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RESULTS OF EXPERIMENTAL STUDIES ON THE IMPROVED SEED DELIVERY SYSTEM OF A PNEUMATIC PRECISION SEEDER

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The research is dedicated to improving the structural and technological parameters of pneumatic seeders, particularly the seed delivery system in John Deere 90 series seeders. It has been identified that existing designs have shortcomings, especially when using No-till, Strip-till, and Mini-till technologies, leading to uneven seeding and reduced yields. To enhance the efficiency of the crop seeding process, it is necessary to refine the design of the elements within the seed delivery system of the pneumatic seeder, including the seed decelerator, seed channel of the seeder shoe, and seed stabilizer, by employing well-founded structural and technological parameters that ensure precise seeding and by using materials that increase their durability.

The goal of the research was to optimize the structural parameters of the seed delivery system by developing and testing a new seed decelerator. Experimental studies were conducted using a laboratory setup that allows for variation in parameters such as air flow speed, seeder movement speed, seed injection speed, and the ratio of outlet areas to the inlet area of the seed decelerator.

As a result of the experimental studies, patterns of changes in air flow speed at the seeder shoe outlet, seed flow speed of rapeseed and peas, seeding rate, and accuracy (coefficient of variation) were established depending on the ratio of outlet areas to the inlet area of the seed decelerator, air flow speed at the inlet, seeder movement speed, and seed injection (dosing) speed. The results showed that increasing the air flow speed at the inlet leads to an increase in the flow speed at the outlet, which affects the seeding rate and accuracy. The seeder movement speed and seed injection speed significantly influence the seeding rate but may reduce accuracy.

A relationship was established between the number of holes in the seed decelerator (ε), seeder movement speed, and seeding rate, allowing for maximum seeding accuracy. The obtained equations will be used for the automated control system of the seed decelerator damper.

Key words: *seed, precision seeding, pneumatic planter, seed delivery system, seed decelerator, experiment, parameters, efficiency.*

Eq. 13. Fig. 6. Table. 2. Ref. 18.

1. Problem formulation

In modern agriculture, significant attention is given to energy-saving technologies for cultivating crops. This is one of the most important and promising areas, involving the use of new-generation agricultural machinery. These machines ensure high quality and precision at all stages of the technological process, particularly during the sowing of crops [1, 2].

To achieve these goals, new machine designs are being developed, considering the requirements for accuracy, multifunctionality, energy efficiency, and durability of structural elements. Special attention is given to the seed delivery systems in universal pneumatic precision seeders, as existing systems require improvement [3, 4]. The John Deere 90 series seeder (US Patent 7,168,376 B2 [5]) is no exception. Many pneumatic seeders manufactured by John Deere face difficulties in maintaining seeds in the seed bed, especially when using No-till, Strip-till, and Mini-till technologies. This becomes an even greater problem when working at higher speeds with shallower seeding depths in heavier soils.

2. Analysis of recent research and publications

Let's take a closer look at the main issues related to the seeding section of this planter and explore possible solutions, considering both practical operational experience and a review of the literature.

The accuracy of seeding with a pneumatic planter primarily depends on the process of transferring seeds from the seeding mechanism to the point of direct placement in the furrow formed by the opener in the soil [6]. In the case of the John Deere 90 series precision planter [7], the furrow is formed by a seed boot and a single-disc opener.

The seeds, having a high initial speed, travel a fairly long distance through the seed tube and the channel of the seed boot. During this movement, they come into contact with the walls of the seed tube, changing their speed and flight trajectory [8, 9]. As a result, even with ideal dosing in the pneumatic planter, seeds are unevenly distributed in the seedbed in all three directions. Additionally, seeds may fall out of the furrow. These factors lead to uneven seeding, with "skips" and "doubles" occurring [10]. Seeding uniformity is determined by three spatial coordinates: the distance between seeds along the seeding line, the scattering of seeds perpendicular to this line, and the seeding depth.

The distance between seeds along the seeding line primarily determines the seeding rate. For each crop in specific soil and climatic conditions, the seeding rate has a rational value, confirmed by numerous agronomic studies [11, 12, 13]. Irregularity in the distance between seeds leads to an uneven seeding rate, which can reduce yield by up to 7%.

