the blade zone.

The process accounts for multiphase interaction between the solid and gaseous phases. Rolling resistance and air-particle interactions were modeled using the «Phase Interaction DEM» sub-module, enabling evaluation of turbulent flow effects on particle trajectories – crucial for determining fertilizer spreading uniformity.

Contact interactions between particles were modeled by the Hertz–Mindlin model, which considers elastic deformation during collisions and energy losses due to friction. This provides a realistic simulation of particle motion on metal blades and allows determination of impact forces and particle detachment moments.

To ensure solution stability, solution interpolation was applied to smooth transitions between regions with varying particle concentration. The simulation was conducted in a transient implicit regime, allowing particle positions to be tracked over time under the influence of centrifugal and gravitational forces. Gravity plays a key role in shaping particle fall trajectories after ejection from the disk.

The main physico-mechanical properties of mineral fertilizer particles influencing their motion, collision, and dispersion were defined as: density – 1200 kg/m^3; diameter – 5 mm; restitution coefficient – 0.3; sliding friction coefficient – 0.4; rolling friction coefficient – 0.05; elasticity modulus – 5–50 MPa; internal friction angle – 35°. Contacts with surfaces (mainly steel) were modeled with a restitution coefficient of 0.4 and a friction coefficient of 0.45.

Result visualization included several scenes and plots (Figs. 3–4).

Figure 3 shows the simulated field scene illustrating the distribution of fertilizer particles on the soil surface at a given time while the spreader moves at a constant speed. The color coding of particles represents coverage density and local fertilizer accumulation.

Figure 4 demonstrates the vector field of particle velocities during ejection from the working unit. The vectors represent each particle's velocity considering tangential and normal components, with a color scale indicating velocity magnitude, allowing for quick identification of maximum and minimum kinetic energies.

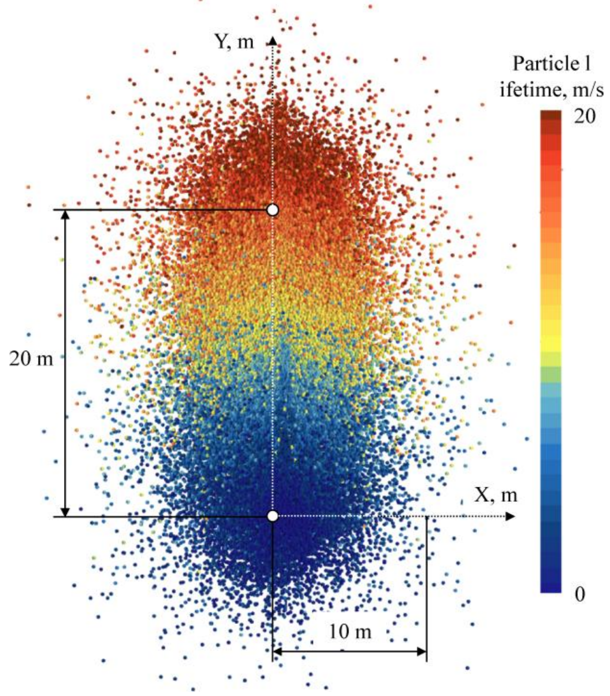


Fig. 3. Scene showing fertilizer particle distribution on a simulated field during spreader movement

