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Simulation of an improved seed delivery system for a pneumatic grain seeder

Abstract. The objective of this research was to enhance the precision of seed placement in the John Deere pneumatic planter by improving the design of its seed delivery system within the seeding section. The upgraded seeding section incorporated several key components: an upper and lower seed sensor, a seed retarder composed of a perforated cylinder with holes, upper and lower narrowing nozzles, a cylindrical shutter with a rigidly mounted curved toothed rack, and a servo drive with a gear wheel. These modifications aimed to improve seed distribution uniformity and optimise planting accuracy. Numerical simulations of the seed retarder, conducted using the Simcenter Star-CCM+ software package, allowed for the visualisation of both seed movement and airflow dynamics within the working area of the retarder. Regression equations of the second order were formulated based on numerical simulations and data processing in the Wolfram Cloud software package. These equations, refined by removing insignificant coefficients in accordance with the Student's t-test, described the dependencies of key parameters: the air velocity at the seed retarder's outlet (V_a^{out}), the seed velocity at the outlet (V_p^{out}), and the seed rate change coefficient (η) as functions of the inlet air velocity (V_a^{in}) and the ratio of the outlet area to the inlet area (ε). According to agronomic standards, the permissible seed rate deviation should not exceed 1%. Comparative numerical simulations were performed for both the standard and modified designs of the John Deere 90 Series pneumatic seeder's seeding section. The results indicated that the improved design yielded superior performance, ensuring more uniform seed placement. The spacing between seeds in the modified version ranged from 0.0404 m to 0.0493 m, with a coefficient of variation of 0.223, corresponding to an average spacing of

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0.0448 ± 0.004 m. These findings confirmed that the enhanced seeding section meets the required precision standards for optimal seeding accuracy, leading to improved crop establishment and yield potential. The research results can be used for further optimisation of pneumatic seeders to improve seeding accuracy and reduce yield losses

Keywords: retarder; parameters; sowing accuracy; speed; air flow

INTRODUCTION

Optimisation of agricultural machinery helps preserve soil structure, enhancing aeration and water permeability, which is essential for maintaining soil fertility. Bionic colters, designed based on natural analogs, minimise soil erosion and contribute to sustainable agricultural practices. By tailoring the design to different soil types, these colters can be used more effectively in various agro-climatic conditions. Implementing such advanced technologies in farming not only increases productivity but also reduces environmental impact, promoting more sustainable and eco-friendly agricultural practices.

To achieve these goals, new machine designs are being developed that take into account the requirements for precision, multifunctionality, energy efficiency, and structural durability. The study by D. Xiong *et al.* (2021) focused specifically on seed delivery systems in universal precision pneumatic planters, as existing systems require further refinement. Many pneumatic planters struggle to retain seeds in the seedbed, particularly under no-till, strip-till, or mini-till conditions. This issue becomes even more pronounced when operating at high speeds, with shallower seeding depths on compacted or harder soils. A closer examination of the key issues related to the seeding section of this type of planter is warranted, with possible solutions being explored based on both practical experience. According to the studies by K. Li *et al.* (2023), the precision of seeding in a pneumatic planter is primarily determined by the process of seed movement from the metering device to the point where they are deposited into the furrow created by the opener in the soil.

Seeds, having high initial velocity, travel a relatively long distance through the seed tube and the seed boot channel. Previous work by M. Wei *et al.* (2022) showed that airflow-assisted seed delivery can reduce variation in plant spacing caused by collisions with seed tube walls, but accelerated seeds may still bounce and lead to uneven spacing. Specifically, in precision seeding devices based on airflow-assisted seed delivery, seeds were observed to contact surfaces and bounce, resulting in uneven plant spacing at higher speeds, demonstrating that controlling seed velocity and trajectory remained an open challenge. Research by H. Tang *et al.* (2023) has also highlighted issues in pneumatic high-speed seed metering for maize, where traditional pneumatic systems, while effective for carrying seeds, did not fully prevent irregularities in seeding quality as operating speeds increased, indicating limitations in controlling seed placement under high dynamic conditions.

Developments by H.-T. Lin & Y.-H. Lee (2023) in precision pneumatic seeding devices, such as a precision pneumatic plug tray seeder with real-time trajectory tracking, addressed trajectory control via adaptive feedback systems, improving single-seeding accuracy but still focusing on tray systems rather than in-row transport dynamics in field planters. Seeding uniformity was determined along three spatial coordinates: the distance between seeds along the planting row, the seed dispersion perpendicular to the row, and planting depth. The distance between seeds along the row primarily determines the seeding rate. For each crop, under specific soil-climatic conditions, the seeding rate had an optimal value, as confirmed by numerous agronomists, including G.S. Dhillon *et al.* (2022). Uneven seed spacing leads to irregular seeding rates, which can reduce yield by up to 7%. Seed dispersion perpendicular to the row decreases the free space between rows. As a result, during inter-row cultivation, plants may be cut, which also lowers yield. Analysis of research by G. Dozet *et al.* (2020) showed that planting depth plays a crucial role in the uniformity of seedling emergence and consistent plant development during the growing season. Such unevenness can reduce yield by up to 9% and pose challenges during harvesting. Despite these advances, problems remained unresolved in prior studies: (1) effective reduction of seed velocity fluctuations within seed tubes of field pneumatic planters, (2) comprehensive understanding of how seed-wall interactions influence three-axis distribution in high-speed planting, and (3) integration of airflow design with seeding unit geometry to minimise “skips” and “doubles” under field conditions.

The aim of this article is to improve the seeding accuracy of the John Deere pneumatic planter by investigating the impact of airflow parameters and structural modifications to the seed retarder on seed velocity and distribution uniformity, as well as developing regression models to assess these effects.