Scattering of seeds perpendicular to the seeding line reduces the free space between rows. As a result, inter-row cultivation can damage plants, also reducing yield.

An analysis of studies [14, 15, 16] has shown that seeding depth plays a significant role in ensuring uniform germination and uniform plant development during the growing season. Such irregularity can reduce yield by up to 9% and complicate the harvesting process.

Based on observations of the basic design of the seeding section of the John Deere 90 Series pneumatic planter during numerical modeling, factors that degrade seeding accuracy were identified: high speed of the air flow and seeds, an imperfect shape of the seed channel in the seed boot, and an imperfect design of the seed decelerator [17]. To improve the efficiency of the crop planting process, it is necessary to refine the design of the elements in the seed delivery system of the pneumatic planter, particularly the seed decelerator, the seed channel in the seed boot, and the seed stabilizer, using well-grounded structural and technological parameters that ensure precise seeding, as well as employing materials that increase their durability. As a result of numerical modelling of the seed decelerator in the John Deere pneumatic planter using the Simcenter Star- CCM+ software package, a visualization of the seed and air flow movement in the working area of the decelerator was obtained [18]. The analysis of numerical modelling and the processing of the obtained data in the Wolfram Cloud software package made it possible to derive second-order regression equations describing the dependencies of air flow velocity, seed speed at the decelerator's exit, and the seeding rate change coefficient η on the air flow velocity at the inlet and the ratio of the outlet area to the inlet area ε.

3. The purpose of the article

The purpose of the experimental research is to verify the dependencies obtained during numerical modelling and to optimize the structural and technological parameters of the improved seed delivery system of the pneumatic precision planter.

4. Results of the researches

For conducting research on the improved pneumatic system of the seeding section, a laboratory setup was developed and implemented, as shown in Fig. 1. The variable factors in the experimental studies were: the air flow velocity at the inlet of the decelerator, V_a^{in}, m/s; the planter's movement speed, V_s, m/s; the seed injection (dosing) rate, Q_p, seeds/s; and the ratio of the outlet area to the inlet area, ε (Table 1).

$$\varepsilon = \frac{S_h N_h}{S_{in}} = \frac{N_h}{900}, \tag{1}$$

where S_h is the outlet area, $S_h = \pi(1/2)^2$ mm²; N_h is the number of outlet holes; and S_{in} is the inlet area, $S_{in} = \pi(30/2)^2$ mm².

Table 1

Factor variation levels

Level	The speed of the air flow at the entrance V_a^{in}, m/s	The speed of movement of the planter V_s, m/s	Seed injection (dosage) rate Q_p, pieces/s	The ratio of the area of the outlet openings to the area of the entrance ε
	x_1	x_3	x_4	x_2
-1	10	2	10	2.77
0	15	1.5	25	1.73
1	20	1	40	0.69
Δ	5	0.5	15	1.04

