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Extended Analysis of the Effect of Seeder Tilt on the Seeding Rate — Simulation Results and Experimental Validation

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Broadcast seeders are commonly used in Poland for fertilisation, but they do not ensure precise and uniform fertiliser distribution. Strip-tillage systems utilise mechanical and pneumatic seeders, which allow seeds to be placed at the appropriate depth and in even rows. However, these devices follow the surface of the ground and are therefore susceptible to uneven fertiliser distribution depending on the terrain (slope). Uneven fertiliser distribution results in localised overfertilisation or nutrient deficiencies (nitrogen, phosphorus, potassium); the former, if excessive, can lead to plant lodging or frost damage, while the latter can lead to weakened plant growth and reduced yields. Competition between plants for sunlight and water can further inhibit the development of weaker individuals. This article presents the results of research on the effect of the tilt of the seed hopper and the measuring system (ranging from $-15°$ to $+15°$, with $5°$ intervals) on the dose of granular material sown. Negative angles refer to uphill travel, while positive angles refer to downhill travel. Simulation and laboratory studies have shown that when going uphill, the amount of material spread increases by 5.45% (simulation studies) and 7.86% (laboratory studies). When going downhill, the amounts decrease by 11.63% and 11.86%, respectively. Simulation studies were conducted using Ansys Rocky 2024 software (version R1), based on the discrete element method. The boundary conditions for the simulation, including the static and dynamic friction coefficients and the restitution coefficient of the test object (granular mineral fertiliser in the form of urea), were obtained from literature data. In the first phase of the study, the computational space modelled according to the dimensions of the seeder was unfavourable. Significant improvement in the agreement between the simulation and laboratory data was achieved by increasing the size of the computational space. The simulation results were validated using a laboratory test stand built based on the simulation model. The results were subjected to ANOVA statistical analysis, which confirmed that the effect of the slope on the seeding dose is statistically significant with a significance level of $p = 0.000$. Based on the obtained simulation and laboratory test results, a mathematical equation was generated to calculate the dose distribution depending on the slope of the terrain. After applying the Wilcoxon signed-rank test, it was confirmed, with a significance level of $p = 0.173$, that the discrete element method can be used successfully to simulate the dosing (seeding) process with sufficient accuracy.

topics: seed drill, precision of sowing, discrete element method (DEM), laboratory tests

1. Introduction

Uneven distribution of mineral fertilisers can lead to serious agricultural issues, including local overfertilisation and nutrient deficiencies. This phenomenon affects the availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are critical for optimal plant growth and yield [1] and therefore fundamental for sustainable agriculture [2]. These macronutrients are required by plants in large quantities and play a key role in their development; however, they often exhibit significant spatial variability [3]. Uneven fertiliser application can reduce crop yields by up to 20% [4]. It results in non-uniform growth and maturation and consequently causes losses during mechanised harvesting [5].

The irregular distribution of mineral fertilisers is reflected in the variability of crop yields and soil nutrient content [6]. Studies have shown that uneven nutrient distribution directly affects root growth [7]. Plants exhibit reduced root and shoot growth, as well as lower nutrient content when fertilisers are applied unevenly [8]. Localised overfertilisation can inhibit root elongation due to elevated cytokinin levels at root tips, thus decreasing crop drought resistance [9]. It is important to emphasise that uneven fertiliser distribution increases nutrient loss and soil pollution, negatively impacting the environment [4, 9]. High concentrations of mineral fertilisers can also lead to nutrient surpluses and risk of contamination, particularly of groundwater [10]. The uneven application of nitrogen fertilisers (excessive) contributes to elevated nitrate concentrations in groundwater, which pose significant health risks [11, 12]. This issue is common in agricultural regions around the world, including Western Europe, northeastern Algeria, and the Central Valley [12–15]. Nitrate concentrations often exceed permitted drinking water standards, creating health risks such as methemoglobinemia in infants and potential long-term health effects [16, 17]. Intensive agricultural practices, including excessive fertiliser use, contribute significantly to nitrate pollution. Studies conducted in regions such as the Indus Basin and the South Plains of Texas have shown that nitrate levels in groundwater are closely related to agricultural activity and crop type [18, 19]. Unfortunately, groundwater contamination typically occurs for many years before restrictions on mineral fertiliser use are implemented [20, 21]. A potential solution to this problem lies in the implementation of modern approaches and technologies, such as advanced precision fertiliser application techniques. Therefore, this topic has been tackled.