MATERIALS AND METHODS

The improved seeding system of the pneumatic planter (Fig. 1) included an upper seeding sensor mounted on the seed tube, a lower seeding sensor placed on the seeding boot, and a seed retarder located between the seed tube and the seeding boot. The seed retarder consisted of a perforated cylinder with holes, an upper narrowing nozzle, a lower narrowing nozzle, a cylindrical curtain with a rigidly attached curved toothed rack, and a servo drive with a toothed wheel. The control unit was connected by electrical wiring to the upper and lower seeding sensors, as well as the servo drive.

Based on research by E. Aliiev (2019; 2023), a model of the seed retarder was constructed in the Simcenter

STAR-CCM+ software package to achieve the stated goal. The design and generated mesh of the internal area of the seed retarder, along with the geometric dimensions, were presented in Figure 2.

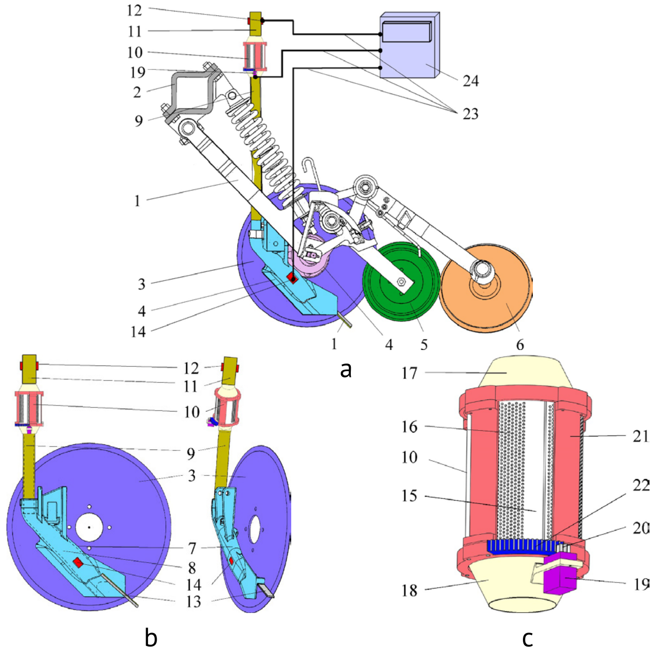

Figure 1. Structural-technological scheme of the improved seeding section of the pneumatic planter
Note: 1 – frame; 2 – clamp; 3 – single-disc furrow opener; 4 – bearing assembly; 5 – gauge wheel; 6 – closing wheel; 7 – seeding boot; 8 – seed channel; 9 – seed tube; 10 – seed retarder; 11 – seed conduit; 12 – upper seeding sensor; 13 – seed agitator; 14 – lower seeding sensor; 15 – perforated cylinder; 16 – perforations; 17 – upper narrowing nozzle; 18 – lower narrowing nozzle; 19 – servo drive; 20 – toothed wheel; 21 – cylindrical curtain; 22 – curved toothed rack; 23 – electrical wires; 24 – control unit
Source: compiled by the authors

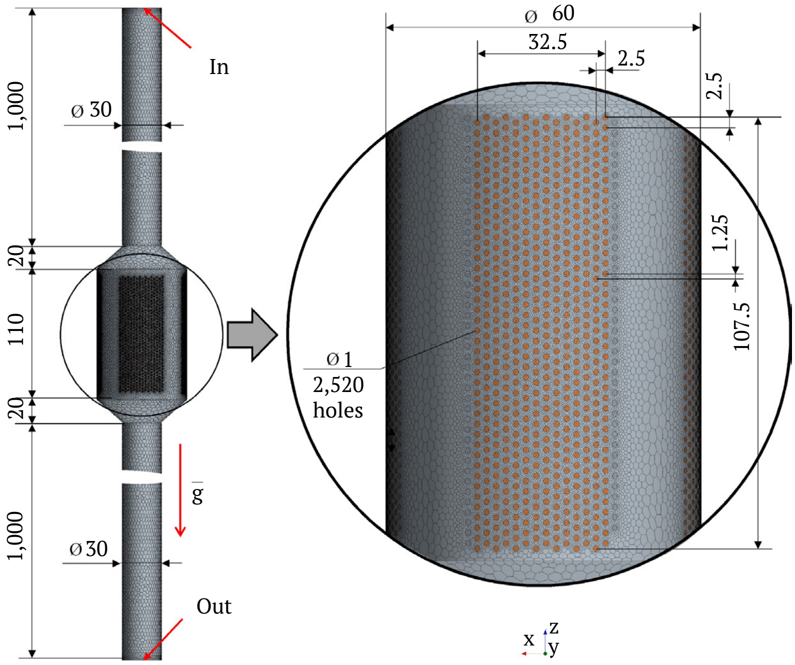

Figure 2. Design and generated mesh of the inner region of the seed retarder
Note: all sizes are in mm; g – free fall acceleration, m/s²
Source: compiled by the authors

The geometric dimensions of the seed retarder were determined considering its possible placement and the structural features of the John Deere pneumatic planter. The following volume mesh generation models were applied in the Simcenter STAR-CCM+ software package: polyhedral mesh generator, surface mesh generator, extruder. The supporting parameters of these generators were set as follows: base size – 0.004 m; surface growth rate – 1.3; relative minimum size for cell decomposition – 10 %; minimum acceptable quality of facets – 0.001 m. The following physical models were applied for numerical simulation: real gas (air) Van der Waals model; *k-ε* turbulence model; segregated flow model; Lagrangian multiphase model, specifically the discrete element method (DEM) accounting for multiphase interaction. The simulation was conducted in a three-dimensional space with a non-stationary implicit solver. For air, the following physico-mechanical properties were assigned: dynamic viscosity – 1.85508×10^{-5} Pa · s; turbulent Prandtl number – 0.9; molecular mass – 28.9664 kg/kmol.