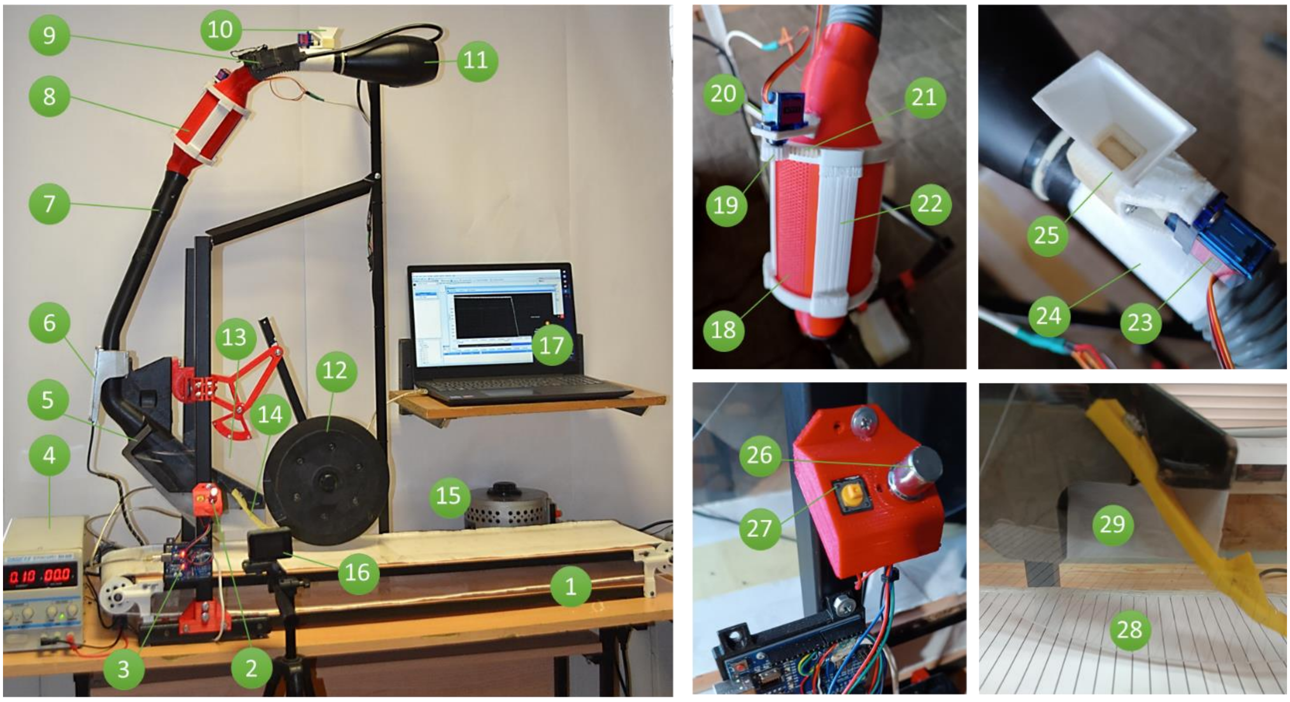


Fig. 1. Laboratory setup for studying the pneumatic system of the seeding section:

1 – Conveyor belt "moving field"; 2 – Seed delivery and decelerator control unit; 3 – Arduino Uno ATmega328P-PU; 4 – Power supply Zhaoxin RXN-305D; 5 – Seed boot; 6 – Lower seeding sensor; 7 – Air duct; 8 – Developed decelerator; 9 – Upper seeding sensor; 10 – Seed dosing feeder; 11 – Fan; 12 – Pressing wheel; 13 – Opener; 14 – Seed stabilizer; 15 – Laboratory autotransformer; 16 – Aspiring Repeat 4 Ultra HD 4K camera; 17 – Computer; 18 – Holes; 19 – Gear wheel; 20, 23 – Servo motor; 21 – Gear sector; 22 – Cylindrical shutter; 24 – Ejector; 25 – Feeder hopper; 26 – Shutter position regulator of the decelerator; 27 – Seed delivery button; 28 – "Moving field" marking; 29 – Millimeter grid.

Optimization criteria: Air flow velocity at the outlet of the boot V_a^{out}, m/s; seed flow velocity at the outlet of the boot V_p^{out}, m/s; seeding rate N, million seeds/ha; seeding accuracy (lengthwise) (coefficient of variation) δ, %. The set seeding rate N_t is calculated considering the row spacing (b_r = 0.19 m), the planter's movement speed V_s, and the seed injection (dosing) rate Q_p:

$$N_t = \frac{10000\,Q_p}{V_s b_r 1000000} = \frac{Q_p}{100 V_s b_r} \tag{2}$$

The research was conducted using the optimal Hartley-Kono plan for four factors Ha-Ko4, with a total of 18 experiments and three replications.

The laboratory setup consists of a conveyor belt "moving field" (1), above which are mounted the elements of the pneumatic system of the seeding section: a seed boot (5) with a seed stabilizer (14), a lower seeding sensor (6), an air duct (7), a seed decelerator (8), an upper seeding sensor (9), and a seed dosing feeder (10). A transparent acrylic sector (13), simulating a disc opener, is pressed against the seed boot (5), and the seed stabilizer (14) is pressed into position by a pressing wheel (12).

The seed decelerator (8) is designed with the capability to change the total cross-sectional area of the air discharge openings (18) by adjusting the position of the cylindrical shutter (22) using a servo motor (20) through a gear wheel (19) and a gear sector (21). The desired position of the shutter (22) is set remotely using the regulator (26).