The use of advanced agricultural machinery, such as subsoilers or cultivation machines equipped with row fertiliser seeders, can improve soil cultivation quality, enhance subsurface fertilisation efficiency, and simultaneously reduce the risks of overfertilisation (uneven distribution) and environmental or groundwater contamination [22]. Uniform fertiliser distribution is essential because uneven application can lead to yield reductions and increased harvest losses [5].

The objective of this study is to determine the effect of the inclination angle of the seed box and the metering system in a newly designed row fertiliser seeder (within the range of 15° to +15°, at 5° intervals) on the fertiliser discharge rate of granular mineral material, using both simulation and experimental validation. Based on the obtained simulation and laboratory test results, a mathematical equation will be derived to calculate the fertiliser rate distribution as a function of terrain topography (slope angle). This equation can be applied in the development of prototype fertiliser seeders capable of maintaining uniform application rates. An additional advantage of the proposed system is the reduction in labour and energy costs achieved by combining soil cultivation and fertilisation processes [23], as enabled by the new design of the row fertiliser seeder. By adopting more precise and intelligent fertilisation methods, farmers can increase yields while minimising negative environmental impacts.

2. Material and study methods

The research object was a peg-type metering unit used in SEED mechanical seeders, provided by AKPIL (Pilzno, Poland) as part of an established collaboration. To carry out the study, a test stand was designed, consisting of a seed box equipped with two metering devices. For simulation purposes, a 3D CAD model of the test stand was developed using SOLIDWORKS 2022 (Dassault Systèmes), followed by the construction of a laboratory test stand. The research was conducted in two stages: first, simulation tests, and second, laboratory tests. The results of laboratory experiments were used to validate the simulation results. During both simulation and laboratory tests, mineral fertiliser was dispensed (sown).

According to the manufacturer, Grupa Azoty (Tarnów, Poland), the fertiliser contains 46% nitrogen in the form of amide nitrogen. Furthermore, 90% of the granules fall within a size range. Based on data from the literature, the coefficient of friction between urea granules was assumed to be 0.27, and between a urea granule and polyvinyl chloride (PCV) — the material used to manufacture the measuring devices, 0.32. The restitution coefficient between urea granules was taken as 0.26, and between a urea granule and PVC as 0.35 [24]. The coefficient of friction between a urea granule and metal was assumed to be 0.50 [25]. The experimental plan aimed to investigate the fertiliser (urea) discharge rate as a function of terrain inclination (topography).

A review of the literature indicated that the cultivation of cereals, maize, and similar crops on slopes up to 15° does not significantly affect soil degradation or yield reduction [26, 27]. Therefore, to reflect real sowing conditions, the seeder was tested at inclination angles ranging from −15° to +15°, in 5° intervals. A negative inclination angle represented an uphill operation, the 0° angle corresponded to the optimal position (level), and a +15° angle simulated a downhill operation. In the subsequent step, the fertiliser dosing (dispensing) process and the measurement of the mass of the discharged material were performed, as described in detail in Sect. 2.2. for simulation studies and Sect. 2.3. for laboratory investigations.

2.1. Laboratory bench

The 3D seeder model (Figs. 1 and 2) was designed to carry out laboratory tests.

The model consists of a granular material hopper (element 1) and two measurement units (element 2).

The laboratory test stand, constructed for experimental investigations, consists of a granular material hopper (element 3), six metering units equipped with peg-type metering wheels (element 4) and a

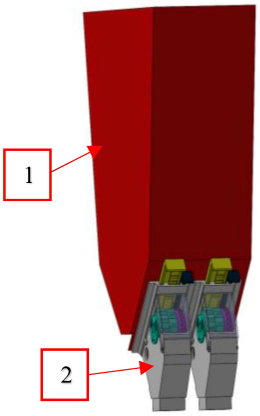

Fig. 1. 3D model of the simulation station, where: 1 — hopper, 2 — seeding devices.