Pea seeds were selected as DEM particles, assuming a spherical shape. The physico-mechanical properties of the seeds were determined based on laboratory studies of pea seeds in accordance with M. Paksoy & C. Aydin (2006), İ. Yalçın *et al.* (2007), and K.M. Mahawar *et al.* (2018): effective diameter – 0.008 m; true density – 1,180 kg/m³; Poisson's ratio – 0.32; Young's modulus – 70 MPa. The following values were applied for particle-particle interactions: static friction coefficient – 0.62, normal and tangential coefficient of restitution – 0.3, absence of linear cohesion. The gravitational force vector according to Figure 2 had coordinates (0; 0.0; –9.81) m/s². The following boundary conditions were applied (according to Fig. 2): "In" boundary (diameter – 30 mm) – air velocity inlet model (V_{in}); "Out" boundary (diameter – 30 mm) – implicit outlet model; "holes" boundary (diameter – 1 mm, total quantity – 2520 pcs) – implicit outlet model; other boundaries – wall model. All boundaries except "Out" were impermeable to DEM particles (seeds). An injector of DEM particles (seeds) with 100 points was placed on the "Inlet" boundary. The probability of using a point for seed generation was set to 0.5. According to studies by S.I. Popov *et al.* (2022), the seeding rate of peas using conventional technology was 1.2 million seeds/ha. Considering the row spacing of 0.19 m, this gave 22.8 seeds/m or a seed spacing in the row of 0.044 m. The planter's seeding speed was assumed to be 1.5 m/s in accordance with V. Salo *et al.* (2022). Then, the injection speed of seeds at the top of the seed tube was calculated as 34.09 seeds/s. The initial seed velocity was assumed equal to the flow velocity.

The timestep of the solver was set to 0.01 s, with a maximum internal iterations value of 10, and an exposure time of 10 s. As research factors, the following were applied: the inlet air flow velocity V_a^{in} (5-25 m/s, step – 5 m/s), the ratio of the area of the outlet holes to the inlet area ε, defined as:

$$\varepsilon = \frac{S_h N_h}{S_{in}}, \quad (1)$$

where S_h – the area of the outlet hole (mm²), S_{in} – the inlet area (mm²), N_h – number of holes. By varying the number of outlet holes, the range of the $\boldsymbol{\varepsilon}$ factor was obtained: $\varepsilon = 0$ ($N_h = 0$), $\varepsilon = 0.4$ ($N_h = 360$), $\varepsilon = 0.8$ ($N_h = 720$), $\varepsilon = 1.2$ ($N_h = 1{,}080$), $\varepsilon = 1.6$ ($N_h = 1{,}440$), $\varepsilon = 2$ ($N_h = 1{,}800$), $\varepsilon = 2.4$ ($N_h = 2{,}160$), $\varepsilon = 2.8$ ($N_h = 2{,}520$). By sequentially assigning factor values, 40 experiments were conducted (8 × 5). The criteria for the experiments included the outlet air flow velocity V_a^{out}, the seed velocity at the outlet V_p^{out}, and the coefficient of seeding rate change η, defined as:

$$\eta = \frac{Q_{out}}{Q_{in}}, \quad (2)$$

where Q_{out} was defined the seeding rate at the outlet (seeds/s) and Q_{in} as the seeding rate at the inlet (seeds/s).

The second phase of the numerical modeling process used the Simcenter STAR-CCM+ software suite to develop 3D models of the key components of the precision seed section of the John Deere 90 Series pneumatic planter (Fig. 3), based on the data from M. Johnston (2003).

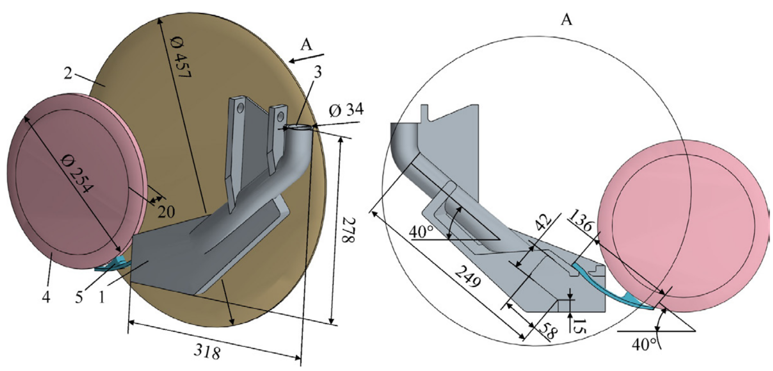

Figure 3. Geometric dimensions of the 3D model of the precision seed section of the John Deere 90 Series pneumatic planter

Note: all sizes are in mm; A – projection; 1 – seed boot; 2 – single disc furrow opener; 3 – seed tube; 4 – seedlock wheel; 5 – seed flap

Source: compiled by the authors

As the Lagrangian phase of the soil, DEM particles were applied with the following models: spherical particle, solid, constant density. The physico-mechanical properties of the soil particles were adopted according to research I. Shevchenko (2016) and had the following values: density – 1,100 kg/m³, Poisson's ratio – 0.41, Young's modulus – 1.5×10^7. The interaction between seeds with each other and with the impermeable walls of the seed retarder was governed by the Hertz-Mindlin contact model. The static friction coefficient was assumed to be 0.61, the normal coefficient of restitution was 0.5, and the tangential coefficient of restitution was 0.3. According to research I. Shevchenko (2016), the particle size distribution of the soil followed a normal Gaussian distribution ranging from 10 mm to 36 mm. The distribution of soil particles in the study area (overseed, seeding, and undersowing layers) by size was shown in Figure 4. The soil depth was divided into 10 layers with a thickness of 0.02 m. The parameters of the non-stationary implicit solver Simcenter STAR-CCM+ were set as follows: time interval between steps – 0.01 s; maximum number of iterations per step – 5; time discretisation – first-order accuracy; minimum and maximum values of the Courant number for Lagrangian multiphase – 0.2 and 0.5, respectively; the total simulation time was 10 s.

