Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(1), 59–73
https://doi.org/10.12913/22998624/209986
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.07.16
Accepted: 2025.09.27
Published: 2025.11.21

Influence of seeder inclination and hopper filling level on the dosing process of granular material: A case study of triticale

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ABSTRACT

Uniform seed distribution is a critical factor that affects both the quality and yield of crops. In small and medium-sized farms, mechanical seeders with a working width of up to 3 meters are the most common. These machines are typically mounted on low- and medium-power tractors. To evaluate the influence of tank filling level and inclination on the precision of granulated material dosing, a new laboratory test stand was used. The stand was equipped with a mechatronic drive system for the seeder's dosing unit, enabling precise control of the seeding rate. Additionally, a prototype piezoelectric impact sensor was installed to count the number of seeds dispensed. Based on literature analysis, a research gap was identified regarding the variability of seeding rates for granulated material in the form of triticale seeds depending on terrain features and hopper fill level. Triticale is an important feed crop in both Poland and Europe. The purpose of the study was to determine the effects of the angle of tilt angle relative to the vertical axis and the filling level on the seeding dose. The tilt of the tank by +15° from the vertical (simulating downhill operation) was found to reduce the mass of dispensed seeds by up to 8.15%, while a tilt (simulating uphill operation) increased it by up to 22.88%. However, the fill level of the tank did not have a statistically significant effect ($p = 0.05$) on the seeding rate. The results provide new information on factors that affect seeding precision and may support the development of improved control strategies for agricultural machinery.

Keywords: seed drill, mechatronic drive system, factors affecting granular dosing mixtures, precision of sowing, not proper sowing, seeding disorders.

INTRODUCTION

Cultivation methods are evolving due to continuously changing climatic conditions, including weather variability, the specific requirements of cereal and other cultivated crops, and ongoing technological advancements. Regardless of the type of soil cultivation applied, such as conventional tillage, strip-till, or no-till, the sowing process is always present and is considered one of the most important agronomic practices. Sowing involves placing seed material, most often treated with fungicides to prevent the development of fungal diseases, at a defined depth and spacing, followed by covering the seed with soil [1]. Precise placement over a given area ensures uniform germination and healthy plant development [2]. This operation is carried out using machines known as seeders. These machines are increasingly being combined with other implements to form integrated tillage and seeding units [3]. There are three main types of seeders: mechanical, pneumatic, and precision seeders [4]. In Poland and other Eastern European countries, mechanical seeders are the most commonly used. Their construction typically includes one of two types of metering mechanism: the pegwheel or the fluted roller type [5]. The metering unit is a key component that affects the uniformity of seed distribution. It is usually driven by a stepped or continuously variable gearbox, which is powered by the seeder wheel or a spiked wheel. In modern seeders, electric or hydraulic drive systems are also being implemented increasingly [6].

It is believed that the uniformity of seed distribution in mechanical seeders can still be improved by refining the construction of the seeding mechanism. Previous studies have shown that improved seeding uniformity has a positive effect on both crop yield and quality. Uniformly sown plants have equal access to sunlight and water, which supports healthy and even growth [7,8]. The improvement in granulated material dosing was also addressed by Fiedurek et al. in 2022, who developed a new screw-type metering system [9]. Nemtinov et al. implemented a similar screw dosing mechanism in 2019 [10], as well as by Aduov et al. in 2023, who improved the uniformity of grass seed distribution [11]. A review of the literature also revealed research focused on the influence of selected factors on the uniformity of wheat seed dosing using a peg-wheel metering system [12]. Additional studies are available that identify factors that affect seed distribution uniformity in pneumatic seeders [13, 14]. Other works present methods and systems designed to measure the distribution of seeds in rows, which is directly related to the evaluation of seeding uniformity [12, 15]. Rogacki in 2020, in his doctoral dissertation, investigated the effect of seeder tilt and seed box filling level on the seeding rate for basic cereal grains [16]. However, his study did not address the influence of these factors on the seeding rate of triticale, which is the most important forage cereal in Poland. According to FAOSTAT data, global triticale production in 2017 amounted to 15.5 million tonnes, of which Poland contributed 5.3 million tonnes. This means that domestic production represented up to 34% of the total [17]. Research on triticale grain was also carried out by Gierz et al. in 2021 [18].Given this significant share, triticale grains were selected for use in the present study. The research used the weight method to measure the amount of dosed granular material. This method was successfully used by Gierz et al. in 2020 [19], Gierz and Markowski in 2020 [14], and Rogacki in 2020 [16], which confirms the validity of its application. A scientific novelty is the development of the dependence of the influence of the inclination of the test stand (seeder inclination) and the filling level of the seed hopper on the sowing efficiency of triticale grain using a grooved dosing device and its presentation in the form of a mathematical algorithm. Previous studies have focused primarily on basic cereals (such as wheat and barley), overlooking triticale, which holds significant importance as a feed crop. Therefore, this study addresses a notable gap in the literature and provides new data relevant to agricultural practice. The purpose of the research was to determine the effect of the inclination of the test stand (seeder tilt) and the tank filling level on the seeding rate of triticale grains using a fluted roller metering system.

MATERIALS AND METHODS

Laboratory bench (Test Facility)

The research object was the groove dosing system used in mechanical seed drills manufactured by the Meprozet Agricultural Machinery Factory (Międzyrzecz Podlaski, Poland) [20]. A research stand with two sowing units was designed and constructed based on such a seed drill (Figure 1). This stand was prepared to study the effect of both the level of inclination and the filling of the seed tank on the dose (quantity) of the dosed seeds. The angle of inclination of the seeder in the range from -15° to 15° was adjusted using adjustable washers (element 8 in Figure 1) inserted under the frame of the research stand. The stand is equipped with a seed tank, which was filled with granular material (triticale) to the indicated volume of 0.25, 0.5, 0.75, 1.0. Seeds from one cereal species were used for the study: triticale variety ROTONDO, Plant Breeding Danko (Choryń, Poland) with a thousand-seed weight (TSW) of 41.21 ± 0.73 g and a moisture content of 12.5%, moisture content tests were performed because the studies conducted by Gierz et al. 2022 showed that the grain moisture content has a significant impact on grain volume [21, 22]. Excessive moisture content in cereal seeds may lead to the development of fungi and molds, as well as the degradation of the sown material [23]. These were certified seeds purchased from Poznan Seed Headquarters (Poznan, Poland).