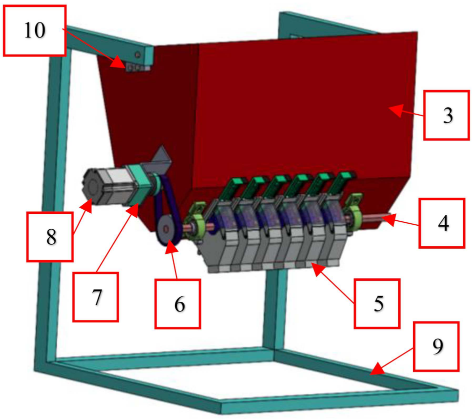

Fig. 2. 3D model of the laboratory test stand, where: 3 — hopper, 4 — seed metering units, 5 — drive shaft, 6 — chain drive, 7 — BLDC motor, 8 — planetary gear, 9 — frame, 10 — wedge.

drive shaft (element 5) powered by a chain transmission (element 6) by a brushless direct–current (BLDC) electric motor (element 7) coupled with a planetary gearbox (element 8). The hopper 1 is mounted on a frame (element 9) that allows the inclination of the seeder by attaching wedges (element 10) at various angles.

2.2. Simulation studies

Simulation tests were carried out using Rocky 2024 R1 software (Ansys), which is based on the discrete element method (DEM). To perform these simulations, the previously developed 3D computer-aided design (CAD) model of the test stand, created in SolidWorks (Dassault Systèmes), was converted to the STL format. The shape and size parameters of the dosed material were then defined. Since the urea fertilisers are approximately spherical, a sphere with a diameter of 3 mm was selected as the representative particle shape for simulation. In the first stage, a simulation of the hopper filling process was performed with a feed rate of 2 t/h, lasting 5 s. In the second stage, a simulation of the dispensing (metering) process was carried out by rotating the metering wheel at an angular velocity of 2.5 rad/s, also for 5 s. To determine the mass of the discharged material, the 'CUBE' measurement function was used. This function calculates the mass of fertiliser granules in the hopper before and after the dispensing process, providing the mass of the granules discharged during the 5-s dosing operation. For validation purposes, the simulation results were multiplied by a factor of 12, which corresponds to a 60-s dosing period (as in laboratory tests). This approach enabled a direct comparison between the simulation and the laboratory results.

2.3. Laboratory studies

On the basis of the 3D model, a laboratory test stand was designed and constructed, consisting of six dosing (metering) units. The dosing units were driven by a Nanotec BLDC motor (model DB80M048030-A) coupled with a planetary gearbox (model GPLE60-1A-5-F80, Nanotec) and connected by chain transmission with a gear ratio of 2.5:1. To perform the experiments, the seed hopper was filled with 25 kg of mineral fertiliser (urea), which is half the capacity of the hopper. The stepper motor was then activated using Plug & Drive Studio 2.1.7 software. Each dispensing trial lasted 60 s. To achieve the desired inclination angles specified in the test plan, wedge-shaped pads were fabricated using the rapid prototyping method on a 3D printer (original Prusa MK4, Prusa Research a.s., Partyzánská 188/7a, Holešovice, 17000 Prague 7, Czech Republic). In total, six pads were produced, two for each angle of 15°, 10°, and 5°. After each dosing process, the mass of the discharged granules was measured using a Radwag PS 6000/X (Radom, Poland) precision balance with an accuracy of 0.01 g. For each angle of inclination, 12 repetitions were performed, with the two extreme results discarded as outliers according to the gross error criterion [28].

3. Results

In this study, two measurement methods were used to determine the fertiliser application rate as a function of the inclination angle of the test stand (representing the newly designed row fertiliser seeder). The first method was a simulation-based approach using Rocky 2024 R1 software (Ansys) and the 'CUBE' function, while the second method used a laboratory precision balance (Radwag PS 6000/X, Radom, Poland) with an accuracy

TABLE I

Laboratory test results with average values of mass [g].

Inclination [°]	Number										
	1	2	3	4	5	6	7	8	9	10	Average
15	491.00	489.67	490.33	493.00	492.33	488.00	491.33	486.00	481.00	488.00	489.07
10	513.67	514.00	509.33	509.33	512.67	508.67	506.67	506.00	509.67	508.67	509.87
5	526.33	522.33	524.33	526.00	530.67	532.00	533.67	533.00	529.00	529.00	528.63
0	550.00	551.33	553.00	553.00	554.67	553.00	560.33	561.33	557.00	555.33	554.90
−5	559.67	558.67	565.33	567.00	561.00	560.33	566.67	565.67	558.67	556.00	561.90
−10	569.67	565.33	576.00	577.67	585.00	585.33	588.00	572.00	571.33	573.00	576.30
−15	595.33	593.67	597.67	599.67	603.00	600.67	603.00	603.00	596.33	593.00	598.53

TABLE II

Comparison of laboratory and simulation results.