A cross-section of the soil model area where the seed boot and single disc furrow opener of the precision seed section of the pneumatic planter passed was shown in Figure 4. In Figure 4, seeds that entered the tillage horizon of the soil consisting of the overseed (0-0.04 m), seeding (0.04-0.08 m), and undersowing (0.08-0.24 m) layers were marked.

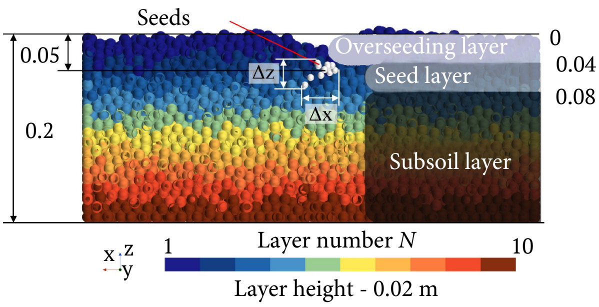

Figure 4. Cross-section of the soil model area
Note: all sizes are in m; N – layer number; Δx, Δz – deviation of the location of seeds in the soil along the x and z axes, respectively, m
Source: compiled by the authors

As a research factor, two variants were applied: the basic and improved (with seed retarder) designs of the seed section. The presence of the seed retarder in the seed section design was represented by changing the initial seed and air feed velocities. The quality criteria for seeding included the uniformity of seed distribution along the seeding line $\varepsilon_{\Delta y}$ and the dispersion of seeds in the depth Δz and width Δx of seeding. Data processing of numerical modelling was performed in the Wolfram Cloud software package.

RESULTS AND DISCUSSION

As a result of the first stage of numerical modelling, visualisations of the seed movement process in the seed retarder were obtained (Fig. 5).

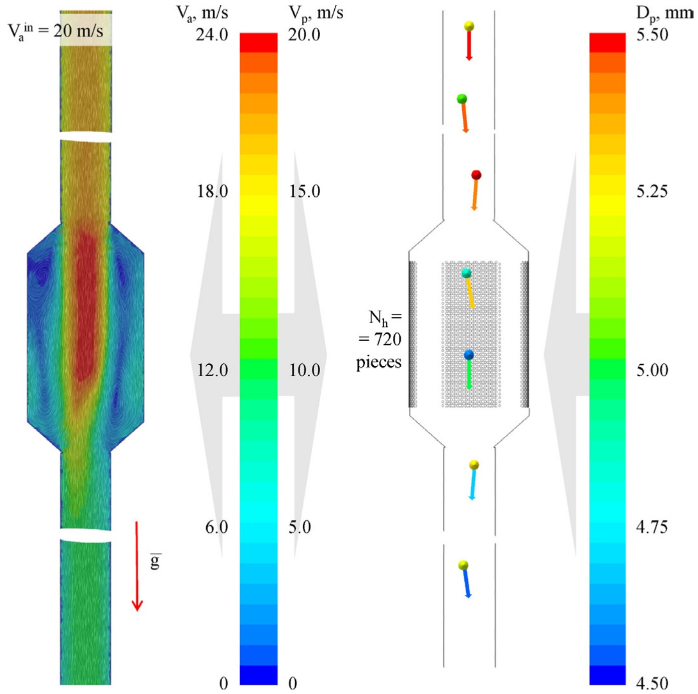

Figure 5. Visualisation of seed movement process in the seed retarder at $V_a^{in} = 20$ m/s, $\varepsilon = 0.8$
Note: V_a^{in} – inlet air flow velocity, m/s; V_a – air flow velocity, m/s; V_p – seed velocity, m/s; N_h – is number of holes; D_p – seed diameter, mm
Source: compiled by the authors

Based on the results of numerical modelling and processing of the obtained data, regression equations of the third order $V_a^{out}(V_a^{in}, \varepsilon)$ were obtained in decoded form without considering insignificant coefficients using the t-Student criterion (Fig. 6):

$$V_a^{out} = 0.4622 + 0.9319\, V_a^{in} - 2.558\, \varepsilon - 0.5134\, V_a^{in}\, \varepsilon + \\ + 2.436\, \varepsilon^2 + 0.1010\, V_a^{in}\, \varepsilon^2 - 0.5795\, \varepsilon^3. \quad (3)$$

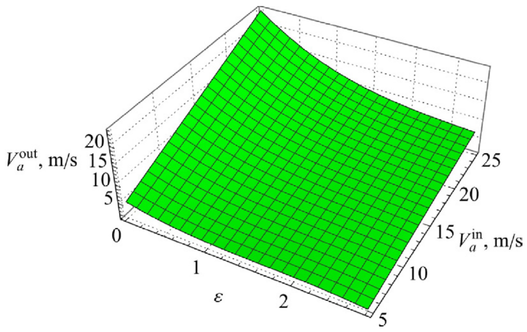

Figure 6. Dependence of outlet air flow velocity V_a^{out} of the seed retarder on the inlet air flow velocity V_a^{in} and the ratio of outlet hole area to inlet area ε
Note: V_a^{in} – inlet air flow velocity, m/s; ε – ratio of outlet hole area to inlet area; V_a^{out} – outlet air flow velocity, m/s
Source: compiled by the authors