The test stand consists of a seed tank supported by a frame made of 40 × 40 mm aluminum profiles. To allow experimentation and meet Agriculture 4.0 standards, the stand was equipped with a mechatronic drive system, with its control unit housed in an external control box. During the tests, the fluted roller metering system extracted seeds into seed tubes and then into collection containers over a period of 60 seconds. After each test cycle, the containers were weighed using a

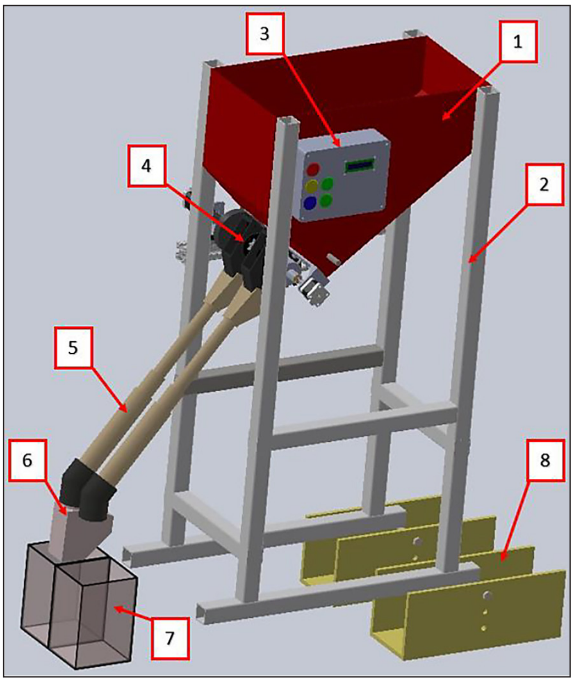

Figure 1. 3D CAD model test stand, where: 1 – seed tank; 2 – aluminum profiles; 3 – control box; 4 – mechatronic control system, 5 – seed tube; 6 – piezoelectric sensor; 7 – seed containers; 8 – wedge

Radwag PS 6000/X (Radom, Poland) scale with a measurement accuracy of 0.01 g. Additionally, a seed counting system based on a piezoelectric sensor was installed on the second seed tube [24, 25]. Figure 1 shows a 3D CAD model of the mechatronic drive system that operates two fluted roller metering units. Each metering unit consists of a housing mounted to the seed tank. Inside the housing, sliding gates regulate the seeding slit through which seeds fall onto the fluted roller.

Laboratory bench control system

The control system of the mechatronic dosing system was built on the basis of the ATmega 328P microcontroller, which allows programming of all the commands necessary during the tests. The system is powered by 12V DC, available in all agricultural tractor [26]. The entire electronic system was designed in the EAGLE Autodesk program and then made on a PCB, which has recently gained popularity in the construction of electronic system prototypes [27]. For the needs of designing the constructed system, the source code was developed in the Arduino IDE application. The source code defines the functions of the buttons responsible for controlling the system, including setting the sowing (dosing) slot, starting the calibration test lasting 60 s, and interrupting the dosing processes as a safety function. Figure 2a shows a diagram of the control algorithm, which illustrates the relationship between commands and conditions of the performed activities. Figure 2b shows a block diagram of the emergency stop button. In Figure 2c, a block diagram of the application of the patented system for detecting blockages and counting seeds [24] is attached, which was installed on the second seed channel as an alternative method of controlling the amount of seed dispensed. This system was developed in LIDER VIII project no. 0137/L-8/2016, within which a piezoelectric impact sensor was patented, which is an alternative to optical sensors [24, 28]. The innovative sensor that counts the amount of seeds communicates with a smartphone equipped with the Android operating system through a wireless Wi-Fi network. It counts the number of grain hits on the flat surface of the sensor and displays the result on the phone display via the dedicated application [24].

Research plan (indicators and calculations)

For the purposes of conducting the indicated tests, each calibration test would be performed in 60 s. Each test with the appropriate settings was repeated 12 times.

In the laboratory tests conducted for triticale seeds, the following factors were assumed:

a) Constants:
- Assumed (theoretical) sowing speed – 2 m/s;
- Calibration test time – 60 seconds;
- Seed material – ROTONDO triticale variety;
- Drive shaft rotation speed – 16.5 rpm;
- Agitator speed – 17 rpm.

b) Variables:
- Sowing slot width – 6 mm, 10 mm, 14 mm, 18 mm, 22 mm, 26 mm, 30 mm;
- Seed tank fill level – 25%, 50%, 75%, 100%;
- Vertical tilt of the position (seeder) -15°, -10°, -5°, 0°, 5°, 10°, 15°, where positive values simulate a descent and negative values simulate an uphill climb.

c) Results:
- Mass of seeds sown with the first sowing device;
- Mass of seeds sown with the second sowing device;
- Number of seeds counted by the control system with a piezoelectric sensor.