Inclination [°]	Laboratory research [g]	Simulation research [g]	Corrected simulation research [g]
15	489.07	311.44	490.35
10	509.87	335.17	527.70
5	528.63	346.78	545.98
0	554.90	352.44	554.90
−5	561.90	363.11	571.70
−10	576.30	367.78	579.04
−15	599.63	371.67	585.16

of 0.01 g (laboratory validation tests). When evaluating the performance of the newly designed row fertiliser seeder equipped with peg-type metering (dispensing) units, the following research hypothesis (H0) is applicable. The inclination of the seeder, corresponding to variations in the topography of the terrain, has a significant effect on the rate of application of granular fertiliser (urea).

Table I presents the laboratory test results, showing the average mass of the fertiliser granules from two meters for the specified inclination angles. Each dosing trial was repeated ten times to obtain a sufficient data set for statistical analysis.

In the current stage, to align the results of the simulation and laboratory tests, a correction factor (k) was calculated as the ratio of the mass of discharged granules obtained in the laboratory tests to the mass of granules obtained in the simulation tests, as expressed in

$$k = \frac{\text{Mass of granules (laboratory research)}}{\text{Mass of granules (simulation research)}} = \frac{554.90}{352.44} = 1.574. \quad (1)$$

The calculated correction factor k was 1.574. The difference in application rate between the simulation and laboratory test results may be attributed to the complexity of the process and the insufficient precision of the input parameters used in the fertiliser granule dosing simulation, specifically the friction coefficient and the restitution coefficient, which were selected based on data from the literature.

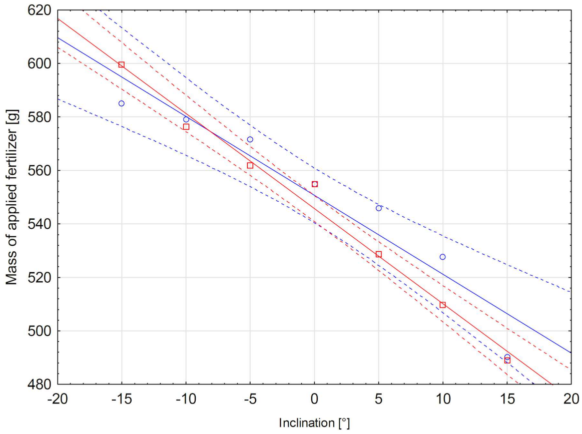

Fig. 3. Fertiliser application weight depending on the seeder inclination.

Table II presents the average mass of the granular material obtained from 10 laboratory tests, the mass obtained from simulation tests, and the corrected mass of dispensed granules adjusted using the correction factor k.

Figure 3 illustrates the mass of the granular material (fertiliser) as a function of the angle of inclination of the test stand (seeder). On the graph, the red points represent the laboratory test results, while the blue points correspond to the simulation results. Both data sets indicate that the amount of fertiliser applied increases with increasing inclination angle. For both cases, a linear model was fitted, and the dashed lines represent the 95% confidence interval for the estimated mean value.

The dependencies of the mass of the granules used in the simulation tests and the mass in the laboratory tests as a function of the vertical inclination angle [in degrees] are expressed, respectively, as

$$m_{sym} = 550.6886 - 2.9487\,\alpha, \quad (2)$$

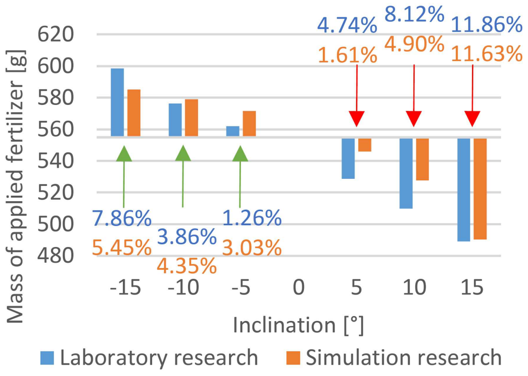

Fig. 4. Comparison of simulation and laboratory test results for urea mineral fertiliser granules.

and

$$m_{lab} = 545.7571 - 3.5558\,\alpha. \tag{3}$$

The R^2 parameter, which indicates the goodness of fit of the equations with the data, is 0.9163 for the simulation tests and 0.9862 for the laboratory tests.

Figure 4 presents the percentage deviation of the application of granular material (fertiliser) for both laboratory and simulation tests, relative to the optimal position (0°). In laboratory tests, a negative seeder angle (corresponding to an uphill operation) increased the amount of fertiliser dispensed by 1.26% to 7.86%, while a positive inclination (corresponding to a downhill operation) decreased the amount of material dispensed by -4.74% to -11.86%.

