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THE MODEL FOR RANDOM PACKAGING OF SMALL-SEEDED CROPS' SEEDS IN THE RESERVOIR OF SELECTION SEEDERS SOWING UNIT

Vitalii Yaropud[1], *Inna Honcharuk*[1], *Dmytro Datsiuk*[1], *Elchyn Aliiev*[2]

[1]*Vinnytsia National Agrarian University, 3 Sonyachna St, Vinnytsia, 21008, Ukraine*
[2]*Institute of Oilseed Crops of the National Academy of Agrarian Sciences of Ukraine,*
1 Institutskaya St, v. Sonyachne, Zaporozhye region, 69093, Ukraine

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Vastutav autor: Corresponding author:	Vitalii Yaropud

E-mail: yaropud77@gmail.com

ORCID:
0000-0003-0502-1356 (VY)
0000-0002-1599-5720 (IH)
0000-0002-4614-2245 (DD)
0000-0003-4006-8803 (EA)

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ABSTRACT. The sowing unit is one of the most important working bodies of the drill. It is used to select from the total mass of a certain number of seeds and the formation of their output flow with the specified parameters. Therefore, the advantages and disadvantages of seeders, in terms of the quality of seed distribution in a row and general in the sown field, are mainly determined by the work of sowing machines. The research was carried out to develop a model of random packing of seeds of small-seeded crops in the tank of the sowing apparatus of the selection drill. The research was conducted based on numerical simulation in the software package of the CAE-system Simcenter STAR-CCM +. Because of research, the mathematical model of casual packing of seeds of small-seeded cultures in the capacity of the sowing device of a selection seeder is developed that allowed defining the equation of regression of its density from the effective diameter of seeds and coefficient of variation of this diameter. As a result of research of process of work of the batcher of the sowing device of a selection seeder regularity of change of its throughput from an angle of inclination of a gate, type of a form of executions (triangle, semicircle, rectangle) in the form of a polynomial of the third degree are received. It is established that the choice of the triangular shape of the dispenser allows for ensuring the highest accuracy of seed dosing.

Introduction

In the sphere of selective production of small-seeded crops' seeds, the interest in sowing problems has grown significantly in recent times. This is due to the significance of obtaining high-quality crops at the initial point of research and preliminary propagation of new varieties and hybrids of small-seeded crops (Molotsky *et al.*, 2006; Hakansson *et al.*, 2013; Shepelev *et al.*, 2016; Vasylkivsky, Kochmarsky, 2016; Shackley *et al.*, 2019; Mazur *et al.*, 2021). By the conditions required for the normal development of plants, high agrotechnical requirements are put forward to the quality of crops sown on selection sites for preliminary reproduction and variety testing, since more expensive sowing material is used. Important agronomic requirements have to ensure uniform distribution of seeds along the row at a level not lower than 95% (Kryuchin, 2009).

The sowing method depends on soil and climatic conditions and the sowing qualities of small-seeded crops' seeds. The task of sowing is to create favourable conditions for the germination of seeds and plants, as well as to ensure their required density with uniform placement in rows. The required density of crops and the order of seeds placement in the field is the basis for choosing the method of sowing the seeds of small-seeded crops. On this basis, the row spacing and the interval between seeds are selected (Khalansky, Gorbachev, 2004; Kryuchin, 2009).

Technical-operational and production-technological indicators make an integral part of agro-technical requirements to seeders. They determine the main parameters of the sowing unit: capture width, operational speeds, power consumption, output, service life, coefficients of technological process's preparedness and reliability, occupational safety conditions and operational convenience, the quantity of service personnel, *etc.* (Alhassan *et al.*, 2018; Ovtov, Abrosimov, 2020; Hrushetskyi *et al.*, 2021). In addition, the seeds should be aligned in size and free from pubescence, hooks and similar roughness, characterized by high germination (Aliiev *et al.*, 2019; Aliiev, 2020; Paziuk *et al.*, 2021; Shevchenko *et al.*, 2021).

Thus, the main qualitative, quantitative and operational characteristics of sowing and other machines are determined based on agrotechnical requirements, the perfection and exact execution of which ensure the development of efficient and cost-effective sowing units.

The sowing unit is one of the most important working bodies of the seeder. It is used to select the particular number of seeds from the total mass and to form an output stream from them with specified parameters (Pankov *et al.*, 2016; Shevchenko *et al.*, 2018). Therefore, the advantages and disadvantages of seeders, in terms of quality of seed distribution in rows and sown fields in general, are mainly determined by the seeder's operation.

When sowing small-seeded crops in varietal testing and pre-propagation areas, electromechanical seeders have become widespread. However, the problem with their use lies in an insufficient uniformity of seed distribution along the row, which is due to random processes that occur during sowing. As a result, crops appear to be uneven – with thickening or rarefying of plants in a row, which ultimately leads to a decrease in yields of selection-valuable small-seeded crops.

In this regard, studies aimed at improving the process of seed dosing by sowing units of selection seeders are of great scientific and practical significance.