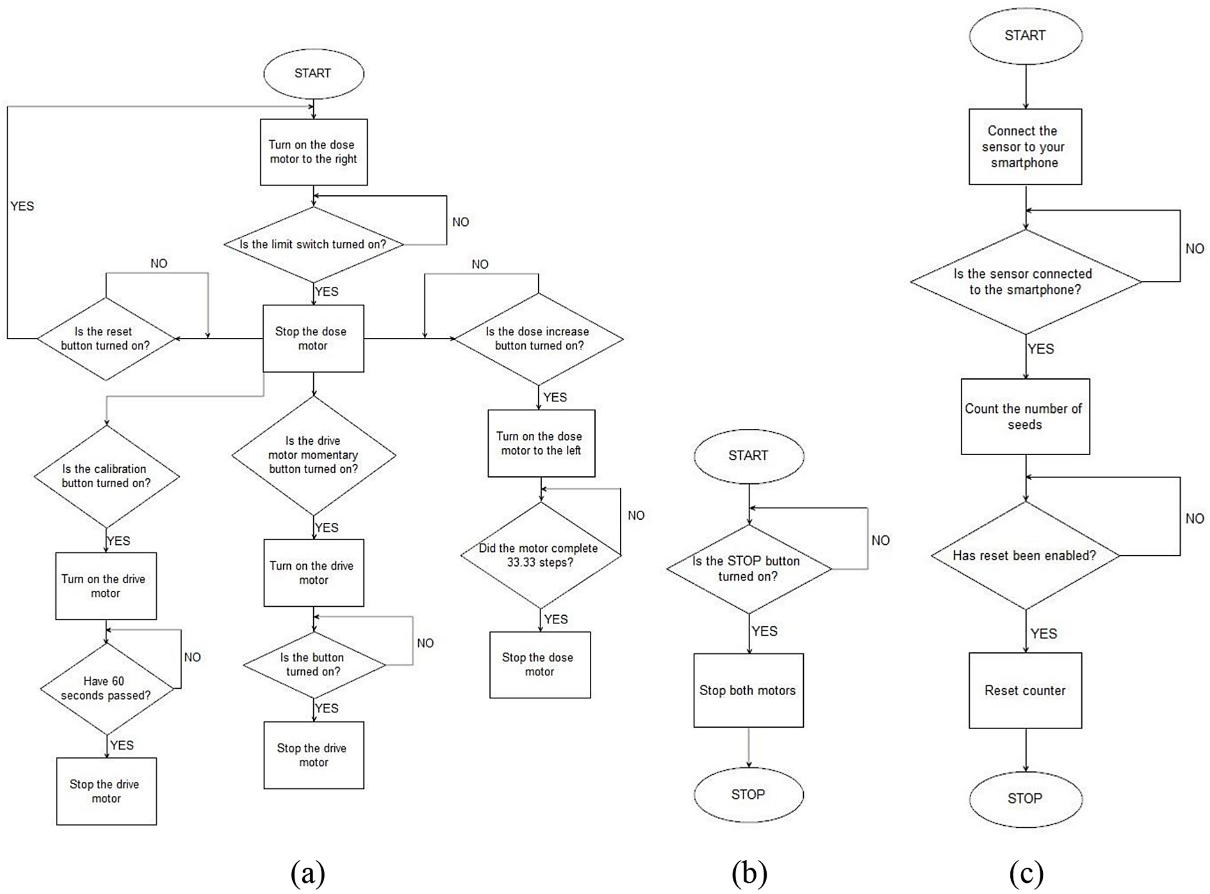

Figure 2. Block diagram: (a) motor control, (b) emergency stop, (c) grain counting application

The moisture content of the research material was measured using the TwistGrain pro device from Dramiński (Sząbruk, Poland). The measurement accuracy of this device is ±0.5%, and the measurement range for triticale grain is 9.0–30.0%

To compare the test results and calculate the number of seeds registered (pieces) of seeds by the system with a piezoelectric sensor, formula (1) was used:

$$M_c = \frac{L_n \times MTS}{1000} \quad (1)$$

where: M_c is Seed weight calculated sensor [g], L_n is Numer of seeds, *MTZ* is Mass of one thousand seeds [g].

Statistical analysis

Statistical analysis was performed using the Statistica 13.3 statistical software package from TIBCO Software Inc. First, the Shapiro-Wilk test was performed to check whether the data collected were in accordance with the normal distribution. Thus, the null hypothesis H0: The sample data come from a normal distribution and the alternative hypothesis H1: The sample data do not come from a normal distribution, and the authors put forward. Based on statistical analyses, the null hypothesis was confirmed when the level of significance was greater than 0.05 ($p > 0.05$). Then, Levene's test was performed to check whether the collected variables are equal in the scope of the analyzed groups. If $p > 0.05$, there is homogeneity of the data distributions. If there is homogeneity, you can perform the analysis of variance in which two hypotheses are accepted. Null hypothesis H0: all values in the groups are the same and Alternative hypothesis H1: there is at least one value different from each other. To reject the null hypothesis, the significance level p must be less than 0.05; then the alternative hypothesis is accepted, indicating that one of the variables has a significant effect on the uniformity (quantity) of the sowing [29]. Gierz et al. in 2020, 2023, also used the indicated statistical methods when analyzing the research results [14, 30]

To indicate the effect of the seed box filling, pilot studies were carried out with the sowing opening at a width of 6 mm and the seeder tilted from the vertical in the range of -10°, 0°, 10°. The measurement results were subjected to statistical analysis. The study aimed to check whether the mass of sown seeds differs significantly depending on the angle of the seeder tilt from the vertical and on the level of seeds in the tank, i.e. the level of filling of the seed box. Additionally, it was decided to check whether the mass of seeds calculated on the basis of the number of seeds registered with a piezoelectric sensor differs from the mass of seeds weighed on a scale.

RESULTS

When assessing the effect of the seed box filling level and the seeder inclination angle with the metering units, it was important to answer the question: Does the sowing rate of triticale seeds differ significantly depending on the adopted independent variable parameters, i.e., the seed box filling level and the 6 seeder (position) inclination angles from the original (standard) position for different sowing slot widths?

Therefore, ANOVA analysis of variance with a significance level of 0.05 was used to consider the null hypothesis H0 that the seed box filling level has no significant effect on the dose of seed material, and the alternative hypothesis H1 that the box filling level has a significant effect on the multiplicity of the dose of sown material. The research and analysis showed that the significance level of this variable is 0.1834, therefore, the alternative hypothesis H1 was rejected and the null hypothesis H0 was retained, stating that the level of filling of the seed hopper has no significant effect on the dose of seed material.