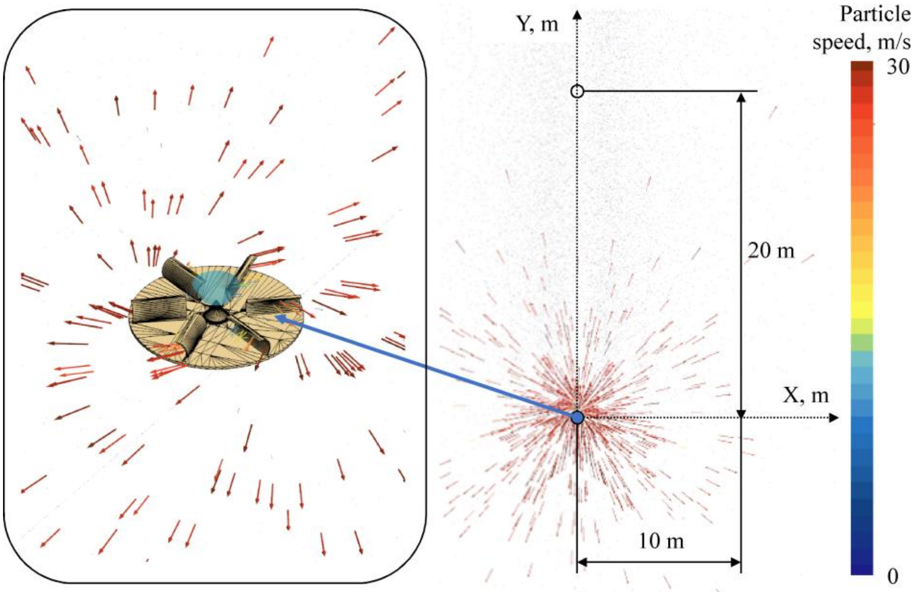


Fig. 4. Vector scene of fertilizer particle velocity distribution during ejection from the working unit

The modeling factors were:
– spreader travel speed V=1.0–3.5 m/s (3.6–12.6 km/h);
– disk rotational speed n=300–900 rpm;
– hopper outlet diameter D=50–100 mm.
Evaluation criteria:
– uniformity of distribution δ:

$$\delta = \left(1 - \frac{\sigma}{\overline{x}}\right) \times 100\%, \quad (5)$$

where σ – standard deviation of mass per sector (kg); $\overline{x}$ – mean mass per sector (kg); the smaller δ, the more uniform the spreading.

– application rate (mass rate) q

$$q = \frac{M}{S}, \quad (6)$$

where M – mass of particles in a sector (kg); S – sector area (m²).

– maximum flight distance L, defined as the distance from the ejection point to the impact point on the soil surface.

The study was carried out according to a full factorial experimental plan $3^3 = 27$, varying each of the three key factors at three levels. Statistical analysis of results was conducted in Wolfram Cloud using built-in functions for multifactor analysis: LinearModelFit – to build regression equations between factors and criteria; ["ParameterTable"] – to assess factor significance using Student's t-test; FindMaximum, FindMinimum – to identify factor optima for maximum and minimum response values; Plot3D – to visualize response surfaces and define optimal operation zones.

As a result of the numerical simulation, the particle distribution on the simulated field was obtained (Fig. 5) for both a single pass and multiple passes. For visualization purposes, Fig. 5 shows an example with six passes. The resulting distribution illustrates the density of particle deposition using color shading, which makes it possible to evaluate the uniformity of fertilizer application across different field areas. A 1 m × 1 m square was used as the elementary cell, which served as the basis for further calculations.