Methods

Sowing of small-seeded crops' seeds in the electromechanical sowing unit is reduced to the process of their dosing and transportation to the seed pipeline. In most designs of electromechanical seeders, the seeds are unloaded into the seeders reservoir, wherein mathematical terms are formed into random packages. Further, using a valve through dosing holes so formed, seeds enter the distributor, being supplied to the seed pipeline. Given the fact that the said study was conducted to develop the model for random packaging of small-seeded crops' seeds in the reservoir of selection seeders sowing unit.

Recent theoretical studies of mechanical and technological processes of seed movement under the action of the machines' working bodies are reduced to analytical methods, this leading to the compilation of complex systems of differential equations with boundary and initial conditions (Aliev *et al.*, 2018). In practical terms, these systems cannot be solved in conventional ways, so the need exists for their numerical solution using computer simulation.

Among up-to-date methods of computer simulation of mechanical and technological processes of bulk medium's (seed mixture's) movement, particular emphasis is put on the methods based on the concept of discrete representation of matter – the method of particle dynamics and the method of discrete elements (Rutkevych *et al.*, 2022). The method of particle dynamics is represented by media in the form of sets of interacting particles – material points or solids. Their motion is described by equations of classical mechanics. When simulating the motion of particles using the method of particle dynamics at each step, iterative methods solve the Cauchy problem – differential equations are integrated under given initial conditions. The best-known programs for calculations using the particle dynamics method are AMBER, CHARMM, GROMACS, GROMOS and NAMD. The discrete element method may be deemed the generalization of the finite element method. When simulating the process, this method sets particles' initial positions and velocities. Then, based on these initial data of given physical laws of particles' interaction, forces acting on each particle are calculated. At the same time, it is possible to consider various laws of interaction themselves; the existence of solvable equations to describe them is sufficient. For each particle, the resultant force is calculated and the Cauchy problem is solved at a selected time interval. The result is initial data for the next step. The following programs implementing the method of discrete elements are the best-known ones: Chute Maven (Hustrulid Technologies Inc.), PFC2D and PFC3D, EDEM (DEM Solutions Ltd.), GROMOS 96, ELFEN, MIMES, PASSAGE and Star CCM +. The discrete element method is based on the laws of momentum conservation and impulse-momentum for Lagrange models of multiphase medium (Aliev *et al.*, 2018). However, to generate a physical-mathematical model, one should assume that particles of components are represented by balls with particular density and effective diameter.

Therefore, further theoretical research was conducted based on numerical simulation in Simcenter STAR-CCM + CAE-system software package.

The first stage of theoretical research lies in the development of the model for random packaging of small-seeded crops' seeds in the reservoir of selection seeders sowing apparatus and substantiation of its dispenser's geometrical parameters.

Let us approximate the geometrical shape of small-seeded crops' (rapeseed, mustard, camelina, millet, *etc.*) seeds in the form of balls with the effective diameter of D. According to previous studies (Shevchenko *et al.*, 2018; Aliiev *et al.*, 2019; Aliiev, 2020) even calibrated seed mixtures contain seeds with different effective diameters. Therefore, let us assume that seeds' effective diameters are subject to normal distribution and characterized by the probability density of:

$$f\left(D, D_{\mu}, \sigma_{D}\right) = \frac{1}{\sigma_{D}\sqrt{2\pi}} \exp\left(-\frac{\left(D - D_{\mu}\right)^{2}}{2\sigma_{\mu}^{2}}\right), \qquad (1)$$

where D_{μ} is the average value of the effective seed diameter, m; σ_D is the standard deviation of the effective seed diameter, m

That said, the seeds may have the effective diameter being in the range of $D \in [D_{min}; D_{max}]$, where D_{min} is the minimum value of the effective diameter, m; D_{max} is the maximum value of the effective diameter, m

Assuming that the seeds' density is the same and equals ρ, the weight of 1000 seeds is determined using the formula:

$$m_{1000} = \frac{500}{3} \rho \pi D^3, \tag{2}$$

where ρ is the seeds' density, kg m^{3-1}.

The reservoir of selection seeders seed sowing unit has the form of a rectangular parallelepiped with the height of h, the base of which being a square with the side of a.

Generation of random packaging consists of the consecutive launch of spherically shaped seeds with randomly chosen coordinate at the top face of the reservoir of the selection seeders seed-sowing unit (Fig. 1) in its bottom direction. The initial sedimentation rate for all particles is set as the same. For the random generation of seeds, let us assume that the upper plane of the selection seeders seed sowing unit reservoir is divided into $N_G = 4a^2 / (\pi D^2)$ cells of equal size. In these cells, seeds are generated (1) or not generated (0). The probability of seed generation in each cell equals 0.5.