Then tests were carried out on the inclination of the seeder (position) from the original position and using the same analysis with the same level of significance, the following hypotheses were presented: null hypothesis H0, the angle of inclination of the seeder (position) has no significant effect on the dose of sown material, and alternative hypothesis H1, the angle of inclination of the seeder (position) has a significant effect on the multiplicity of the dose of sown material. The statistical analysis of this study showed that the null hypothesis H0 should be rejected and the alternative hypothesis H1 should be accepted, stating that the angle of inclination of the seeder has a significant effect on the multiplicity of the dose of sown material. The significance levels for the inclination of the analysis of the seeder (station) from the original position for all sowing slot widths were 0.0000.

Fill level

First, pilot studies were performed at a sowing slot width of 6 mm, taking into account the indicated 4 levels of seed box filling (25%. 50%, 75%, and 100%). The results obtained from this study are presented in Table 1.

The Shapiro-Wilk test proved that the data distribution is consistent with the normal distribution. The test results are presented in Table 2, while the significance level was in the range of 0.2581–0.7788.

Then, Levene's Test was performed, which checked whether the equality of variances was homogeneous. The significance level of this test was 0.164821, which indicates the equality of variances (its homogeneity). After meeting the homogeneity condition, the analysis of variance was performed. The significance level of this analysis was 0.183990, which allowed us to reject the alternative hypothesis, which states that the level of filling of the seed box has a significant effect on the sowing rate.

To present the collected results more clearly, Figure 3 illustrates the average masses of triticale seeds and its value depending on the level of box filling with a sowing slot width of 6 mm. The average mass was 62.49 g and the relative error did

Table 1. Results of the tank filling test with a sowing gap size of 6 mm

Filling level [%]	Average numer of seeds	Average mass calculated from the sensor [g]	Average seed weight in the 1st container [g]
25	2035	83.89	61.87
50	2057	84.78	62.49
75	2224	91.69	62.99
100	2224	91.69	62.61

Table 2. Significance level of the Shapiro-Wilk test

Level of filling [%]	Significane level
25	0.2581
50	0.2667
75	0.3101
100	0.7788

not exceed 1%. Although no significant differences were observed, with the increase in the level of seed box filling, a smaller scatter of results was obtained, i.e., more uniform sowing.

The pilot studies carried out showed that the level of filling of the seed box did not affect the sowing rate, therefore subsequent experiments were carried out with constant filling of the box with triticale at the level of 50%.

Inclination of the tank

According to the developed research plan, the seed mass and the number of seeds sown were measured by an innovative system with an impact sensor for the inclinations of the test stand (seed) in the range from -15° to +15° with an interval of 5 °. Tables 3–6 present selected results of the seed mass dosed by the first dosing unit at the sowing slot widths of: 6, 14, 18, 30 mm.

It can be seen that the average seed mass calculated based on the readings of the impact sensor differs significantly from the average seed mass in container I. These differences range from 0.03% to 56.77%. The sensor overcounts the number of seeds sown by 0.05 g in the case of a sowing slot width of 14 mm and a station inclination of -5° (see Table 4), but undercounts by 192.61 g in the case of a sowing slot width of 30 mm and a station inclination of -5° (see Table 6). To eliminate this difference, an appropriate correction factor should be introduced. The calculated relative error of the mass of the sown material (triticale) depending on the angle of inclination of the test station ranges from 0.01 to 22.88%. The largest difference is 14.29 g. The largest difference in seed mass was observed to be dosed when the position is tilted at an angle of -15°, i.e. when climbing a hill and the sowing slot is 6 mm wide (see Table 3), while the smallest difference in seed mass of 0.02 g is dosed at an angle of -5° and a sowing slot of 18 mm (see Table 5).

The results collected of the effect of the seeder (research station) tilt were also subjected to statistical analysis. During the Shapiro-Wilk test, it was shown that the significance level value is in the range of 0.0571 to 0.9694. These results confirm that the data distribution is consistent with the normal (Gaussian) distribution. Table 7 shows the results of the Shapiro-Wilk test for individual sowing slot widths, indicating that the data distribution is consistent with the normal distribution.

In Table 8, the results of Levene's test for the tests with the seeder (test stand) tilt are presented, which indicate the homogeneity of variance. The level of significance ranges from 0.0889 to 0.9273.

Table 9 also presents the results of the analysis of variance of the effect of the inclination of the

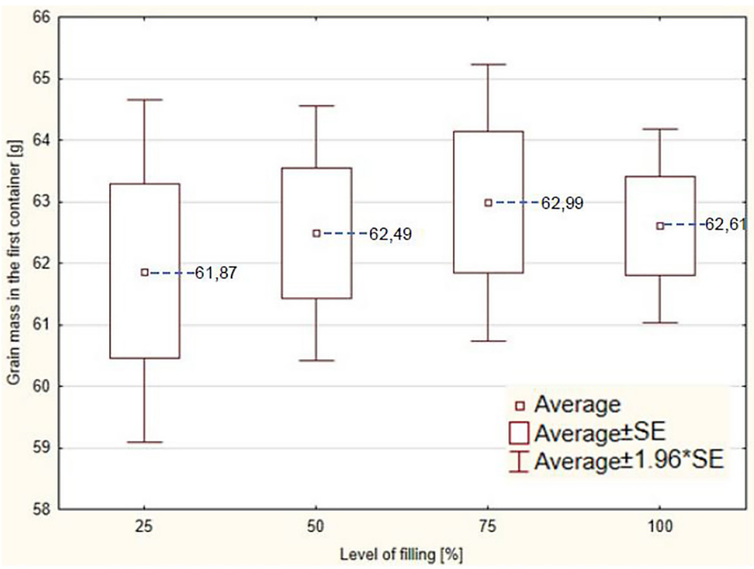

Figure 3. Mass of seeds weighed from the first container relative to the tank filling