For seed delivery into the pneumatic system of the seeding section, a seed dosing feeder (10) is provided, consisting of a hopper (25) equipped with a sector gate, which is operated by a servo motor (23). From the hopper (25), seeds pass through the controlled gate to the ejector (24), where they are picked up by the air flow created by the fan (11). The gate opening is also remote-controlled via button (27).

The conveyor belt "moving field" (1) is driven by a DC motor powered by the laboratory power supply Zhaoxin RXN-305D (4), with a variable speed range from 0 to 2 m/s. The required conveyor speed was monitored using a Benetech GM8905 contactless tachometer.

To determine seeding accuracy on the conveyor belt (1), markings (28) were made, and seed ejection was recorded using the Aspiring Repeat 4 Ultra HD 4K camera (16) against the backdrop of a millimeter tape (29) attached to the seed boot (5) and the marking (29). This allows for the determination of seed ejection speed and its dispersion on the conveyor (Fig. 2).

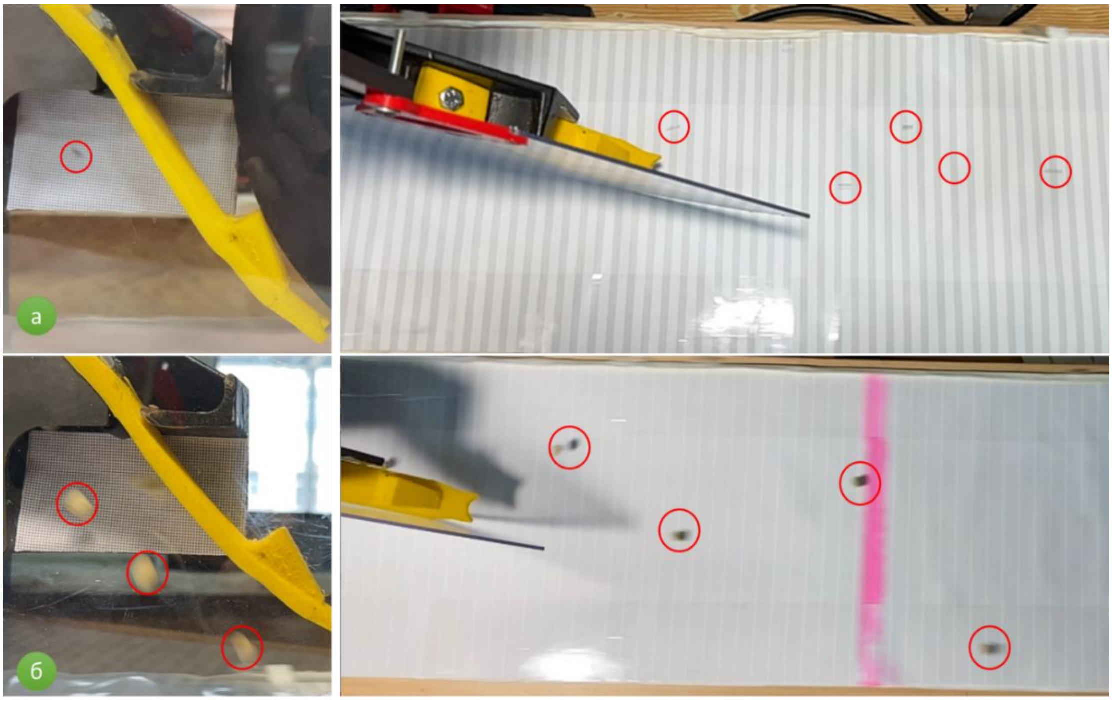


Fig. 2. Example of results obtained from the experimental setup: a – rapeseed; b – pea

The air flow velocity at the inlet of the ejector (24) was regulated by adjusting the voltage of the fan motor (11) using the laboratory autotransformer (15). The air velocity was measured using a Benetech GM816 anemometer. To monitor the movement of seeds through the seed tube, appropriate sensors were used: an upper sensor (9, AA27652, infrared) and a lower sensor (6, PP 700285, ultrasonic). Data from the sensors were sent to the Arduino Uno ATmega328P-PU board (3), and subsequently transmitted to the computer (17).

For planting material, rapeseed of the Veritas KL variety and pea of the SOMERVUD F1 Syngenta variety were used. To simplify the counting of seeds according to the experimental number, a seed vibration counter was developed and implemented.