Validation of the obtained equation using the Pearson correlation coefficient ($r = 0.95$) confirmed the adequacy of equation (3) within the investigated range of factor variation. Similarly, third-order regression equations $V_p^{out}(V_a^{in}, \varepsilon)$ were derived in decoded form without insignificant coefficients using the t-Student criterion (Fig. 7):

$$V_p^{out} = 0.5722 + 0.9093\, V_a^{in} - 3.747\, \varepsilon - 0.6304\, V_a^{in}\, \varepsilon + \\ + 3.566\, \varepsilon^2 + 0.1383\, V_a^{in}\, \varepsilon^2 - 0.8478\, \varepsilon^3. \quad (4)$$

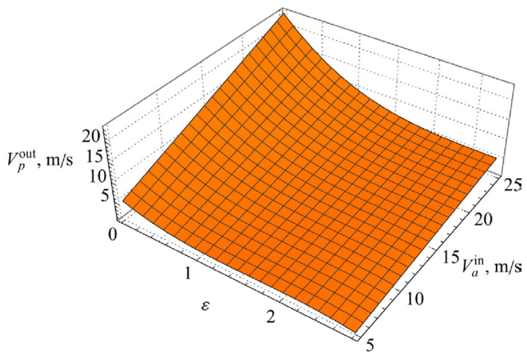

Figure 7. Dependence of seed velocity at the outlet V_p^{out} of the seed retarder on the inlet air flow velocity V_a^{in} and the ratio of outlet hole area to inlet area ε
Note: V_a^{in} – inlet air flow velocity, m/s; ε – the ratio of outlet hole area to inlet area; V_p^{out} – seed velocity at the outlet, m/s
Source: compiled by the authors

Validation of equation (4) using the Pearson correlation coefficient ($r = 0.94$) confirmed its adequacy within the investigated factor range. Similarly, a third-order regression equation $\eta(V_a^{in}, \varepsilon)$ was obtained in decoded form without insignificant coefficients using the t-Student criterion (Fig. 8):

$$\eta = 0.9795 + 0.000099\, V_a^{in} + 0.07435\, \varepsilon - 0.00341\, V_a^{in}\, \varepsilon - \\ - 0.0687\, \varepsilon^2 + 0.00238\, V_a^{in}\, \varepsilon^2 + 0.0165\, \varepsilon^3. \quad (5)$$

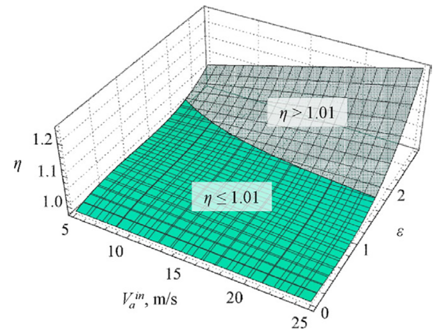

Figure 8. Dependence of the seeding rate change coefficient η on the inlet air flow velocity V_a^{in} and the ratio of outlet hole area to inlet area ε of the seed retarder
Note: V_a^{in} – inlet air flow velocity, m/s; ε – the ratio of outlet hole area to inlet area; η – seeding rate change coefficient
Source: compiled by the authors

Validation using the Pearson correlation coefficient ($r = 0.92$) confirmed the adequacy of equation (5) within the investigated range. Since optimal factor values differed for individual research criteria, a compromise optimisation problem was formulated as:

$$\begin{cases} V_p^{out}(V_a^{in}, \varepsilon) \to min, \\ \eta(V_a^{in}, \varepsilon) \le 1{,}01. \end{cases} \quad (6)$$

Problem (6) was solved using the Wolfram Cloud software package. A graphical interpretation of the solution of equation (6) together with equations (4) and (5) was presented in Figure 9. The boundary separating the two regions determined the relationship between ε and V_a^{in}, expressed as:

$$\varepsilon = 0.567137 + 0.172935\, V_a^{in} + \\ + 0.00344297\, (V_a^{in})^2 - 0.0000296843\, (V_a^{in})^3. \quad (7)$$

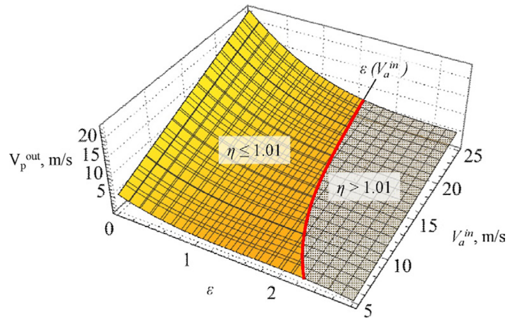

Figure 9. Graphical interpretation of the solution to equations (6) together with (5) and (4)
Note: V_a^{in} – inlet air flow velocity, m/s; ε – the ratio of outlet hole area to inlet area; V_p^{out} – seed velocity at the outlet, m/s; η – seeding rate change coefficient
Source: compiled by the authors

Substitution of equation (7) into equations (3), (4), and (5) made it possible to determine the following ranges of variation of the research criteria: $V_a^{out} \in [1.8; 9.4]$ m/s, $V_p^{out} \in [1.5; 6.6]$ m/s, $\varepsilon \in [1.60; 2.26]$. Equation (7) described the dependence of ε on V_a^{in} under condition (6). Within the specified range of V_a^{in}, ε was adjusted from 1.60 to 2.26.