The simulation tests exhibited an identical trend. For the negative angle of inclination, the increase in the application rate ranged from 3.03% to 5.45%, while for the positive angle, the decrease ranged from -1.61% to -11.63%.

The experimental data were subjected to statistical analysis using Statistica 13.3 (TIBCO Software Inc.). First, the Shapiro–Wilk test was performed to verify whether the data conformed to a normal distribution. The significance level (p-value) ranged from 0.1830 to 0.7394, indicating that the sample data could be considered to be normally distributed. Then, Levene's test was conducted to assess the homogeneity of the variances between the analysed groups. The significance level was 0.008, indicating that the variances were not homogeneous. Consequently, Welch's analysis of variance (ANOVA) was applied, which allows statistical analysis when variances are unequal. The significance level for this test was 0.000, leading to the rejection of the null hypothesis (H0) that all group means are equal, and the acceptance of the alternative hypothesis (H1), indicating that at least one group mean differs significantly. In all analyses, a significance level of 0.05 was adopted. Also, a paired Wilcoxon test was conducted to compare two research methods, laboratory measurements and adjusted simulation-based measurements, performed on the same objects. The following hypotheses were formulated. Null hypothesis (H0) reads: There is no difference between the results of laboratory measurements and the adjusted simulations. Alternative hypothesis (H1) reads: There are significant differences between the measurements. The significance level of the test was $p = 0.173$, which is higher than the chosen significance threshold of $\alpha = 0.05$. Therefore, the null hypothesis was not rejected, indicating that there are no statistically significant differences between laboratory measurements and the adjusted simulation-based measurements.

4. Discussion

Similar trends in dose variability $(-22.88\%, 8.15\%)$ were also observed with respect to terrain slope in an earlier publication that examined the variability of triticale seed sowing rates at a site inclination of ±15° [29].

The effect of seeder inclination on wheat seed sowing was also studied in R. Rogacki's doctoral thesis [30], where for a slope of ±14°, the dose varied from -6.2% to 4.1%. For downhill sowing of wheat, the obtained test results are comparable with a small error; however, for uphill sowing, there is a larger discrepancy, likely due to the different material and shape of the test material.

For example, a study of fertiliser dosing mechanisms showed that a ±10° inclination changed the fertiliser application rate in a horizontal toothed rotor by -5.9% and 20.9%, and in a screw feeder with a side overflow by -4.4% and 6.5% [31], which shows convergent trends in the application rate changes with the obtained research results. The added value, however, is the attempt to simulate the mineral fertiliser dosing process, which already at this stage shows acceptable convergence with laboratory results.

5. Conclusions

In this study, a new seed drill for fertilisation was developed, and the effect of seed drill tilt on the seed application rate was investigated. This resulted in mathematical equations to calculate the fertiliser application rate distribution as a function of slope. The simulation test results were compared with the laboratory test results for validation. A consistent trend in application rate was observed based on the data obtained, but a correction factor ($k = 1.574$) was required to fully align the results.

The simulation results showed that the vertical tilt of the seed drill significantly affected the application rate, especially at extreme deviations. At a negative slope of $-15°$, the application rate increased by 5.45%, while at a positive slope of $+15°$, it decreased by 11.63%.

The laboratory test results confirmed this trend and showed even more pronounced changes. At an angle of $-15°$, the application rate increased by 7.86%, while at an inclination of $+15°$, it decreased by 11.86%.

Statistical analysis using ANOVA of laboratory tests confirmed the significance of these differences at a significance level of $p = 0.000$. Also, the Wilcoxon signed-rank test did not show significant differences between the laboratory test results and simulation results after applying the correction factor ($p = 0.173$).

The most likely cause of the observed discrepancies between the simulation test results before correction and the laboratory results is the complexity of the granular flow process and the insufficient precision of the simulation input parameters, particularly the friction and restitution coefficients obtained from the literature.

The studies conducted showed that changing the seeder inclination angle leads to a change in the balance between the forces of gravity and the friction resistance acting on the granular material, which directly translates into a change in the application rate. This is a new, quantitative physical relationship that can be modelled using the developed mathematical model.

The next stage of research will involve the construction of a precise test rig to determine the static and dynamic friction coefficients and the coefficient of restitution, which will allow for even greater agreement between simulation and laboratory results.

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