The seed decelerator research was conducted as follows. Initially, for each crop, control measurements were taken without the decelerator. Only the seed injection (dosing) rate Q_p was varied. The air flow velocity at the inlet V_{ain} and the planter's movement speed V_s were kept constant at the upper level. Then, according to the experimental number, the corresponding values of the variable factors were set and the optimization criteria values were recorded.

As a result of the research, a data set was obtained, which, when processed using the Wolfram Cloud software package, allowed for the derivation of second-order regression equations in decoded form with significant regression coefficients:

– air flow velocity at the outlet of the boot V_a^{ou}, m/s (Fig. 3, a):

$$V_a^{out} = 9.63376 - 0.244213\, V_a^{in} + 0.0396402\, (V_a^{in})^2 - 6.03654\, \varepsilon - 0.243376\, V_a^{in}\, \varepsilon + 1.7651\, \varepsilon^2; \qquad (3)$$

– seed flow velocity of rapeseed at the outlet of the boot V_{pr}^{out}, m/s (Fig. 3, b):

$$V_{pr}^{out} = 1.88875 + 0.297615\, V_a^{in} - 2.59285\, \varepsilon - 0.090357\, V_a^{in}\, \varepsilon + 0.812033\, \varepsilon^2; \qquad (4)$$

– seed flow velocity of pea at the outlet of the boot V_{pg}^{out}, m/s (Fig. 3, b):

$$V_{pg}^{out} = 1.22357 + 0.225777\, V_a^{in} - 1.57189\, \varepsilon - 0.069286\, V_a^{in}\, \varepsilon + 0.525253\, \varepsilon^2; \qquad (5)$$

– rapeseed seeding rate N_r, million seeds/ha (Fig. 4):

$$N_r = 0.712862 + 0.073121\, Q_p - 0.36613\, V_s - 0.0298485\, Q_p\, V_s + 0.0228953\, \varepsilon; \qquad (6)$$

– pea seeding rate N_g, million seeds/ha (Fig. 4):

$$N_g = 0.874804 + 0.0664262\, Q_p - 0.485912\, V_s - 0.0257776\, Q_p\, V_s + 0.0452553\, \varepsilon; \qquad (7)$$

– rapeseed seeding accuracy (lengthwise) (coefficient of variation) δ_r, % (Fig. 5):

$$\delta_r = 80.0421 - 0.0635693\, Q_p + 0.430617\, V_a^{in} - 0.076686\, (V_a^{in})^2 - 3.18328\, V_s + 13.6126\, \varepsilon + 0.586668\, V_a^{in}\, \varepsilon - 4.33725 \qquad (8)$$

– pea seeding accuracy (lengthwise) (coefficient of variation) δ_g, % (Fig. 5):

$$\delta_g = 438 - 0.102739\, Q_p - 1.28936\, V_a^{in} + 0.00635584\, (V_a^{in})^2 - 1.79227\, V_s + 8.84909\, \varepsilon + 0.30107\, V_a^{in}\, \varepsilon - 2.20525\, \varepsilon^2 \qquad (9)$$

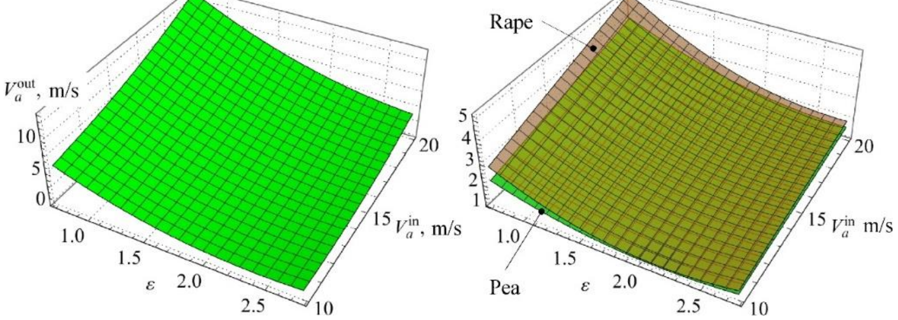
The statistical analysis (ANOVA) of the obtained equations is presented in table 2. Comparing the calculated Fisher criterion with the tabulated values shows that $F > F_{t\,0.05}$. This indicates the statistical adequacy of the obtained regression equations.