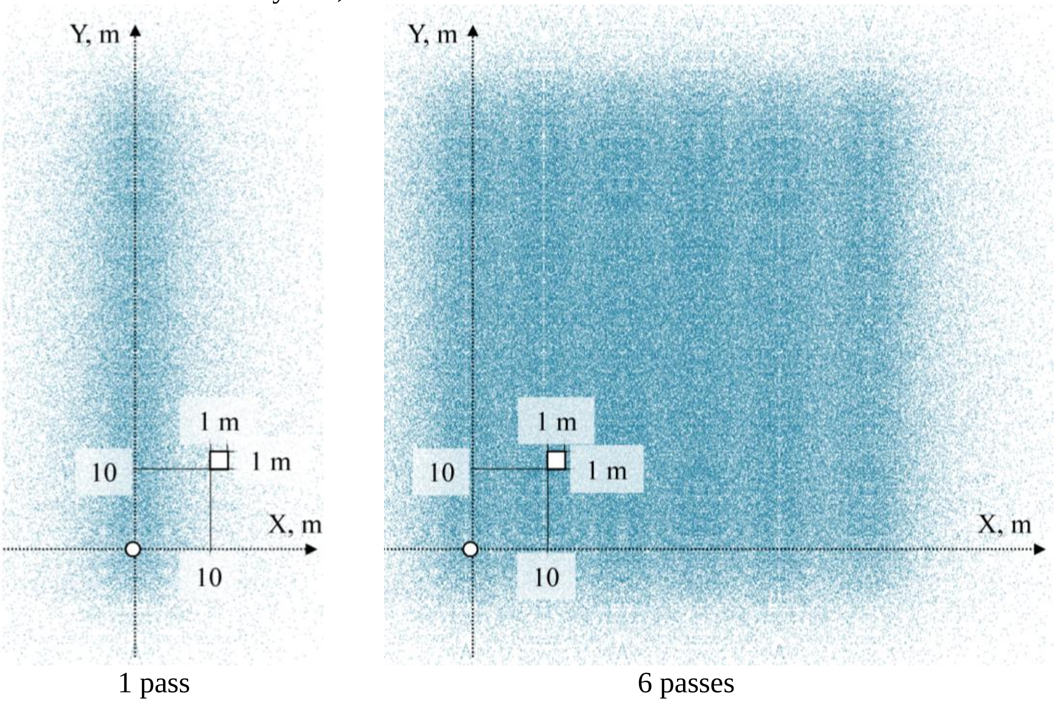


Fig. 5. Particle distribution on the simulated field

Analysis of the results showed that:

– after a single pass, particle spreading exhibits characteristic zones of concentration and gaps, indicating non-uniform distribution;

– as the number of passes increases, the distribution becomes more homogeneous, and the number of zones with fertilizer surplus or deficiency decreases;

– the visualization of distribution density allows determination of the optimal travel speed of the spreader and disk rotation parameters to achieve maximum uniformity of application.

For clarity, graphs of the application rate (mass rate) q in elementary cells (1 m × 1 m) were plotted in the corresponding coordinates (Fig. 6). The distribution along the X-coordinate shows that the application rate initially increases to a maximum value and then gradually decreases to 0 g/m². Since, during each pass of the spreader, the number of fertilizer particles adds up per unit area, the optimal spacing between passes is taken as twice the distance to the peak of the mass rate.

Along the Y-coordinate, only fluctuations of q are observed, which depend on the operational parameters of the unit and other experimental factors, such as the travel speed of the spreader and the disk rotational speed. This analysis makes it possible to evaluate application uniformity and determine optimal technological parameters to ensure uniform field coverage.

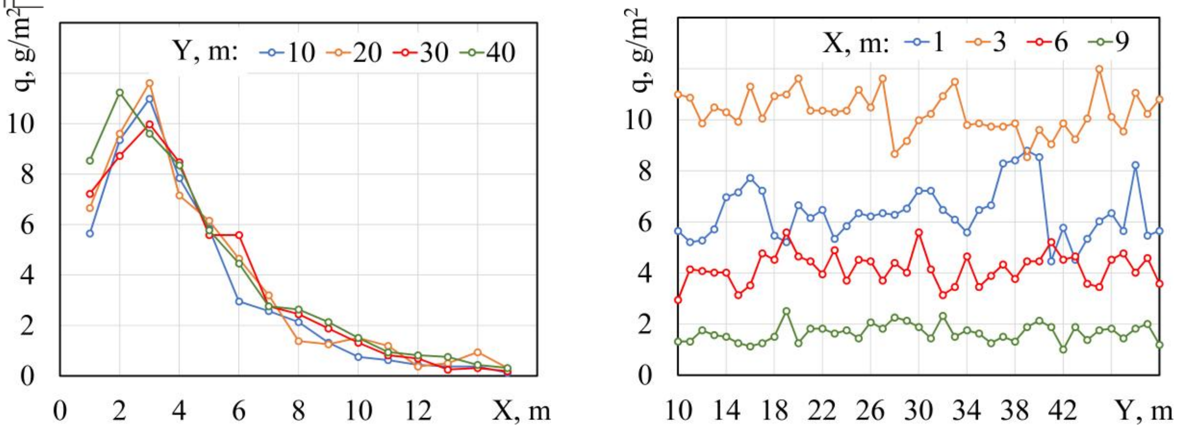


Fig. 6. Graphs of fertilizer application rate (mass rate) q in elementary cells (1 m × 1 m) in the corresponding coordinates

As a result of processing the numerical modeling matrix using Wolfram Cloud, the regression equations (excluding statistically insignificant coefficients) were obtained in decoded form from the experimental factors (Fig. 7):

– uniformity of application δ (%):

$$\delta = 58.5306 + 0.2562\,D - 0.0026507\,D^2 + 0.044431\,n + 0.0001657\,d\,n - 0.0000277407\,n^2 - 1.26\,V + 0.0021\,n\,V - 0.816667\,V^2; \quad (7)$$

– application rate q (kg/m²):

$$q = 18.3296 + 0.362222\,D + 0.00113778\,D^2 + 0.019537\,n - 8.95062\cdot10^{-6}\,n^2 - 6.76667\,V - 0.0886667\,d\,V; \quad (8)$$

– maximum flight distance L (m):

$$L = 4.69259 + 0.019463\,n - 1.79012\cdot10^{-6}\,n^2; \quad (9)$$

where V – spreader travel speed, m/s; n – rotational speed of the working disk, rpm; D – diameter of the hopper outlet, mm.