Table 3. Analysis of seeds the quantity of sown in the case of a width of the sowing gap width equal to 6 mm and when the tank is 50% full

Inclination angle [°]	Average numer of seeds	Average mass calculated from the sensor [g]	Average seed weight in the 1st container [g]	Average seed weight in the 2nd container [g]	Relative error of the seed mass in the 1st container compared to the mass at 0° inclination [%]	Relative error of the seed mass in the 1st container compared to the seed mass calculated from the sensor [%]
15	2173	89.55	59.12	56.99	5.39	51.46
10	2168	89.36	62.95	58.09	0.74	41.95
5	2062	84.96	62.29	56.55	0.31	36.39
0	2058	84.79	62.49	58.94	0.00	35.69
-5	2314	95.37	69.06	63.21	10.52	38.09
-10	2407	99.18	68.93	63.33	10.32	43.88
-15	2885	118.91	76.78	69.51	**22.88**	54.87

Table 4. Analysis of seeds the quantity of sown in the case of a width of the sowing gap equal to 14 mm and when the tank is 50% full

Inclination angle [°]	Average numer of seeds	Average mass calculated from the sensor [g]	Average seed weight in the 1st container [g]	Average seed weight in the 2nd container [g]	Relative error of the seed mass in the 1st container compared to the mass at 0° inclination [%]	Relative error of the seed mass in the first container compared to the seed mass calculated from the sensor [%]
15	3482	143.50	133.92	130.92	8.15	7.15
10	3543	146.00	141.84	136.45	2.72	2.93
5	3501	144.29	141.84	136.74	2.72	1.72
0	3636	149.86	145.81	138.99	0.00	2.78
-5	3574	147.28	147.23	138.39	0.97	**0.03**
-10	3664	151.00	146.15	137.68	0.24	3.32
-15	3855	158.87	151.54	140.74	3.93	4.84

Table 5. Analysis of seeds the quantity of sown in the case of a width of the sowing gap width equal to 18 mm and when the tank is 50% full

Inclination angle [°]	Average numer of seeds	Average mass calculated from the sensor [g]	Average seed weight in the 1st container [g]	Average seed weight in the 2nd container [g]	Relative error of the seed mass in the 1st container compared to the mass at 0° inclination [%]	Relative error of the seed mass in the first container compared to the seed mass calculated from the sensor [%]
15	3899	160.66	170.28	160.8	3.21	5.65
10	3994	164.61	173.33	164.37	1.47	5.03
5	3884	165.88	176.49	165.88	0.32	9.30
0	3966	163.46	175.92	168.40	0.00	7.09
-5	4058	167.25	175.94	164.50	**0.01**	4.94
-10	4164	171.58	177.86	164.18	1.10	3.53
-15	4191	172.72	179.16	163.46	1.84	3.59

stand (seeder) on the size of the sowing dose. The significance levels in all cases were 0.000000. These results indicate that the null hypothesis H0 should be rejected: all values in the groups are the same, and the alternative hypothesis H1 should be accepted: there is at least one value different from each other.

In order to facilitate the interpretation of the collected research results, they are presented in Figure 4. Graph a) shows the relationship between the sowing rate and the angle of inclination of the test stand (seeder) for a sowing slot width of 6 mm, b) 10 mm, c) 14 mm, d) 18 mm, e) 22 mm, f) 26 mm, g) 30 mm, along with the average value.

Table 6. Analysis of seeds the quantity of sown in the case of a width of the sowing gap equal to 30 mm and when the tank is 50% full

Inclination angle [°]	Average numer of seeds	Average mass calculated from the sensor [g]	Average seed weight in the 1st container [g]	Average seed weight in the 2nd container [g]	Relative error of the seed mass in the 1st container compared to the mass at 0° inclination [%]	Relative error of the seed mass in the first container compared to the seed mass calculated from the sensor [%]
15	3743	154.25	312.04	298.33	5.59	50.57
10	3692	152.14	319.98	304.69	3.19	52.45
5	3562	146.79	328.89	304.69	0.49	55.37
0	3624	149.34	330.52	308.27	0.00	54.82
-5	3559	146.67	339.28	311.75	2.65	**56.77**
-10	3551	146.35	337.73	313.50	2.18	56.67
-15	3623	149.29	343.44	311.25	3.91	56.53

Table 7. Significance level of the Shapiro-Wilk test: α – inclination [°]; p – significance level

Vertical tilt of the position	Sowing slot width						
	6 mm	10 mm	14 mm	18 mm	22 mm	26 mm	30 mm
-15°	0.7021	0.8530	0.4959	0.4381	0.6336	0.7753	0.7885
-10°	0.0770	0.0571	0.4403	0.4811	0.6205	0.3900	0.9887
-5°	0.8546	0.4665	0.8212	0.4603	0.3525	0.8856	0.4731
0°	0.3022	0.9694	0.4814	0.7847	0.7499	0.8963	0.7983
5°	0.3230	0.2510	0.6453	0.1594	0.1679	0.1954	0.7631
10°	0.8201	0.7748	0.5049	0.2262	0.2610	0.0863	0.1920

Table 8. Results of Leven's test for tests with the seeder inclination

Sowing slot width [mm]	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
6	6.756179	6	1.126030	39.01765	63	0.619328	1.818148	0.109803
10	0.697361	6	0.116227	23.30229	63	0.369878	0.314230	0.927264
14	10.15964	6	1.693274	60.01530	63	0.952624	1.777485	0.118147
18	0.517857	6	0.086310	27.79434	63	0.441180	0.195633	0.976910
22	4.200834	6	0.700139	22.75961	63	0.361264	1.938028	0.088325
26	12.86134	6	2.143556	82.91604	63	1.316128	1.628684	0.153994
30	9.196537	6	1.532756	82.81357	63	1.314501	1.166036	0.335810

Furthermore, when testing the new system with an impact sensor, it was observed that for a sowing slot width of 14 mm, it overcounts the number of seeds sown, while for larger sowing slots it undercounts. To make a mass comparison, the number of registered triticale grains was multiplied by the TSW. This proved that the smallest difference in the mass of seeds sown and the mass of seeds calculated by the new system occurred for a slot width of 14 mm, which was 0.05 g. On the other hand, the largest difference in the mass of seeds weighed and calculated on the basis of sensor readings occurred for the largest sowing slot of 30 mm. Figure 5 presents a comparison of the results of the sowing dose weighed and recorded by the innovative system with an impact sensor for a sowing slot width of 22 mm. An appropriately adjusted correction factor would be able to eliminate the differences.