As a result of the second stage of numerical modelling of the operation of the precision seed section of the John Deere 90 Series pneumatic planter, visualisations of soil aggregate distribution and velocity fields were obtained (Fig. 10). The maximum velocity of soil aggregates was 1.5 m/s. Based on the visualisation, the distribution of seeds within the tillage horizon and the furrow formed by the rolling of the seedlock wheel was clearly observed.

Visualisation of seed distribution along the seeding line (*y*-axis) and in depth (*z*-axis) was presented in Figure 11. The spatial distribution of seeds within the tillage horizon was illustrated in Figures 11 and 12. Based on these figures, the main statistical indicators of seeding accuracy were determined, including minimum, maximum, and average values, range, root-mean-square deviation, and coefficient of variation. The obtained indicators were summarised in Table 1.

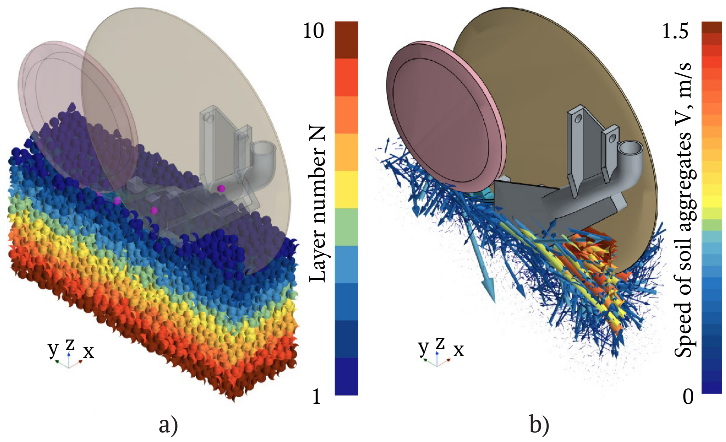

Figure 10. Visualisation of soil aggregates distribution (a) and their velocities (b) under the action of the precision seed section of the pneumatic planter

Source: compiled by the authors

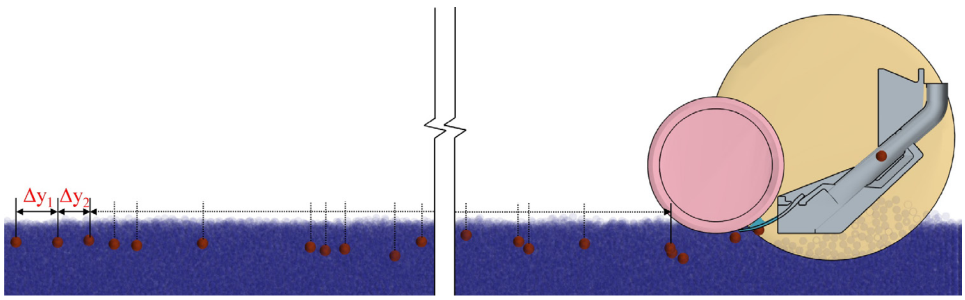

Figure 11. Visualisation of seed distribution resulting from seeding by the pneumatic planter

Note: Δy_1, Δy_2 – distance between seeds in the soil, m

Source: compiled by the authors

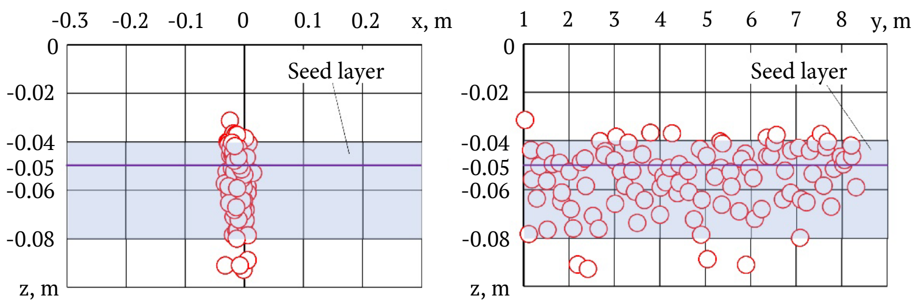

Figure 12. Seed distribution in the tillage horizon of the soil during seeding by the John Deere 90 Series planter

Note: x, z – coordinates, m

Source: compiled by the authors

Table 1. Results of numerical modelling of the seeding process by the John Deere 90 Series pneumatic planter for basic and improved designs

Indicator	*x, m*	*Δy, m*	*z, m*
Basic construction: $V_a^{out}=20$ m/s, $V_p^{out}=19.4$ m/s, ε = 0			
Minimum value	– 0.03308	0.001752	– 0.09262
Maximum value	0.014296	0.119157	– 0.03118
Limit	0.023688	0.058703	0.030719
Mean square deviation	0.009868	0.029303	0.013423
Average value	– 0.00851	0.043593	– 0.04164
Coefficient of variation	– 1.15896	0.672183	– 0.32239
Improved design (with seed retarder): $V_a^{out}=9.4$ m/s, $V_p^{out}=6.6$ m/s, ε = 2.26			
Minimum value	– 0.02977	0.040433	– 0.04631
Maximum value	0.01286	0.049324	– 0.04011
Limit	0.02131	0.004445	0.003101
Mean square deviation	0.005052	0.010627	0.00953
Average value	– 0.00827	0.044878	– 0.04973
Coefficient of variation	– 0.61091	0.223679	– 0.21306
Requirements for sowing accuracy			
Normalized value	± 0.025	0.044 ± 0.015	– 0.05 ± 0.01

