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Comparison of experimental and numerical results on flow uniformity of seeds transmitted from the studded feed roller

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Abstract: Studded feed rollers are widely used in seed metering units of seed drills. The flow evenness is an important indicator of the performance of studded feed rollers. With this research, the effects of studded feed rollers with different stud numbers (27, 36, and 45 studs) on flow evenness were investigated both in the laboratory and by simulation in case of using different ground speeds (1.5, 2, and 2.5 m·s^{-1}). While the experiments were carried out on the seed drill model prepared in the laboratory, the simulation was done with the Rocky DEM software program. In the laboratory and simulation studies, it was determined that the flow evenness increased with the increase in the number of studs and the ground speed. The results obtained from the laboratory and simulation studies show parallelism with each other. However, it was seen that the results obtained in the laboratory were slightly higher than the results obtained from the simulation. With this study, it has been seen that it would be very beneficial to use the DEM model to improve the performance of the seed metering unit and to develop a new seed metering unit.

Keywords: discrete element method; seed drill; seed metering unit; stud type roller; wheat

Cereals are the basic products used directly or indirectly in human nutrition. Among the cereals, wheat is the most widely grown crop plant in the world. Thanks to its great adaptability, it has the advantage of being grown in all kinds of climates and regions. However, it is a strategic product in the food industry. It was easy to increase production by expanding agricultural areas in the past. But today, acquiring new agricultural areas requires very expensive investments. Instead, increasing production will be possible by buying more products from the unit area. There are some important concepts that need to be focused on in order to increase productivity. High grain yield can be achieved with high field output and uniform development of each plant. In order to achieve this, in addition to the uniform distribution depth, a uniform seed distribution on the surface is required (Speelman 1975; Heege 1993). To achieve this, an appropriate seed drill must be used. Cereals are now commonly planted with a seed drill. These machines can be produced in different types according to different climatic and agronomic conditions. But the basic elements are the same in all seed drills. A seed drill consists of some important basic parts in order to carry out a suitable operation. These basic parts are the seed box, the seed metering unit, the drop tube, the opener, the covering device, the transmission system, the depth adjustment device, the frame, and the wheels. In addition to these. there are fertilizer distribution systems in the combined seed drills. The most important part that affects the performance and seed distribution uniformity of a seed

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drill is the seed metering unit (Bansal et al. 1989; Khan 1992; Tabassum 1992). The task of the seed metering unit is to convey the seed taken from the seed box to the seed tube in a measured manner. The seed metering unit is generally as much as the number of rows of the seed drill, and these feed rollers are connected to a common shaft. The feed rollers are usually located in the seed metering unit with the base flap on the underside of the seed box. Various seed metering devices have been designed in the development process of the seed drill. In today's agricultural technique, since the grains are planted with the continuous sequential sowing method, the seed distribution systems used are also types that provide continuous flow (Srivastava 2006). The studded feed roller is the most common seed delivery device used in seed planting. In this feeder type, the teeth are arranged in rows around the pulley. Transmission of the seed occurs with the pressure exerted by the front of the tooth on the seed. The seeds are delivered to the seed tubes over the base flap. A part of the seed reaches the teeth of the roller and is thrown out with the rotation speed of the roller. The design parameters that affect the amount and flow evenness of seed thrown into a studded feed roller are the roller's outer diameter, the active length of the roller, the number of studs on the roller, and the cross-sectional area between the studs. (Collins 1978; Svensson 1994). In the geared studded feed roller seed distribution system, the sowing norm adjustment is made by changing the transmission ratio between the wheels and the drive shaft (Bernacki et al. 1972; Culpin 1992). It uses different measurement methods to determine the precision of the studded feed roller under laboratory conditions. These are adhesive tape systems, using high-speed cameras, boxing, and precision scales (Boydas and Turgut 2007). Experimental testing of seed metering mechanisms is both expensive and time-consuming. Another method used to determine the performance of the seed metering mechanism is the numerical approach. The rapid increase in the use of powerful computers and developed software in recent years has prompted researchers working on a granular flow to use this method. Among these methods, the Discrete element method (DEM), which was first proposed by Cundall and Strack in 1980, has been widely used. The DEM is a numerical method that takes into account the interactions of discrete particles in contact and allows the evaluation of mutual force interactions. With this method, simulation is performed by using translational and rotational motion equations for each particle. The DEM is nowadays used with Computational fluid dynamics (CFD) and Finite element analysis (FEA) (Bilgili et al. 2017; Młynarczyk and Brewczyński 2021). Rocky DEM, one of the DEM software packages, is also fully integrated with ANSYS (Canonsburg, USA). With DEM, values such as particle-particle, particle-geometry, geometry-geometry, static friction coefficient, rolling friction coefficient, and restitution coefficient are defined. In addition, the physical and mechanical properties of the product can be defined. The discrete element method is used in many fields such as mining, agriculture, chemistry, medicine, construction, and transport. Especially, DEM is used for the design, optimisation, and performance testing of agricultural machines, such as seed drills, harvesting machinery, and soil tillage. For example, Huang et al. (2018) improved operating parameters and the flow evenness of the fluted roller meter for diammonium phosphate fertilizer by using the DEM. Marcinkiewicz et al. (2019) tested four different studded feed rollers for wheat both experimentally and the DEM. The aim of the study was to investigate the effect of the change in the structural properties of the studded feed rollers, which are widely used in sowing machines, on the wheat seed flow evenness both in laboratory conditions and in the DEM simulation model, to compare the results obtained in the laboratory with the results obtained from the DEM simulation model, to test the input parameters and methodology used in the DEM simulation model, to show the relationship between them, and to highlight the advantages of the DEM simulation model in the design of seed drill metering units.