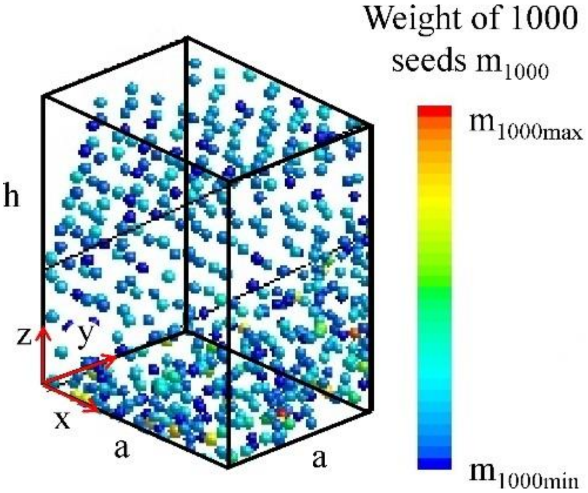

Figure 1. Simulation of filling the selection seeders seed sowing unit reservoir with spherical seeds

The movement of launched seeds is subsequently monitored. To exclude the calculation of the seed's movement from the reservoir's upper limit to its first contact with the already formed package, the seed is launched from some point inside the reservoir above the package, in which such moving seed is close enough to the level of the package. z` coordinate of controlled seed acquires z`value = z + D_1/2 + D_2/2, where z is the coordinate of the centre of the highest seed from among the seeds that settled at the bottom of the reservoir; D_1 is the diameter of the moving seed and D_2 is the diameter of the seed in the package centred in z. x` and y` coordinates are determined by a random number generator, which with equal probability acquires the values from 0.5a - (λ - D_1/2) to 0.5a + (λ - D_1/2), where λ is the predetermined number between D_{min}/2 and D_{max}/2. Setting λ number allows us to set the size of the seed launch source. With λ = D_1/2, launched seeds are on x` line = 0.5a and y` line = 0.5a.

When the seed collides with a seed in the package, the spring/dash-pot contact occurs. One can assume that the following forces can act on seeds:

- gravity (Dinesh, 2009):

$$\overline{F_g} = \pi D^3 \rho \overline{g} / 6, \tag{3}$$

where $\overline{F_g}$ is gravity vector, N.

- the total force of seeds' contact interaction between themselves and the wall, which is based on Hertz-Mindlin's spring/dash-pot contact model (Di Renzo, Di Maio, 2004; Komiwes *et al.*, 2006):

$$\overline{F_{contact}} = \overline{F_n} + \overline{F_t}, \tag{4}$$

where $\overline{F_{contact}}$ is the interaction effort between the seeds and the wall, H; $\overline{F_n}$ is a normal effort component, H; $\overline{F_t}$ is a tangential effort component, N.

The normal force component is determined using the following equation:

$$\overline{F_n} = -K_n \overline{d_n} - N_n \overline{V_n}, \tag{5}$$

where K_n is the elastic component's normal stiffness factor, kg s^{2-1};

$$K_n = \frac{4}{3} E_{eq} \sqrt{d_n R_{eq}}, \tag{6}$$

where N_n is the damping component's normal damping ratio, kg s^{-1};

$$N_n = \sqrt{(5 K_n M_{eq})} N_{n\ damp}. \tag{7}$$

According to researches (Di Renzo, Di Maio, 2004; Komiwes *et al.*, 2006), the tangential component of force is defined as:

$$\overline{F_t} = -K_t \overline{d_t} - N_t \overline{V_t} \tag{8}$$

if $\left| K_t \overline{d_t} \right| < \left| K_n \overline{d_n} \right| C_{fs}$, where C_{fs} is the statistical coefficient of friction between the seeds or with the wall. Otherwise, the tangential component of force is determined using the following equation:

$$\overline{F_t} = \left| K_n \overline{d_n} \right| C_{fs} \overline{d_t} / \left| \overline{d_t} \right|, \tag{9}$$

where K_t is the elastic component's tangential stiffness factor, kg s^{2-1};

$$K_t = 8G_{eq}\sqrt{d_t R_{eq}}\ , \qquad (10)$$

N_t is the damping component’s tangential damping ratio, kg s^{-1};

$$N_t = \sqrt{\left(5K_t M_{eq}\right)} N_{t\ damp}\ , \qquad (11)$$

N_{damp} is the attenuation factor

$$N_{damp} = -\ln\left(C_{n\ rest}\right) \Big/ \sqrt{\pi^2 + \ln\left(C_{n\ rest}\right)^2}\ , \qquad (12)$$

R_{eq} is the equivalent radius of two seeds A and B, m;

$$R_{eq} = \left(\frac{2}{D_A} + \frac{2}{D_B}\right)^{-1}, \qquad (13)$$

M_{eq} is the equivalent weight of two seeds A and B, kg;

$$M_{eq} = \left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{-1}, \qquad (14)$$

E_{eq} is the two seeds’ equivalent Young's modulus ‘ A and B, Pa;

$$E_{eq} = \left(\frac{1-\nu_A^2}{E_A} + \frac{1-\nu_B^2}{E_B}\right)^{-1}, \qquad (15)$$

G_{eq} is the equivalent shear modulus of two seeds A and B, PA;

$$G_{eq} = \left(\frac{2\left(2-\nu_A\right)\left(1+\nu_A\right)}{E_A} + \frac{2\left(2-\nu_B\right)\left(1+\nu_B\right)}{E_B}\right)^{-1} \qquad (16)$$

M_A, M_B are weights of seeds A and B, kg; d_n, d_t, being virtual overlaps of seeds A and B in normal and tangential directions, m; D_A, D_B are effective diameters of seeds A and B, m; E_A, E_B are Young's modules of seeds A and B, Pa; ν_A, ν_B are Poisson's ratios of seeds A and B; $\overline{V_n}$, $\overline{V_t}$ are normal and tangential components of seed surface’s relative velocity at the point of contact, m s^{-1}.