Note: V_a^{out} – outlet air flow velocity, m/s; V_p^{out} – seed velocity at the outlet, m/s; *ε* – the ratio of outlet hole area to inlet area; *x*, *y*, *z* – seed placement coordinate, m
Source: compiled by the authors

Comparison of the obtained indicators with standardised values demonstrated that seed distribution along the x-axis met the specified requirements for both variants. Along the *z*-axis (seeding depth), the basic design exceeded standardised limits, with an average seeding depth of 0.041 ± 0.03 m, compared to 0.0497 ± 0.003 m for the improved design, while the standardised value was 0.05 ± 0.01 m. Visual analysis showed that some seeds in the basic design did not reach the seeding layer (0.04-0.08 m). For the basic design, a high unevenness of seeding along the seeding line was identified, with seed spacing ranging from 0.0017 m to 0.1192 m and a coefficient of variation of 0.672, compared to the standardized spacing of 0.044 ± 0.015 m. Only 47.5% of seeds met the standardised accuracy requirements. For the improved design, significantly better results were obtained, with seed spacing ranging from 0.0404 m to 0.0493 m and a coefficient of variation of 0.223, corresponding to 0.0448 ± 0.004 m. Thus, the improved design fully met the seeding accuracy requirements. The results of numerical modelling confirmed the effectiveness of incorporating a seed decelerator into the design of the pneumatic seeding unit. Adjustment of the decelerator parameters ensured stabilisation of seed outlet velocity and reduced seed dispersion in both depth and width of sowing. The obtained third-order regression equations confirmed the adequacy of the developed model and its compliance with real operating conditions. Thus, the improved seeding unit of the pneumatic seeder equipped with a seed decelerator ensured enhanced uniformity of seed distribution, which contributed to increased yield potential and improved efficiency of agricultural operations. The obtained results represent an important step toward the development of advanced precision farming technologies aimed at optimising seed use and increasing productivity.

The obtained results confirm the importance of improving the design of the sowing unit of the John Deere 90 Series pneumatic seeder. Numerical modelling and experimental studies demonstrated that the proposed technical solution with a seed decelerator significantly improves the uniformity of seed distribution in the seedbed. According to the studies by L.J. Liu *et al.* (2016), the main issue affecting the seeding accuracy of pneumatic seeders is the high velocity of seeds during transportation. The present study confirms this finding, as the uneven seed distribution is caused by significant velocity fluctuations during seed movement through the seed tube. However, unlike previous studies, the improved design incorporating a seed decelerator allows these effects to be minimised. The findings of K. Li *et al.* (2023) indicated that the accuracy of pneumatic seeders largely depended on the trajectory of seed movement, which is influenced by airflow conditions and interactions between seeds and internal surfaces of the seeding system. In the study by Y. Li *et al.* (2016), a global review of precision maize planters showed that pneumatic seeding systems provide high metering accuracy but suffer from unstable seed trajectories during transportation through the seed tube. High seed velocities and turbulent airflow were identified as the main causes of uneven seed spacing and depth variation. However, the study did not propose specific technical solutions to reduce seed velocity or seed-wall collisions. The work of A. Boiko *et al.* (2018) focused on structural improvements of precision seeders aimed at increasing efficiency and reducing resource consumption. While improved metering performance was demonstrated, the influence of airflow and seed dynamics inside the seed tube on three-dimensional seed distribution was not sufficiently analysed, leaving the problem of seed motion stabilisation unresolved. In the study by A.A. Koller *et al.* (2005), the importance of controlling seed trajectory and orientation to improve planting accuracy was emphasised. The authors showed that uncontrolled seed motion and impacts with internal surfaces reduced placement precision. However, airflow-assisted seed transport and methods for reducing seed velocity in pneumatic systems were not addressed. Thus, despite these contributions, unresolved issues remained regarding excessive seed velocity, seed-wall collisions, and trajectory instability in pneumatic seed tubes. The present study addressed these gaps by proposing a seed decelerator that reduced seed velocity before reaching the seedbed, thereby improving seeding uniformity in spacing, depth, and lateral distribution.

As stated in the works of J. Turan *et al.* (2015), seeding uniformity is determined in three dimensions: seed spacing within the row, lateral seed distribution perpendicular to the row, and seeding depth. The results of this study show a significant improvement in uniformity across all three parameters. This is confirmed by a reduction in the standard deviation of seed spacing and increased stability of seed placement depth. An analysis of the studies by H.Y. Cao *et al.* (2015), A. Özköse (2017), and G. Dozet *et al.* (2020) showed that sowing depth was a key factor affecting seedling emergence uniformity and subsequent plant development. In the study by H.Y. Cao *et al.* (2015), it was demonstrated that deviations from the optimal sowing depth of maize resulted in delayed emergence and uneven root development. Excessive depth limited oxygen availability, while shallow sowing increased sensitivity to soil moisture variability. However, technical factors related to seeding mechanisms were not considered. The work of A. Özköse (2017) confirmed that uniform sowing depth significantly improved emergence and yield stability of pea genotypes, whereas depth variability led to uneven plant development. The causes of this variability associated with seed delivery dynamics were not analysed. According to G. Dozet *et al.* (2020), non-uniform sowing depth negatively affected soybean stand establishment and optimal plant density. Although the agronomic consequences were clearly identified, the influence of pneumatic seeding parameters on depth stability was not addressed. Thus, previous studies highlighted the importance of stable sowing depth but did not investigate the role of airflow conditions and seed motion control in pneumatic seeders. The present research addressed this limitation by establishing relationships between airflow velocity, seed decelerator configuration, and seeding depth stability, contributing to more uniform seed placement in the soil.