MATERIAL AND METHODS

Seed. For this study, wheat seed was used. The means and standard errors (SE) of some physical properties of the seeds used in the experiment are given in Table 1. Seed dimensions were measured by using a vernier caliper with a sensitivity of 0.01 mm.

Studded feed roller. The experiment used studded feed rollers made of Delrin material with three different tooth numbers. Each studded feed roller had three rows of studs. Each row had 9, 12, and 15 studs (*S1*, *S*2, and *S*3, respectively). The stud dimensions of each studded feed roller are given in Figure 1.

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Table.1. Some physical properties of seeds used in the experiment

Seed	Bulk density (kg·m^{-3})	Bulk angle of repose (°)	Thousand-grain weight (g)	Moisture content (%)	Seed dimensions (mm)		
					length	width	thickness
Wheat	714 ± 6.3	29.4 ± 1.2	41.2 ± 1.7	12 ± 0.2	6.34 ± 0.31	3.32 ± 0.22	2.82 ± 0.18

(A) (B) (C)

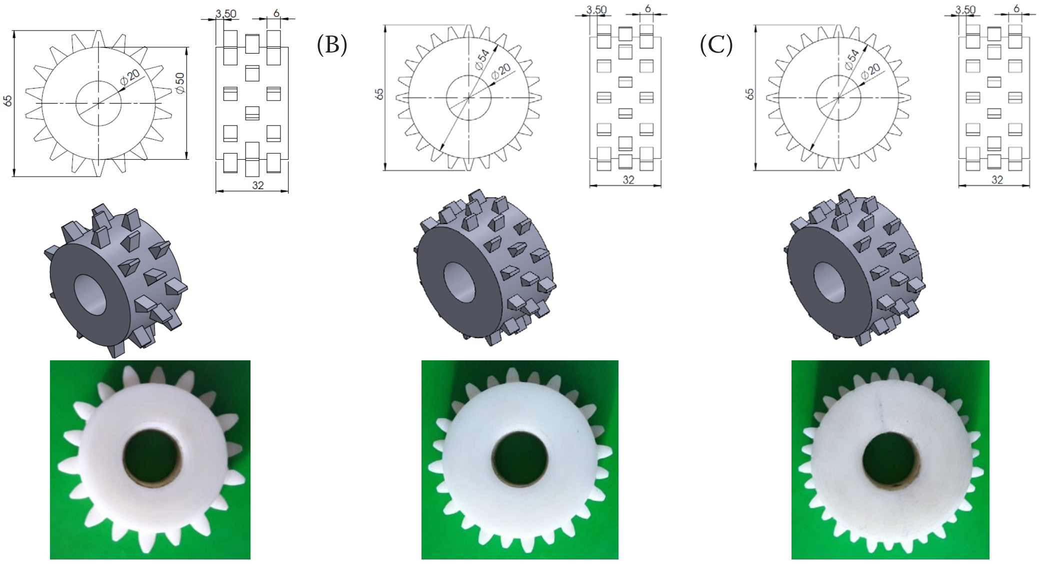

Figure 1. Dimensions of (A) 27 teeth, (B) 36 teeth and (C) 45 teeth studded feed roller used in the experiment and Rocky discrete element method (DEM) simulation

Test stand, and a description of the equipment. The experiments were conducted at the laboratory of the Agricultural Farm Machinery Department, Ataturk University, Erzurum, Turkey. The laboratory temperature and relative humidity were measured at 20 °C and 25%, respectively. A test stand was set up in the laboratory to simulate a seed drill (Figure 2). The test stand consisted of the hopper, the seed metering unit, the agitator, a three-phase electric motor, an AC three-phase inverter that changed the speed of the electric motor, a load cell used for precision weighing (a precision scale), a data logger, and a personal computer. The hopper was 250 mm wide and had a volume of 0.0122 m^3. The angles of the hopper floor with the horizontal were 62 and 28°.