The relationship between the mass of the seeds sown and the angle of the seeder (station) from the vertical expressed in degrees and the width of the sowing slot expressed in micrometers is presented by the equation. This relationship was determined in the MathWorks MATLAB version R2024b program. The best representation of the data was achieved with the second-degree polynomial regression (2):

Table 9. Results of the analysis of variance for data with variable seeder inclination

Sowing slot width [mm]	SS effect	df effect	MS effect	SS error	df Error	MS Error	F	p
6	2169.021	6	361.5035	126.3329	63	2.005284	180.2755	0.000
10	675.389	6	112.5649	75.48995	63	1.198253	93.94080	0.000
14	1860.783	6	310.1305	179.0854	63	2.842626	109.1000	0.000
18	522.534	6	87.08907	90.43521	63	1.435480	60.66897	0.000
22	4896.777	6	816.1296	63.42145	63	1.006690	810.7062	0.000
26	3525.962	6	587.6604	641.9062	63	10.18899	57.67603	0.000
30	7503.328	6	1250.555	276.0423	63	4.381623	285.4090	0.000

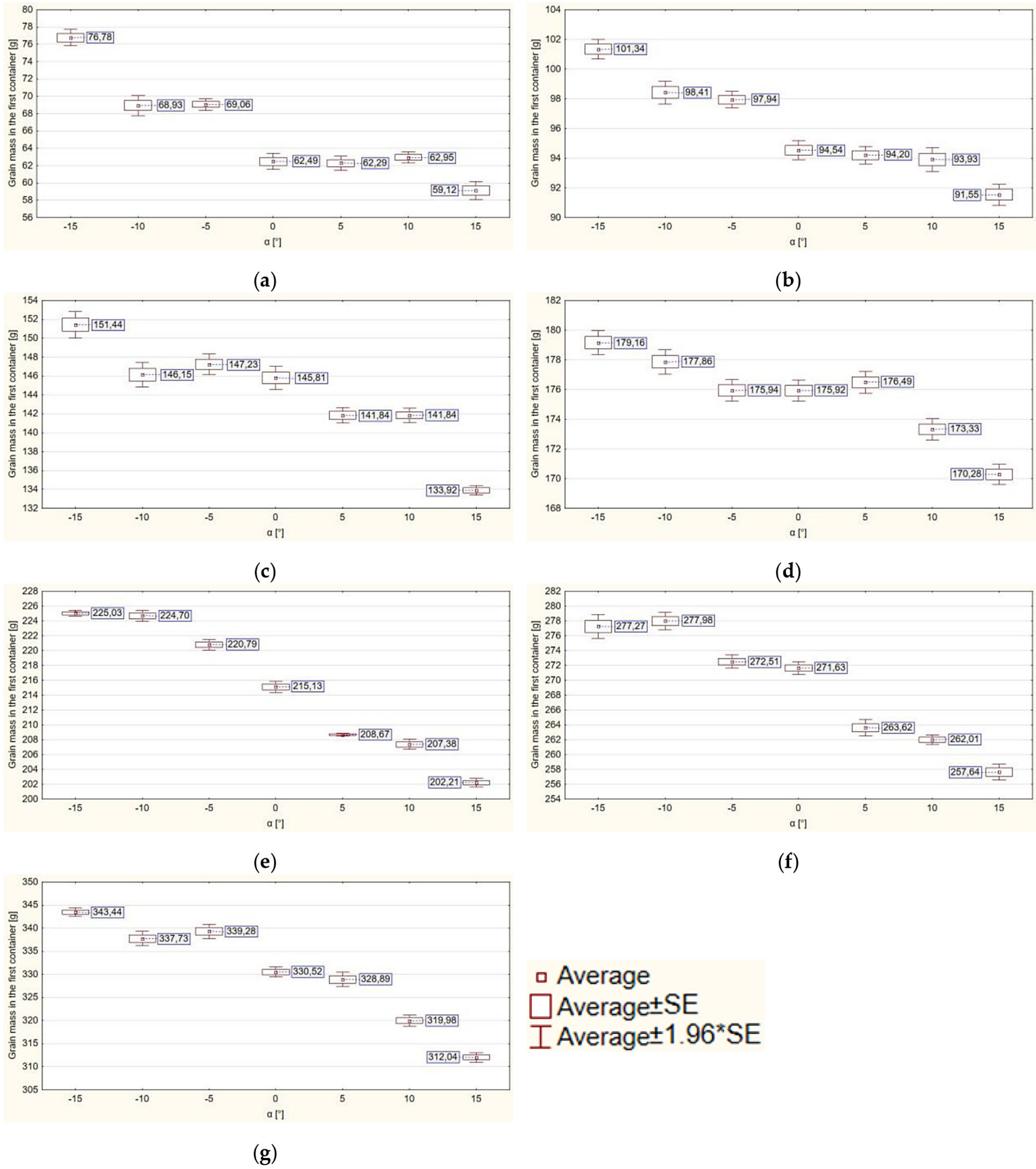

Figure 4. Weight of seeds sown by the first metering unit for the slot width: (a) 6 mm; (b) 10 mm; (c) 14 mm; (d) 18 mm; (e) 22 mm; (f) 26 mm; (g) 30 mm