Table 2

Statistical analysis (ANOVA) of the obtained equations

Equation	A type of dispersion	Sum of squared deviations	Estimation of variance	Fisher's criterion	
				F	$F_{t\,0,05}$
(3)	Model	775.43	51.70	298.94	2.003
	Error	0.519	0.173		
(4)	Model	134.75	8.98	75.61	1.781
	Error	0.356	0.119		
(5)	Model	66.57	4.44	53.06	1.781
	Error	0.251	0.084		
(6)	Model	31.00	2.07	70.60	1.812
	Error	0.001	0.029		
(7)	Model	29.50	1.97	81.48	1.996
	Error	0.001	0.024		
(8)	Model	29.27	1.95	311.63	2.003
	Error	0.002	0.006		
(9)	Model	1404.00	93.11	203.23	2.003
	Error	0.014	0.458		

Analysis of Fig. 3 shows that increasing the air flow velocity at the inlet V_a^{in} leads to an increase in the air flow velocity at the outlet of the boot V_a^{out} and the seed flow velocity of rapeseed and pea at the outlet of the boot V_{pr}^{out}. These velocities can be reduced by increasing the number of openings on the seed decelerator, i.e., by increasing the ratio ε. Fig. 3 also shows that the seed velocity of pea is lower than that of rapeseed. This is mainly explained by the different geometric sizes and mass of the seeds.



a ***b***

Fig. 3. Dependencies of the air flow velocity at the outlet of the boot \(V_{aout}\) (a) and the seed flow velocity of rapeseed and pea at the outlet of the boot \(V_{pout}\) (b) on the factors of the study

Figures 4 and 5 show the dependencies of the seeding rate N and seeding accuracy (lengthwise) δ for rapeseed and pea on the factors of the study. Increasing the air flow velocity V_a^{in} has little effect on the seeding rate N. However, increasing the number of openings on the seed decelerator (ratio ε) leads to a slight increase in the seeding rate N (up to 8%), which needs to be corrected by adjusting the seed injection (dosing) rate Q_p. The seeding accuracy (lengthwise) δ is significantly influenced by the number of openings on the seed decelerator (ratio ε) and the air flow velocity at the inlet \(V_{ain}\). This is explained by the fact that changes in these factors affect the seed velocity V_p^{out} (Fig. 3), which in turn strongly influences the seeding accuracy δ. The speed of the planter V_s and the seed injection (dosing) rate Q_p logically affect the seeding rate N. However, increasing these speeds leads to a decrease in seeding accuracy by up to 4%. Therefore, the best seeding accuracy is achieved at lower planter speeds.

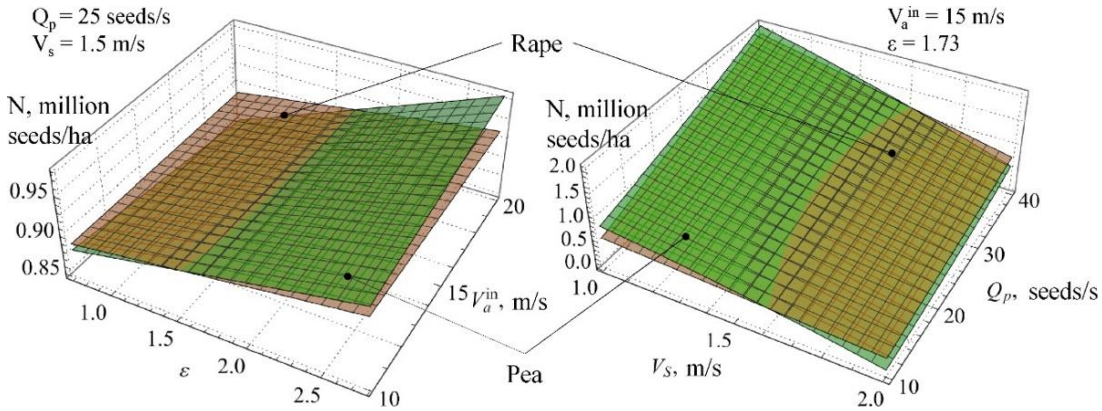


Fig. 4. Dependencies of the seeding rate of rapeseed and pea N on the factors of the study