Optimization was carried out under the following conditions: the uniformity of fertilizer application δ should be maximized for a given application rate q, maximum travel speed V, and particle flight distance L

$$q(V,n,d) = q_0, \qquad \delta(V,n,d) \to \max, \qquad L(V,n,d) \to \max, \qquad V \to \max. \quad (10)$$

Based on the solution of the system of equations (7)–(10) in Wolfram Cloud, a table of rational (optimal) factor values was obtained for various given values of the parameter q_0 (Table 1). This table can be applied under real operating conditions.

Table 1

Rational (optimal) factor values for the given fertilizer application rate q_0

q_0, g/m²	V, m/s	n, rpm	D, mm	δ, %	L, m
10	3,00	300	50,0	88,8	10,4
15	2,74	404	50,3	85,2	12,3
20	2,65	512	60,9	88,7	14,2
25	2,34	621	61,5	85,1	16,1
30	1,99	698	62,8	86,1	17,4
35	1,71	819	64,6	89,0	19,4
40	1,41	900	66,7	90,6	20,8
45	1,09	900	69,2	91,1	20,8
50	1,00	900	77,6	91,4	20,8
55	1,00	900	88,4	91,0	20,8
60	1,00	900	98,7	90,0	20,8

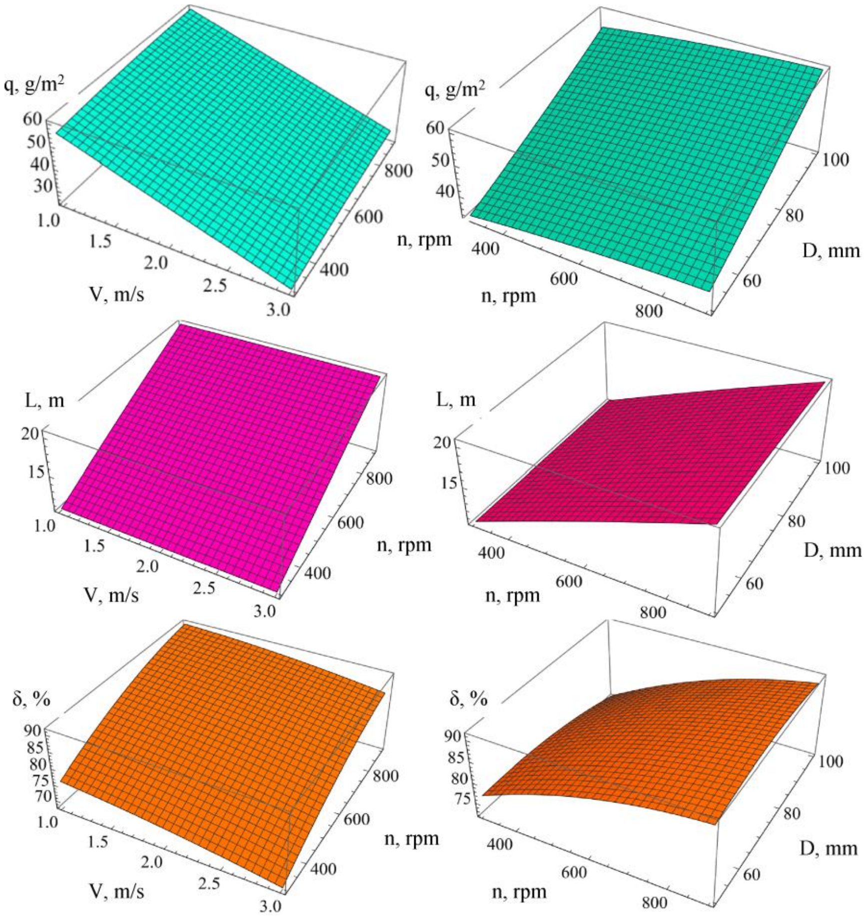


Fig. 8. Dependencies of fertilizer application uniformity δ, application rate q, and maximum flight distance L on the spreader travel speed V, disk rotational speed n, and hopper outlet diameter D