For the process of interaction between seeds and the wall, (2.5) – (2.16) dependencies are adequate, however D_{wall} radius = ∞ and M_{wall} wall mass = ∞ are assumed for the wall. As a result, (2.13) and (2.14) expressions transform into

$$R_{eq} = D_p/2,\ M_{eq} = M_p. \qquad (17)$$

Given the above-mentioned forces, let us write the system of differential equations of motion of one spherical seed in the reservoir of the selection seeder's sowing unit:

$$\begin{cases} \frac{1}{6}\pi D^3 \rho \frac{d_p \overline{V_p}}{dt} = \frac{1}{6}\pi D^3 \rho \bar{g} + \overline{F_n} + \overline{F_t}, \\ \frac{d_p \overline{S_p}}{dt} = \overline{V_p}, \\ \frac{d_p}{dt} = \frac{\partial}{\partial t} + \overline{V_p} \cdot \overline{\nabla}, \end{cases} \qquad (17)$$

where $\overline{V_p}$ is seed velocity vector, m s^{-1}; $\overline{S_p}$ is seed movement vector, m.

To determine the position of each seed in the reservoir of the selection seeders seed sowing unit, one should solve the system of differential equations (17) taking into account formulas (3)–(16), which is analytically quite difficult to do. Therefore, we will subsequently use Star CCM + software package, which is based on the presented mathematical apparatus.

Numerical simulation factors are represented by the average value of effective seed diameter D_μ (0.001; 0.002; 0.003 m) and variation coefficient δ_D (0.1; 0.2; 0.3), which is calculated as the ratio of the standard deviation of effective seed diameter σ_D to its average value (Table 1). The simulation was performed for a full-factor experiment concerning two factors with nine experiments in five repetitions.

The evaluation criterion is represented by package density, which is determined as follows:

$$\varphi = \frac{\sum_{i=1}^{N} \frac{1}{6}\pi D_i^3}{a^2 h} \qquad (18)$$

where *i* is seed No.; N is the total number of seeds.

Table 1. Factors and levels of numerical simulation of random packaging of seeds in the seeders reservoir

No.	Effective seed diameter D_μ, m	Variation factor δ	Standard deviation of effective seed diameter σ_D, m	Minimum seed diameter value D_{min}, m	Maximum seed diameter value D_{max}, m
1	0.001	0.1	0.0001	0.0007	0.0013
2	0.001	0.2	0.0002	0.0004	0.0016
3	0.001	0.3	0.0003	0.0001	0.0019
4	0.002	0.1	0.0002	0.0014	0.0026
5	0.002	0.2	0.0004	0.0008	0.0032
6	0.002	0.3	0.0006	0.0002	0.0038
7	0.003	0.1	0.0003	0.0021	0.0039
8	0.003	0.2	0.0006	0.0012	0.0048
9	0.003	0.3	0.0009	0.0003	0.0057

Please note that for one-dimensional spheres, the densest package in space is represented by a regular icosahedron, which contains 12 vertices (Fig. 2a). Centres of spheres are located at the vertices of this three-dimensional figure. As noted in studies (Conway, Sloane, 1999; Aste, Weaire, 2008), the average density of such packaging is 0.7405. For simple packages (4 spheres): cubic (Fig. 2b) and hexagonal (Fig. 2c) the density is 0.5236 and 0.6043, respectively. Given the above, one can state that for uniform-sized spheres in space, packaging density may range from 0.5236 to 0.7405.

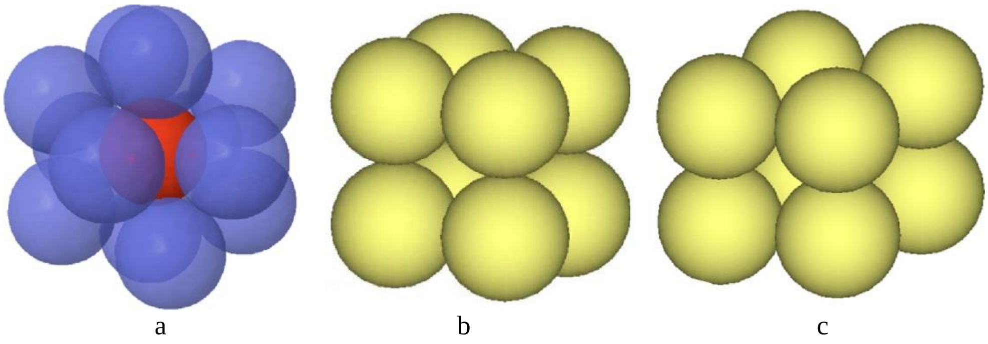

Figure 2. Examples of packages of uniform-sized spheres in space

The next step is to determine the patterns of the dispenser's operation, which is presented in the form of a valve that opens holes of different shapes. Holes of the cylindrical dispenser are made in three designs (Fig. 3): I – as a triangle, II – as a semicircle, and III – as a rectangle. Dependencies between the area of the dispenser's one hole S and valve rotation angle α for different designs are shown in Fig. 3.