(A) (B)

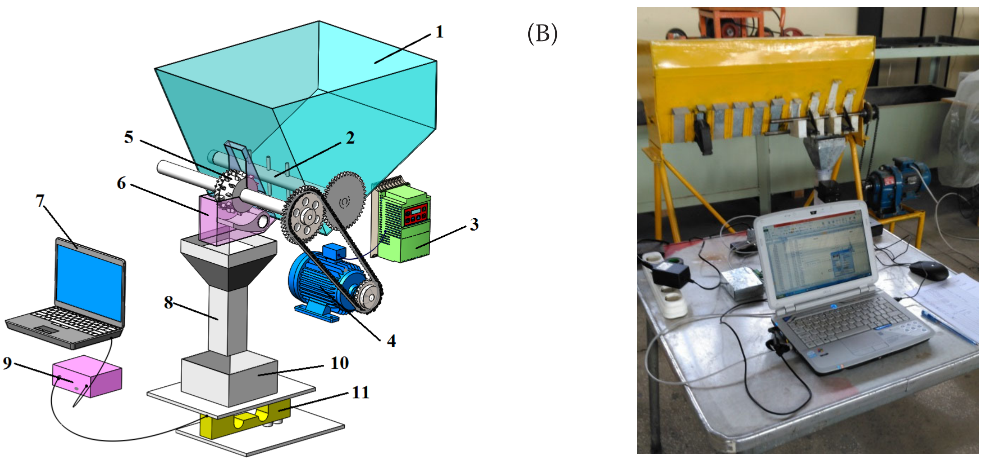

Figure 2. The test stand used in the laboratory: (A) the solidworks model and (B) the experimental setup

1 – hopper; 2 – agitator; 3 – AC three-phase inverter; 4 – three-phase electric motor; 5 – studded feed roller; 6 – base flap; 7 – personnel computer; 8 – seed tube; 9 – datalogger; 10 – seed box; 11 – load cell

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Experiment setup. The experiments were done with a studded feed roller with three different stud counts (27, 36, and 45 studs) for three different ground speeds (1.5, 2.0, and 2.5 m·s^{-1}) and for one seed rate (150 kg·ha^{-1}). Since the test setup is not really a seed drill, the revolutions of the studded feed roller were calculated for each ground speed and for each feed roller. While making this calculation, the row spacing of the seed dill was considered to be 15 cm. According to these data, the theoretical amount of seed that should be planted per unit of time was determined. For this, the following equations are used.

Flow rate for a ground speed of 1.5 m·s^{-1}:

$$= \frac{150 \times 10^3\,\mathrm{g}}{\dfrac{10000\,\mathrm{m}^2}{0.15\,\mathrm{m}} / 1.5\,\mathrm{m{\cdot}s^{-1}}} = 3.38\,\mathrm{g{\cdot}s^{-1}} \tag{1}$$

Flow rate for a ground speed of 2.0 m·s^{-1}:

$$= \frac{150 \times 10^3\,\mathrm{g}}{\dfrac{10000\,\mathrm{m}^2}{0.15\,\mathrm{m}} / 2\,\mathrm{m{\cdot}s^{-1}}} = 4.50\,\mathrm{g{\cdot}s^{-1}} \tag{2}$$

Flow rate for a ground speed of 2.5 m·s^{-1}:

$$= \frac{150 \times 10^3\,\mathrm{g}}{\dfrac{10000\,\mathrm{m}^2}{0.15\,\mathrm{m}} / 2.5\,\mathrm{m{\cdot}s^{-1}}} = 5.63\,\mathrm{g{\cdot}s^{-1}} \tag{3}$$

After the calculation was made, the machine was operated in the laboratory. Thus, the feed roller revolutions that met the calculated flow rate were found with the help of a precision balance and a tachometer. These studded feed roller revolutions are given in Table 2.

After determining the feed roller rotation speeds for the determined seed rate, flow evenness and flow rate were measured with the help of precision scales. Precision scales weighed the seeds falling from the seed metering unit at intervals of 0.05 s. The amount of seed flowing was recorded cumulatively and transferred to the computer via a data logger. The weight of seeds in each interval was determined by subtracting the seed weights in the 0.05 s interval from each other. In this way, the coefficient of variation (CV %) of the seed was calculated according to the following equation (DeCoursey and ScienceDirect 2003).

$$\mathrm{CV\%} = \frac{\sigma}{\mu} \times 100 \tag{4}$$

where: σ – the standard deviation of sample; μ – mean of sample.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N}} \tag{5}$$

where: N – the number of samples; x_i – the mass of the i^{th} sample.

$$\mu = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{6}$$

The discrete element method (DEM) simulation model setup. The DEM, a numerical method, was used to simulate the seed flow through the studded feed roller. With this method, it is aimed to track individual particles or parcels that represent a series of particles in the flow region. Particles in a granular motion have six degrees of freedom and consequently can make translational and rotational movements (Rocky DEM ESSS 2015; Młynarczyk and Brewczyński 2021; Altair 2023). The translational motion of particles is determined by the following equation:

$$m \frac{dv}{dt} = F_g + F_c + F_{nc} \tag{7}$$

where: m – the mass of the particle; v – the translational velocity of the particle; t – the time; F_g – the resultant gravitational force acting on the particle; F_c and F_{nc} – the resultant contacts and noncontact forces between the particle and surrounding particles or walls.