5. Conclusion

In the course of analytical research, a mathematical model was developed to describe the motion of mineral fertilizer particles on a centrifugal disc spreader with forward-inclined blades. The model takes into account the effects of the main forces – gravity, centrifugal, Coriolis, and friction – that arise in a non-inertial reference frame associated with the rotating disc. Based on Newton's second law, a differential equation of particle motion along the blade was derived, the solution of which makes it possible to determine the velocity, trajectory, and ejection angle of the fertilizer depending on the geometric and kinematic parameters of the spreader.

The software implementation of the equations in the Wolfram Cloud environment enabled numerical calculations and the construction of graphical dependencies describing particle position changes over time. It was determined that, at a disc rotation speed of 540 rpm, a blade inclination angle of 20°, and a friction coefficient of 0.6, the fertilizer feed zone has a width ranging from 50 to 100 mm, and the scattering angle is about 90°, which ensures a uniform distribution of fertilizer in the direction opposite to the machine's movement.

As a result of numerical modeling of the fertilizer spreading process using a centrifugal disc spreading mechanism in Simcenter Star-CCM+ and Wolfram Cloud, regression equations were obtained that accurately describe the dependence of distribution uniformity (δ), application rate (q), and particle flight distance (L) on the machine's forward speed (V), disc rotational speed (n), and outlet diameter (D).

Optimization was performed under specified conditions to achieve the maximum uniformity of fertilizer distribution δ for a given application rate q, spreader speed V, and flight distance L. Based on the results of solving the system of equations in Wolfram Cloud, a table of rational (optimal) factor values was obtained for various specified values of the parameter q_0, which can be used under practical field conditions.

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МОДЕЛЮВАННЯ ВІДЦЕНТРОВОГО РОЗКИДАЧА ДЛЯ ВНЕСЕННЯ МІНЕРАЛЬНИХ ДОБРИВ

Ефективність процесу внесення мінеральних добрив значною мірою залежить від рівномірності їх розподілу по поверхні ґрунту. Нерівномірне розсіювання призводить до зниження врожайності, перевитрати добрив, погіршення екологічного стану ґрунтів та нераціонального використання ресурсів. Одним із найпоширеніших технічних засобів для поверхневого внесення гранульованих добрив є відцентрові розкидачі, робота яких базується на складних динамічних процесах взаємодії частинок із розподільним диском. Метою чисельного моделювання було дослідження кінематики руху частинок мінеральних добрив при роботі відцентрового дискового робочого органа, визначення закономірностей формування зони розсіювання та оцінка впливу конструктивних і режимних параметрів на рівномірність внесення матеріалу. У роботі представлено результати чисельного моделювання процесу розсіювання мінеральних добрив відцентровим дисковим розкидачем. Розроблено фізико-математичну модель руху частинок у неінерціальній системі відліку, яка враховує дію відцентрової сили, сили Коріоліса, сили тяжіння та тертя. Отримано диференціальне рівняння руху частинки вздовж лопаті розподільного диска, що дозволяє визначити швидкість і кут вильоту добрив залежно від геометричних і кінематичних параметрів робочого органу. На основі моделювання у середовищах Simcenter Star-CCM+ та Wolfram Cloud проведено тривимірний аналіз траєкторій руху гранул, розподілу частинок на поверхні поля та визначено закономірності впливу швидкості руху агрегату, частоти обертання диска й діаметра випускного отвору на рівномірність внесення добрив. Отримані рівняння регресії дозволили провести оптимізацію параметрів процесу, встановити раціональні режими роботи розкидача та сформувати таблицю оптимальних значень факторів. Результати дослідження можуть бути використані для вдосконалення конструкцій відцентрових розкидачів, підвищення точності дозування і забезпечення рівномірного розподілу добрив у польових умовах.

Ключові слова: *добрива, внесення, поле, відцентровий розкидач, моделювання, фізико-математична модель, дисковий робочий орган, DEM, Simcenter Star-CCM+, рівномірність розподілу, оптимізація параметрів.*

Ф. 10. Рис. 8. Табл. 1. Літ. 20.

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