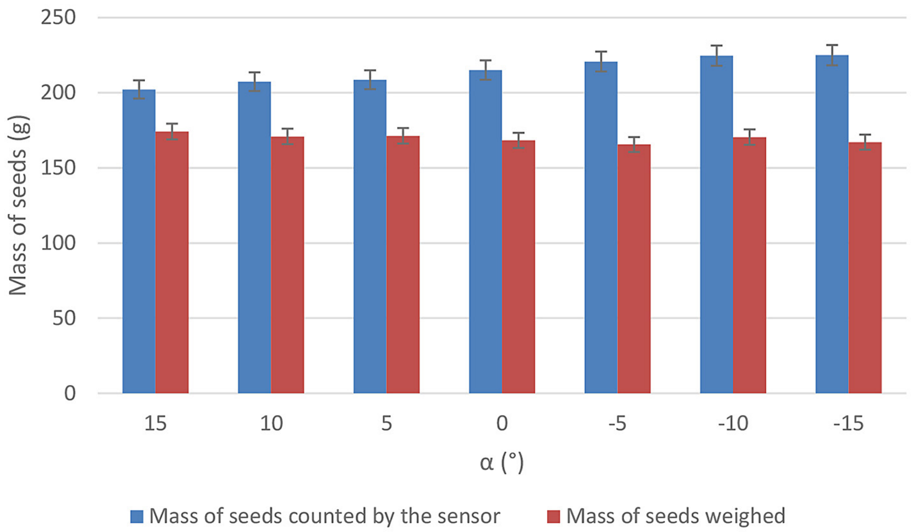

Figure 5. Comparison of the mass of seeds counted by the sensor with the mass of seeds weighed against the inclination at 50% filling and a sowing gap of 22 mm

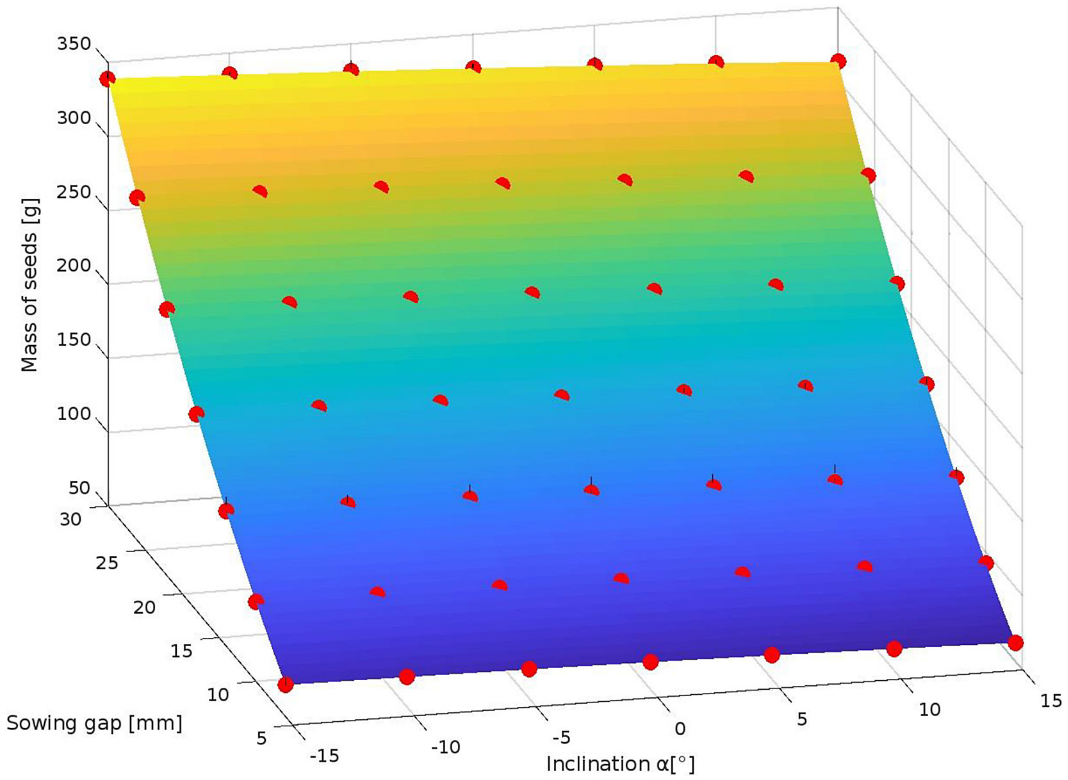

Figure 6. Plane graph of the dependence of the mass of the sown material on the slope and size of the sowing slot

$$m = 30.2748 - 0.1590 \cdot \alpha - 0.0051 \cdot \alpha^2 + \\ +5.3877 \cdot x + 0.1504 \cdot x^2 - 0.0235 \cdot x \cdot y \tag{2}$$

where: m is the mass of the seeds [g], α is angle of the tank deviation from the vertical [°], x is size of the sowing gap [mm].

For the indicated relationship, the multiple correlation coefficient is 0.9963, which indicates a very high correlation between independent and dependent variables. This model is very well fitted.

Figure 6 shows a plane graph representing the above second degree polynomial regression equation along with the average values of the seeding rate marked with red points. The Z axis shows the seeding rate [g], the X axis shows the seeder tilt angle [°], and the Y axis shows the width of the sowing slot [mm].

Figure 6 shows a plane graph illustrating the relationship between the amount of sown material and the inclination and the size of the sowing slot. The analysis of the graph shows that the amount of sown material increases with the increase in the width of the sowing slot. At the same time, a decrease in this amount is observed with increasing the angle of seeder inclination angle from -15° to +15°.