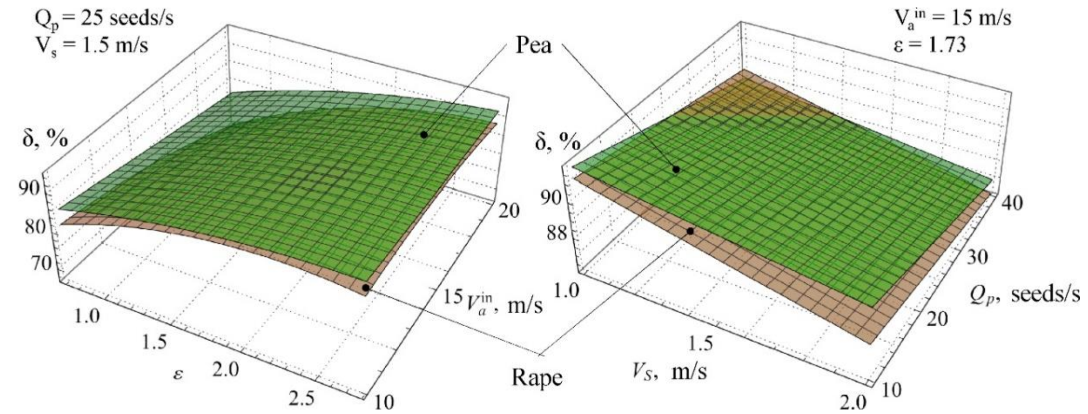


Fig. 5. Dependencies of seeding accuracy (lengthwise) of rapeseed and pea (coefficient of variation) δ on the factors of the study

To determine the equation for how the number of openings on the seed decelerator (ratio \(\epsilon\)) should change, we will use the following condition:

$$\begin{cases} N\left(V_a^{in}, V_s, Q_p, \varepsilon\right) \to N_t = \dfrac{Q_p}{100 V_s b_r}, \\ \delta\left(V_a^{in}, V_s, Q_p, \varepsilon\right) \to \max. \end{cases} \qquad (10)$$

Solving the system of equations (10) together with (3)–(9) in the Wolfram Cloud software yields the dependency of the number of openings on the seed decelerator (ratio ε), the planter speed V_s, and the specified seeding rate N_t, while ensuring maximum seeding accuracy δ (Fig. 6):

$$\varepsilon_r = -1.87928 + 2.63625\ N_t + 0.965211\ V_s - 3.66254\ N_t\ V_s + 1.49507\ N_t\ V_s^2, \qquad (11)$$

$$\varepsilon_g = -2.39305 + 2.73553\ N_t + 1.32923\ V_s - 3.45251\ N_t\ V_s + 1.33979\ N_t\ V_s^2. \qquad (12)$$

Seeding accuracy ranged from 89.6% to 94.3%, while the seed velocity at the outlet of the boot varied from 1.1 m/s to 2.4 m/s.

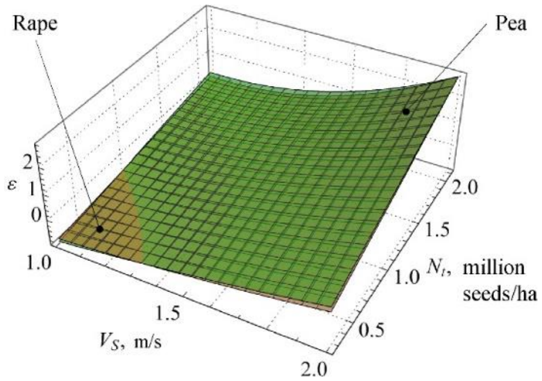


Fig. 6. Dependency of the number of openings on the seed decelerator (ratio \(\epsilon\)) on the planter speed V_s and the specified seeding rate N_t

Analyzing Figure 6, it is evident that the dependencies for rapeseed and pea are nearly identical, which is confirmed by a high correlation coefficient of 0.98. Therefore, by averaging the two equations, we obtain the final formula:

$$\varepsilon = -2.13617 + 2.68589\, N_t + 1.14722\, V_s - 3.55752\, N_t\, V_s + 1.41743\, N_t\, V_s^2. \qquad (13)$$

Equation (12) will be used for the automated control system of the seed decelerator gate, which will allow for the adjustment of the seeding rate during planter movement.