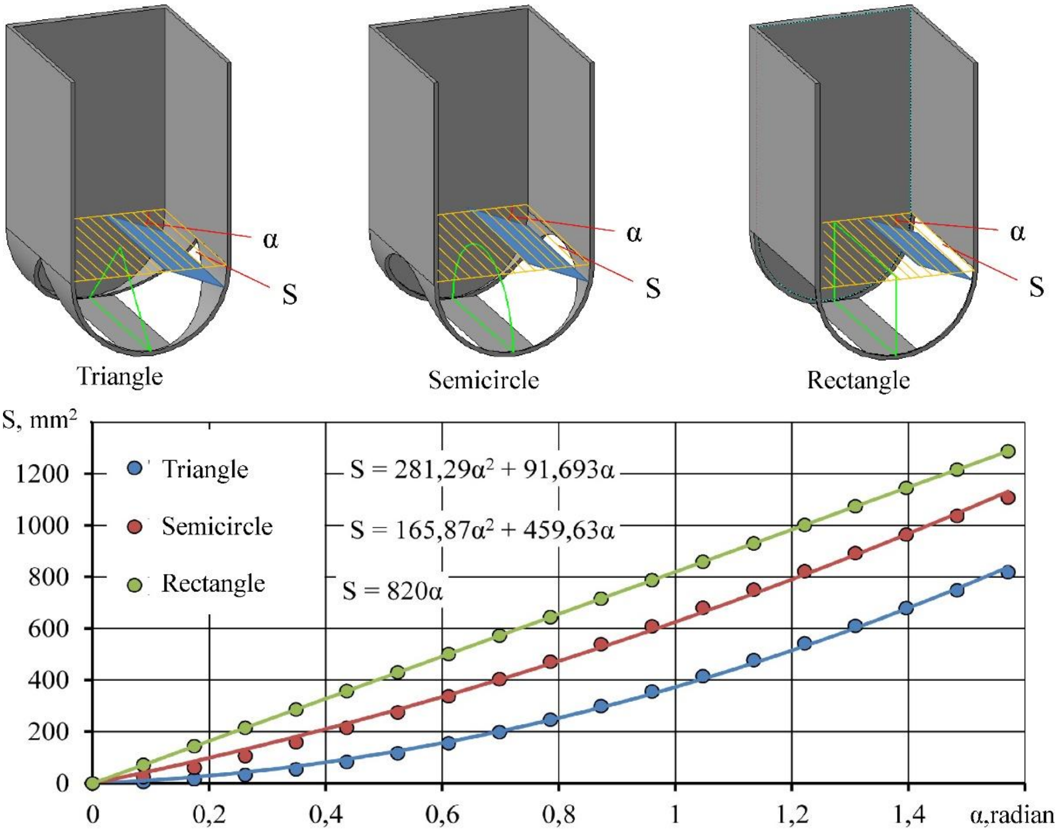

Figure 3. Dependencies between the area of the dispenser's one hole S and valve rotation angle α for different designs

The factors of numerical simulation are represented by package density φ (0.550; 0.575; 0.600) and valve rotation angle α (0.1–1.5 through 0.1).

The evaluation criterion is represented by the reservoir dispenser's throughput Q_d, which is determined using the formula:

$$Q_d = \frac{n}{t} \qquad (19)$$

where t is time, s; n is the number of seeds.

Physical models for dosing process simulation using Star CCM + software package are as follows: three-dimensional model, nonstationary implicit model, the mathematical model of one-component gas (air), model of an ideal gas (air), model of turbulent airflow, k-ε model of air turbulence, isothermal equation of fluid energy, Reynolds-averaged Navier-Stokes equation (Gunko *et al.*, 2021), separate flow, gradient and boundary methods, Lagrangian model of the multi-phase medium (Solona *et al.*, 2020; Kovbasa *et al.*, 2021), multiphase interaction model, discrete elements model (DEM), gravity field (Kubicki, Lo, 2012; Satish *et al.*, 2013; Iguchi, Ilegbusi, 2014; Yaropud *et al.*, 2021; Rutkevych *et al.*, 2022).

The seeds are presented in the form of the Lagrange phase according to the following models: constant density, pressure gradient force, particle resistance force, spherical particles, single-component solid particles, and DEM particles. For example, rapeseed was selected as the seed, which according to the analysis of literature has the following physical and mechanical properties: Poisson's ratio – 0.2; Young's modulus – 0.2 MPa; density – 700 kg $m^{3\,-1}$; coefficient of static friction – 0.58; normal recovery factor – 0.5; tangential recovery factor – 0.5; rolling resistance coefficient – 0.3 (Aliiev, 2019; Paziuk *et al.*, 2019).

Results

According to numerical modelling results, visualization of random packaging of small-seeded crops' seeds in the reservoir of the selection seeders sowing unit with different geometrical sizes of seeds was obtained (Fig. 4). For each numerical experiment, packaging density is calculated, and the results are summarized in Table 2.