The proposed improvement in the design of the sowing unit of the John Deere 90 Series pneumatic seeder significantly enhances seeding uniformity by reducing "skips" and "doubles." Compared to existing seeder designs, the incorporation of a seed decelerator reduces seed velocity prior to entering the furrow, thereby minimising seed scattering and increasing seeding accuracy. The obtained results have practical significance, as their implementation can reduce yield losses caused by uneven seeding. Further research is planned to refine the decelerator control algorithm to adapt it to different seeder operating speeds and variations in soil structure.

CONCLUSIONS

The numerical simulation of the seed decelerator in the John Deere pneumatic seeder, performed in the Simcenter Star-CCM+ software package, provided a visualisation of seed motion and airflow within the working area of the decelerator. Based on numerical modeling and subsequent data processing in the Wolfram Cloud software package, second-order regression equations were derived in decoded form, excluding insignificant coefficients according to Student's t-test. These equations described the dependencies of the outlet airflow velocity V_a^{out}, the outlet seed velocity V_p^{out}, and the seeding rate change coefficient η on the inlet airflow velocity V_a^{in} and the ratio of the outlet area to the inlet area ε. According to agronomic requirements, the deviation of the seeding rate was required not to exceed 1%. The derived equation expressed the dependence of the outlet-to-inlet area ratio ε on the inlet airflow velocity V_a^{in}, ensuring that $\eta \leqslant 1.01$. Within the specified range of inlet airflow velocities, ε was adjusted within the range of 1.60 to 2.26.

Numerical modelling of both the baseline and improved designs of the John Deere 90 Series pneumatic seeder's planting unit revealed key indicators of seeding uniformity. For the baseline design, the seed spacing along the row varied between 0.0017 m and 0.1192 m, with a coefficient of variation of 0.672. The standard spacing was 0.044 ± 0.015 m. Distances below 0.029 m indicated "double seeding," while distances above 0.059 m indicated "skips." The depth distribution of seeds was highly variable, exceeding standardised values. The average planting depth was 0.041 ± 0.03 m, while the required depth was 0.05 ± 0.01 m, with 52.5% of seeds failing to reach the target planting layer (0.04-0.08 m) in the cultivated soil horizon. The improved planting unit design demonstrated significantly better results. The seed spacing ranged from 0.0404 m to 0.0493 m, with a coefficient of variation of 0.223, resulting in an achieved spacing of 0.0448 ± 0.004 m. This confirmed that the improved design fully met the required seeding precision standards.

Further research may focus on the experimental verification of the obtained results under field conditions, allowing for a refinement of the decelerator parameters for different types of seeders and soil conditions. Additionally, studying the impact of other design modifications on seed distribution uniformity is promising, particularly in terms of variations in the geometry of the outlet openings and the materials used in the decelerator's construction. The potential for further development includes the integration of intelligent monitoring and adjustment systems for the seeding process based on real-time sensor data. This will enhance seeding accuracy and automate the adjustment of seeding unit parameters in real time. Moreover, further improvements may facilitate adaptation of the design to different crops, increasing the versatility of the technological solution.

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Симуляція удосконаленої системи подачі насіння пневматичної зернової сівалки

Анотація. Метою цього дослідження було підвищення точності розміщення насіння в пневматичному сівалці John Deere шляхом покращення конструкції системи подачі насіння в висівній секції. Удосконалена висівна секція включала кілька основних компонентів: верхній та нижній датчики норми висіву, сповільнювач насіння, що складається з перфорованого циліндра з отворами, верхні та нижні вузькі розтруби, циліндричне забрало з жорстко змонтованою вигнутою зубчастою рейкою та сервоприводом із зубчастим колесом. Ці удосконалення були спрямовані на поліпшення рівномірності розподілу насіння та оптимізацію точності посадки. Чисельні моделювання сповільнювача насіння, проведені за допомогою програмного пакету Simcenter Star-CCM+, дозволили візуалізувати як рух насіння, так і динаміку повітряного потоку в робочій зоні сповільнювача. Регресійні рівняння другого порядку були сформульовані на основі чисельних моделювань та обробки даних у програмному пакеті Wolfram Cloud. Ці рівняння, уточнені шляхом видалення незначних коефіцієнтів відповідно до t-тесту Стьюдента, описали залежності основних параметрів: швидкість повітря на виході зі сповільнювача насіння (V_a^{out}), швидкість насіння на виході (V_p^{out}) та коефіцієнт зміни норми висіву (η) як функції швидкості вхідного повітря (V_a^{in}) та співвідношення площі виходу до площі входу (ε). Згідно з агрономічними вимогами, допустиме відхилення норми висіву не повинно перевищувати 1 %. Для стандартної та удосконаленої конструкцій висівної секції пневматичної сівалки John Deere 90 Series були проведені порівняльні чисельні моделювання. Результати показали, що поліпшена конструкція забезпечує кращу ефективність, забезпечуючи більш рівномірне розміщення насіння. Відстань між насінинами в удосконаленій конструкції варіюється від 0,0404 м до 0,0493 м, при коефіцієнті варіації 0,223, що відповідає середньому розміру відстані 0,0448 ± 0,004 м. Ці результати підтверджують, що удосконалена висівна секція відповідає необхідним вимогам точності, що веде до підвищення потенціалу урожайності. Результати дослідження можуть бути використані для подальшої оптимізації пневматичних сівалок з метою підвищення точності висіву та зменшення втрат врожаю

Ключові слова: сповільнювач; параметри; точність висіву; швидкість; потік повітря