5. Conclusions and prospects for further research

In order to conduct experimental research, a laboratory setup has been developed for researching the improved seed supply system of the John Deere 90 Series precision pneumatic seeder, which allows you to vary parameters such as the speed of the air flow, the speed of movement of the seeder, the speed of seed injection and the ratio of the area of the outlet holes to the area of the entrance seed retardant.

As a result of experimental studies, the regularities of changes in the air flow rate at the exit from the shoe V_a^{out}, the flow rate of rapeseed and pea seeds V_p^{out}, the rate of N and the accuracy of sowing (coefficient of variation) δ from the ratio of the area of the outlet holes to the area of the entrance of the seed retarder ε, the air flow rates at inputs V_a^{in}, movement of the seeder V_s and injection (dosage) of seeds Q_p. The results showed that an increase in the speed of the air flow at the entrance leads to an increase in the speed of the flow at the exit, which, in turn, affects the accuracy and rate of sowing. The speed of movement of the planter and the speed of seed injection significantly affect the rate of sowing, but at the same time can reduce accuracy.

The relationship between the number of holes on the seed retarder ε, the movement speed of the seeder V_s and the sowing rate N_t was established, which allows to achieve the maximum accuracy of sowing. The resulting equations will be used for the automated control system of the damper on the seed retarder.

Optimized parameters and dependencies can be applied to automate and increase the efficiency of pneumatic planters, which will contribute to improving the quality of crops and reducing seed losses.

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РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ УДОСКОНАЛЕНОЮ СИСТЕМИ ПОДАЧІ НАСІННЯ ПНЕВМАТИЧНОЇ СІВАЛКИ ТОЧНОГО ВИСІВУ

Дослідження присвячене покращенню конструктивних і технологічних параметрів пневматичних сівалок, зокрема, системи подачі насіння у сівалках серії John Deere 90. Визначено, що наявні конструкції мають недоліки, особливо при використанні технологій No-till, Strip-till, Mini-till, що призводить до нерівномірного висіву і зниження врожайності. Для підвищення ефективності процесу сівби культурних рослин необхідно удосконалити конструкції елементів системи подачі насіння пневматичної сівалки, зокрема сповільнювач насіння, насіннєвий канал висівного башмака та *заспокоювач насіння, використовуючи обґрунтовані конструктивно-технологічні параметри, які забезпечують точний висів, а також застосування матеріалів, що підвищують їх довговічність. Мета дослідження полягала в оптимізації конструктивних параметрів системи подачі насіння шляхом розробки і тестування нового сповільнювача насіння. Для цього було проведено експериментальні дослідження з використанням лабораторної установки, що дозволяє варіювати параметри, такі як швидкість повітряного потоку, швидкість переміщення сівалки, швидкість інжекції насіння та відношення площ випускних отворів до площі входу сповільнювача насіння.*

У результаті експериментальних досліджень встановлено закономірності зміни швидкості повітряного потоку на виході з башмака, швидкості потоку насіння ріпаку та гороху, норми і точності висіву (коефіцієнт варіації) залежно від відношення площі випускних отворів до площі входу сповільнювача насіння, швидкості потоку повітря на вході, швидкості руху сівалки та інжекції (дозування) насіння. Результати показали, що збільшення швидкості повітряного потоку на вході призводить до підвищення швидкості потоку на виході, що впливає на точність і норму висіву. Швидкість руху сівалки та швидкість інжекції насіння мають суттєвий вплив на норму висіву, але при цьому можуть знижувати точність.

Встановлено залежність взаємозв'язку між кількістю отворів на сповільнювачі насіння (ε), швидкістю руху сівалки та нормою висіву, що дозволяє досягти максимальної точності висіву. Отримані рівняння будуть використані для автоматизованої системи керування заслінкою на сповільнювачі насіння.

Ключові слова: *насіння, точний висів, пневматична сівалка, система подачі, сповільнювач насіння, експеримент, параметри, ефективність.*

Ф. 13. Рис. 6. Табл. 2. Літ. 18.

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