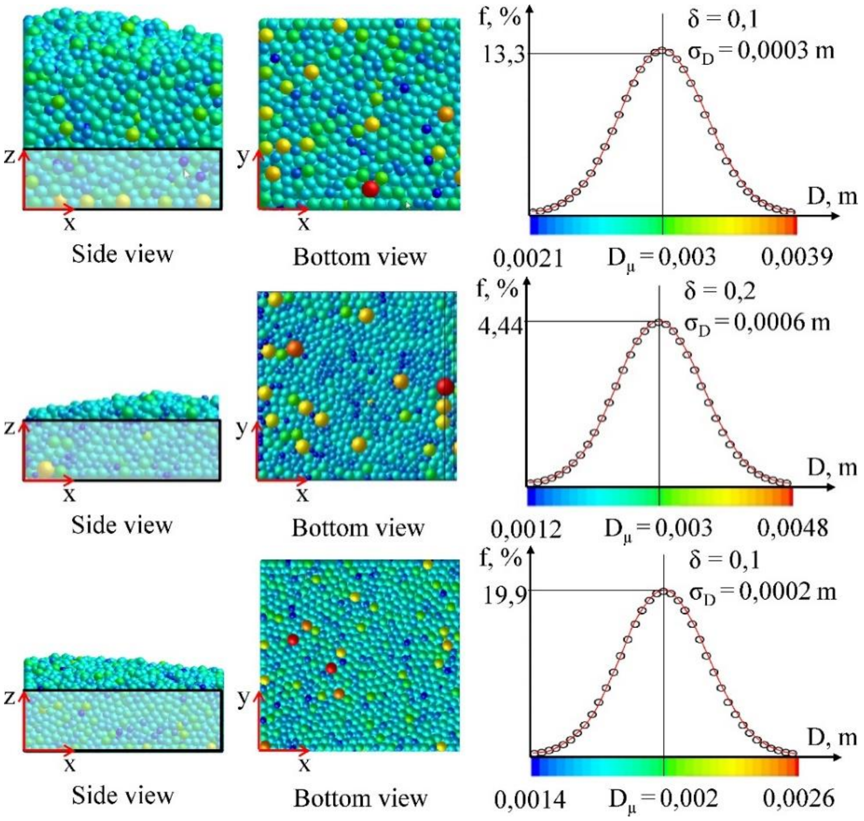

Figure 4. Visualization of random packaging of small-seeded crops' seeds in the reservoir of selection seeders sowing unit

Table 2. Results of simulation of random packaging of small-seeded crops' seeds in the reservoir of selection seeders sowing unit

Effective seed diameter		Diameter variation ratio		Packaging density φ					$\bar{\varphi}$	σ_φ	δ_φ
				Repeatability							
D_μ, mm	x_1	δ	x_2	1	2	3	4	5			
0.001	–1	0.1	–1	0.5628	0.5684	0.5552	0.5611	0.5594	0.5614	0.0048	0.0086
0.001	–1	0.2	0	0.5991	0.6024	0.5955	0.5970	0.5969	0.5982	0.0027	0.0045
0.001	–1	0.3	1	0.6164	0.6227	0.6112	0.6192	0.6130	0.6165	0.0046	0.0075
0.002	0	0.1	–1	0.5587	0.5611	0.5524	0.5585	0.5559	0.5573	0.0033	0.0059
0.002	0	0.2	0	0.5944	0.5977	0.5912	0.5930	0.5939	0.5940	0.0024	0.0040
0.002	0	0.3	1	0.6041	0.6063	0.5975	0.6048	0.6010	0.6027	0.0035	0.0058
0.003	1	0.1	–1	0.5532	0.5564	0.5496	0.5546	0.5522	0.5532	0.0026	0.0046
0.003	1	0.2	0	0.5884	0.5938	0.5842	0.5923	0.5857	0.5889	0.0041	0.0070
0.003	1	0.3	1	0.5995	0.6048	0.5952	0.6032	0.5990	0.6003	0.0038	0.0063

$\bar{\varphi}$ is the average value of packaging density; σ_φ is the standard deviation of packaging density; δ_φ is the coefficient of packaging density variation

Using the Wolfram Mathematica software package, let us present the obtained table data in the form of a second-order regression equation in coded form:

$$\varphi = 0.592558 - 0.00560667\, x_1 + 0.00171333\, {x_1}^2 + 0.0246133\, x_2 - - 0.001995\, x_1\, x_2 - 0.0117867\, {x_2}^2. \qquad (20)$$

Statistical processing of the obtained equation (20) is presented in table 3. Taking into account the number of degrees of freedom of obtained results matrix, the Student's tabular criterion is t(0.05; 36) = 2.03. Comparing the Student's tabular criterion with the one calculated in Table 3, we could discard insignificant coefficients of a regression equation (20) and finally obtain:

$$\varphi = 0.592558 - 0.00560667\, D_\mu + 0.0246133\, \delta - - 0.001995\, D_\mu\, \delta - 0.0117867\, \delta^2. \qquad (21)$$

Table 3. Statistical processing of equation (20)

Ratio	Value	Student's criterion
a_{00}	0.592558	465.7
a_{10}	–0.00560667	–8.04488
a_{20}	0.0246133	35.3171
a_{12}	–0.001995	–2.33729
a_{11}	0.00171333	1.41937
a_{22}	–0.0117867	–9.76439

A graphical representation of equation (21) is shown in Fig. 5. With the decrease in effective seed diameter D_μ and increase in variation coefficient δ, the increase in random packaging density φ of small-seeded crops' spherical seeds in the reservoir of the selection seeders sowing unit is observed. This is because seeds of smaller diameter fill the voids between the seeds of larger diameter. Increasing the density of random seed packaging can lead to the formation of arches, which renders dosing impossible. Let us test this hypothesis by determining the regular patterns of dispenser operation.