DISCUSSION

The study by Lei et al. in 2022 confirmed similar conclusions, showing that the angle of inclination significantly affects seed-filling performance [31]. An increase in the lateral inclination leads to a higher rate of missing seeds and a greater variation in the height of the seed layer. These issues can be mitigated by adjusting the height of the seed layer and incorporating seed-cleaning brushes, which together improve overall seeding performance. Additional factors have also been observed to influence seed uniformity. Operating speed and seed placement are critical variables in this regard [32–34]. Higher operational speeds tend to reduce the precision of seed placement, resulting in greater intra-row spacing and lower seeding quality. To achieve optimal results, the seeding speed must be adjusted according to the specific requirements of each crop to balance efficiency and precision.

Mechanisms of seed distribution are another important factor affecting the uniformity of seed placement [35]. Different systems, such as pneumatic and mechanical seed drills, vary in effectiveness. Pneumatic seed drill with adjustable deflectors can enhance uniformity by compensating for irregularities caused by seeder tilt [30].

The results presented in this study did not show a significant effect of tank filling level on seed dosing. In the existing literature, there is limited direct evidence confirming the claim that the filling level of a tank does not have a significant influence on the dosing of granulated materials such as seeds, with observed variations in dosing generally remaining within a 1%. However, some related observations can be inferred. The behaviour of granular materials, including their flow and distribution, can be affected by factors such as particle size, shape, and cohesion [36–39]. These factors can influence the accuracy and consistency of dosing processes. Studies on granulation processes suggest that filling levels can affect the properties of granules, including size distribution and mechanical characteristics [40–42]. Although these studies focus on granulation rather than direct dosing, they imply that filling levels can influence material behaviour in ways that could impact the accuracy of dosing. Certain experiments have shown that variations in filling levels can affect the mechanical properties and distribution of granular materials [37, 41, 42]. For example, higher filling levels in granulators may lead to increased granule strength and altered size distributions, which can influence dosing consistency. Although the literature does not provide definitive evidence that the fill level has no significant impact on granular material dosing when variations remain within 1%, it emphasises the importance of precise measurement and control in achieving uniform application. Factors such as particle size, cohesion, and granulation processes can influence material behaviour and dosing precision. Therefore, maintaining consistent filling levels and applying accurate measurement techniques are essential to minimise dosing variability.

The study aligns with the current trend of exploring the development of mechanical seed metering systems aimed at improving seed uniformity. Combined pneumatic-mechanical systems, such as SKBM-12, are also gaining attention, as they integrate the benefits of both technologies and provide enhanced distribution performance [43]. Automation and robotics are playing an increasingly important role in seeding operations. Robotic seeders equipped with GPS and microcontrollers can accurately calculate seed spacing and planting depth, significantly improving uniformity [44]. Intelligent monitoring systems based on photoelectric, capacitive and piezoelectric sensors are crucial to ensure seed quality and reduce manual workload [45]. Precision row seeders are being developed specifically to enhance seed placement accuracy in row crops. These new seeders often incorporate automated monitoring and control systems to improve seed consistency [46]. Mixed crop seeding techniques are also being investigated to increase yield and forage quality. The Vega-8w Profi seeder, for example, enables the independent sowing of two different crops in a single row, contributing to higher yields and better forage properties [47]. Another key area of development involves optimising seeding parameters such as the rotation speed, angle, and placement distance of the metering device. Studies have shown that carefully adjusting these parameters can greatly improve the uniformity of the distribution [48]. Finally, modern technologies including automation, precision agriculture, and sensor integration are essential to improve the efficiency and effectiveness of seeding machines. These technologies allow for more accurate process control, resulting in higher crop yields and reduced seed waste [49, 50].

The next stage of activities that aim to improve the uniformity of the sowing can be to conduct detailed fractional studies of the material, which will allow for a better understanding of its physical properties and the effect of granulometric differentiation on the sowing process. Granulometric composition studies were conducted, for example, by Warguła et al. [51]. Then, simulation analyses of the dosing process will be carried out using the discrete element method (DEM), which has already been successfully used in similar studies [52]. Combining fractional studies with DEM numerical analysis will not only reduce the costs associated with the construction of physical experimental stations but also enable the optimization of the device design in order to ensure uniform distribution of material during sowing.

In summary, research in this field is focused on improving seeding uniformity by advancing pneumatic and mechanical technologies, promoting automation, optimising mixed crop planting, refining precision row seeders, and fine-tuning key operational parameters, all while leveraging innovations in smart agriculture.

CONCLUSIONS

The analyzed research results prove that the inclination angle resulting from the shape of the sown area, reflected during the bench tests by the inclination angle of the change in the seed box in the range from -15° to 15°, has a significant impact on the quality of the sowing process for triticale seeds. After an in-depth analysis of the results, it was found that the seeder inclination to -15 degrees, i.e., simulation of an ascent up a hill, significantly increases the dosed seeding dose, while the seeder inclination to +15 degrees (descent down a hill) slightly reduces the dosed seeding dose. This difference is up to 22.88% at an inclination of -15 degrees and a sowing slot width of 6 mm, and at an inclination of +15 degrees and a sowing slot width of 14 mm it is up to 8.15%.

The tank filling level does not have a significant impact on the dose of the dosed granulated material (seeds), because the dose differences are up to 1%. Although no significant differences were observed, with the increase in the degree of filling the tank, a smaller scatter of results was obtained, that is, more even sowing.

For the set width of the raking slot at 14 mm, minimal differences were observed in the mass of the raked seeds between the mass of the weighed seeds and the mass calculated based on the readings of the innovative system with an impact sensor, which is 0.05 g. The largest discrepancies between the seeds mass of the weighed and the mass calculated based on the number of seeds registered by the system with an impact sensor, which amounts to as much as 192.61 g, occurred for the setting of the sowing slot width of 30 mm. The counting system with an impact sensor (strain gauge) requires the introduction of a correction factor.

As part of future work, it is planned to investigate the influence of inclination and hopper filling level using other granular materials, such as mineral fertilizers (e.g., urea), microgranulates containing micro- and macroelements—such as phosphorus, potassium, nitrogen, magnesium, iron, boron, manganese, and molybdenum—as well as catch crop mixtures.

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