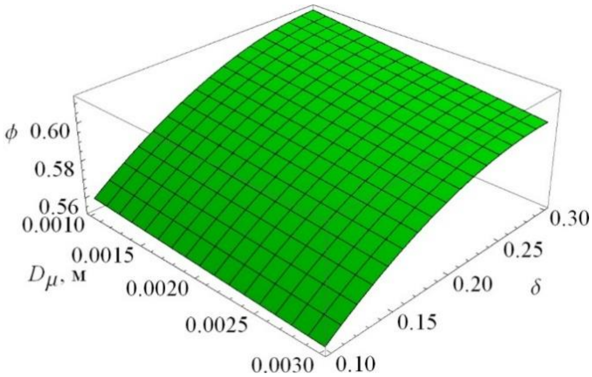

Figure 5. A regular pattern of change in random packaging density φ of small-seeded crops' seeds in the reservoir of selection seeders sowing unit in terms of effective seed diameter D_μ and its δ factor

The results of dispenser operation modelling, obtained was a visualization of the process shown in Fig. 6, while numerical data were summarized in Table 4.

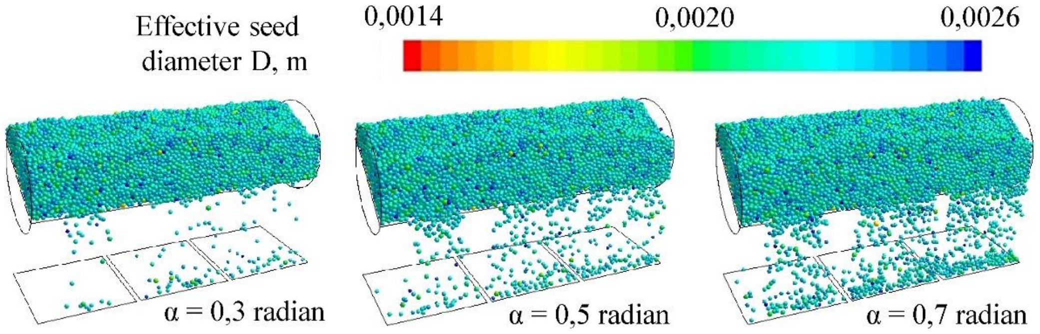

Figure 6. Visualization of dispenser operation process in selection seeders sowing unit

Table 4. Throughput Q_d of selection seeders seed sowing unit (pcs s^{-1})

φ	Hole option	Valve rotation angle α, rad														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
0.550	I	0	0	0	6	18	35	63	103	155	227	319	438	584	764	985
	II	0	0	16	38	69	109	161	227	307	403	516	648	802	978	1179
	III	0	1	30	71	124	187	263	351	450	562	685	819	965	1124	1293
0.575 most common	I	0	0	0	3	13	32	60	99	151	224	316	434	580	761	981
	II	0	0	13	35	66	107	160	224	305	399	513	646	800	976	1176
	III	0	0	11	52	105	169	246	333	432	544	667	801	947	1105	1275
0.600	I	0	0	0	1	12	30	58	97	149	222	314	432	579	760	979
	II	0	0	0	30	61	101	154	219	299	395	508	641	794	971	1172
	III	0	0	0	36	89	153	229	318	417	528	650	786	932	1090	1259
Avg.	I	0	0	0	3	14	33	60	99	152	224	316	435	581	762	981
	II	0	0	10	34	65	106	158	224	303	399	513	645	799	975	1176
	III	0	0	14	53	106	170	246	334	433	545	667	802	948	1106	1276

And – a triangle; II – semicircle; III - a rectangle

It follows from Table 4 that the throughput of dispenser Q_d of the selection seeders sowing unit does not depend on the density of random packaging φ of small-seeded crops' seeds in the reservoir. However, one can see that at the valve's inclination angle of α = 0–0.3 rad, the throughput of metering unit $Q_d = 0$. This is due to the formation of arches in the seeders reservoir. Having found the average value of dispenser's throughput Q_d for three values of density of seeds' random packaging φ, let us approximate the obtained data in the form of a third-degree polynomial (Fig. 7):

- for an option I (triangle):

$$Q_d == 494.05\,\alpha^3 - 387.74\,\alpha^2 + 130.04\,\alpha - 13.729;\; R^2 = 0.9998, \tag{22}$$

- for the II variant (semicircle):

$$Q_d = 220.92\,\alpha^3 + 213.26\,\alpha^2 - 34.755\,\alpha;\; R^2 = 0.9999, \tag{23}$$

- for option III (rectangle):

$$Q_d = -\,57.688\,\alpha^3 + 753.18\,\alpha^2 - 150.99\,\alpha;\; R^2 = 0.9998. \tag{24}$$

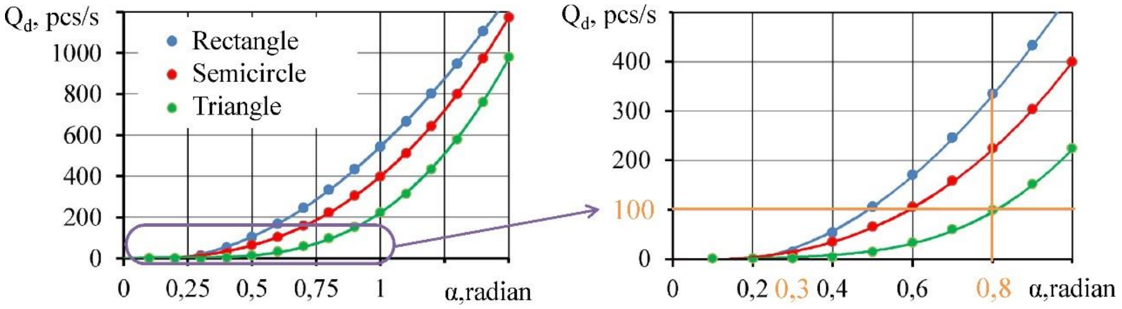

Figure 7. A regular pattern of change in the throughput of dispenser Q_d of selection seeders sowing unit depending on gate α inclination angle

Discussion

Analysis of presented studies (Molotsky *et al.*, 2006; Hakansson *et al.*, 2013; Vakhnenko, Poliakov, 2010; Makhova, Polyakov, 2012; Poliakov, Vakhnenko, 2012) and selection operation patterns (Alhassan *et al.*, 2018; Ovtov, Abrosimov, 2020) depending on biological characteristics of small-seeded crops suggests the need to create such a small seeder that can ensure sowing at all stages of the selection process (creating populations for selection; selection of desired genotypes – original elite plants; progeny testing, reproduction to production-significant volumes).

According to studies (Vakhnenko, Poliakov, 2010; Makhova, Polyakov, 2012; Poliakov, Vakhnenko, 2012; Khalansky, Gorbachev, 2004; Kryuchin, 2009) and the conditions required for normal development of vegetation, before sowing in select areas of preliminary propagation and varietal testing, significant agronomical requirements mean ensuring a uniform distribution of seeds along rows at the level not lower than 95 % (Kryuchin, 2009). Compliance with this requirement contributes to the best possible supply of nutrients to all plants.

As a result of patent data analysis (Pankov *et al.*, 2016; Shevchenko *et al.*, 2018), it has been established that electromechanical seeders are the most expedient for the selection of small-seeded crops, as they ensure high enough accuracy of sowing and have perspective opportunities for management of changes in varietal samples directly during sowing in different areas.

As a result of theoretical studies of seed movement in the reservoir of the selection seeders sowing unit, a respective system of differential equations (17) was compiled taking into account formulas (3) to (16) forming the basis of the mathematical apparatus of Star CCM + software package. According to the results of numerical simulation, obtained was the visualization of random packaging of small-seeded crops' seeds in the reservoir of selection seeders sowing unit and equation of its regression φ (21) between density and effective seed diameter D_μ, as well as coefficient of this diameter's variation δ. According to the results of numerical simulations, it has been established that the throughput of dispenser Q_d of selection seeders sowing unit does not depend on the density of random packaging φ of small-seeded crops' seeds in the reservoir. Because of data approximation, the regular pattern between the change in the throughput of dispenser Q_d of selection seeders seeds sowing unit and valve α inclination angle in the form of a third-degree polynomial (22)–(24) has been obtained. Analysis of Figure 7 and dependencies (22)–(24) allows us to the state where it is necessary to ensure the throughput of dispenser Q_d from 1 pc s^{-1} to 100 pcs s^{-1}, the angle of valve α should vary from 0.3 rad to 0.8 rad. At the seeders movement speed of 1 m s^{-1} (4 m s^{-1}), the dispenser's throughput of 1 pc s^{-1} and 100 pcs s^{-1} corresponds to the sowing rate of 50 000 pcs ha^{-1} (12 500 pcs ha^{-1}) and 5 million pcs ha^{-1} (1.25 million units ha^{-1}). To clarify this relationship, it is necessary to conduct additional research to be implemented in the future. In addition to the foregoing, graphs Q_d (α) show that the graph angle for an option I of the dispenser hole (triangle) is the smallest one. That is, the selection of the triangular shape of the dispenser allows for ensuring the greatest accuracy of seed dosing.

Conclusion

Because of research, the mathematical model of casual packing of seeds of small-seeded cultures incapacity of the sowing device of a selection seeder is developed that allowed defining the equation of regression of its density from an effective diameter of seeds and coefficient of variation of this diameter. As a result of research of process of work of the batcher of the sowing device of a selection seeder regularity of change of its throughput from an angle of inclination of a gate, type of a form of executions (triangle, semicircle, rectangle) in the form of a polynomial of the third degree are received. It is established that the choice of the triangular shape of the dispenser allows for ensuring the highest accuracy of seed dosing.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

IH – drafting of the manuscript;
DD – analysis, interpretation and acquisition of data;
VY – study conception and design;
EA –critical revision and approval of the final manuscript.

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