Table 2. The working speed of studded feed rollers

Ground speed (m·s^{-1})	Roller speed (rpm·s^{-1}, rad·s^{-1})		
	for 27 studs	for 36 studs	for 45 studs
1.5	11–1.15	15–1.57	18–1.88
2.0	15–1.57	20–2.09	24–2.51
2.5	19–1.99	25–2.62	30–3.14

rpm – revolutions per minute

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The rotational motion of particles is determined by the following equation:

$$I\frac{d\omega}{dt}=M \qquad (8)$$

where: I – the moment of inertia; ω – the angular velocity; M – the resultant contact torque acting on the particle.

More detailed information can be found in the Rocky DEM technical manual (Rocky DEM ESSS 2015). The DEM allows to effective simulate the interaction of seed drill parts with an almost unlimited number of seeds of various shapes and sizes. First, the exact dimensions of the experimental seed drill used in the DEM simulation were drawn in Solidworks. Subsequently, the drawings were imported to Rocky DEM (Figure 3). Rocky DEM is a very strong particle simulation software that accurately simulates the flow behaviour of bulk materials with complicated granular shapes and different sizes.

Contact model. Calculations in Rocky DEM are made according to Newton's laws and gravity, including intergranular contacts. The contact models used in the DEM simulations were Hertzian Spring Dashpot for normal forces and Mindlin-Deresiewitcz for tangential forces. Hertzian Spring Dashpot is used for modelling non-linear materials, and Mindlin-Deresiewicz can be used only with the Hertzian Spring Dashpot model (Kruszelnicka et al. 2022). Cohesion is negligible in a dry state. Therefore, cohesion is not taken into account. Typical parameters were entered for simulation in the Rocky DEM. These parameters are given in Table 3.

Wheat particle shape used in the simulation. The shape of the wheat seed is defined as an ellipsoid, which is a three-dimensional figure symmetrical about each of three perpendicular axes, whose plane sections normal to one axis are circles and all the other plane sections are ellipses (Igathinathane and Chattopadhyay 1998). Therefore, three main dimensions are used to define the shape (length, width, and thickness). Based on the actual dimensions of the wheat, wheat seeds were modelled in the Rocky DEM as ellipsoid (Figure 4). The values related to the designed wheat parameters are given in Table 3.

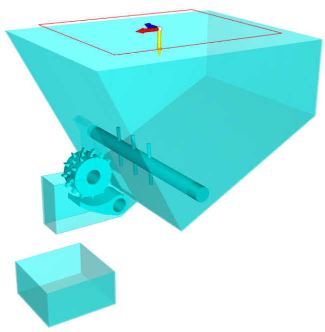

Figure 3. Rocky discrete element method (DEM) model used in the simulation

Filling the seed into the hopper. An inlet was placed just above the hopper to fill the wheat seed model in the hopper. The seed mass flow rate from this inlet into the hopper with continuous injection of Rocky DEM was 240 t·h^{-1}. In this way, the hopper was filled quickly (Figure 5).

Table 3. Input parameters used for simulation in Rocky discrete element (DEM) method

Properties	Value
Particle (wheat) parameters	
Bulk density (kg·m^{-3})	714
Inlet mass flow rate (t·h^{-1})	240
Particle shape	Sphere-polyhedron
Particle size distribution (%)	100
Gravity acceleration (m·s^{-2})	9.81
Young's modulus (MPa)	1 800
Poisson's ratio	0.32
Vertical aspect ratio	2.10
Horizontal aspect ratio	0.88
Smoothness	0.14
Numbers of corners	50
Super quadric degree	2
Studded feed roller material	
Density (kg·m^{-3})	1 415
Poisson's ratio	0.41
Young's modulus (MPa)	3 150
Seedbox and agitator material	
Density (kg·m^{-3})	7810
Poisson's ratio	0.3
Young's modulus (GPa)	207
Material interaction between two particles	
Static friction coefficient	0.55
Dynamic friction coefficient	0.50
Tangential stiffness ratio	1
Restitution coefficient	0.3
Material interaction between particle and studded feed roller	
Static friction coefficient	0.38
Dynamic friction coefficient	0.30
Tangential stiffness ratio	0.80
Restitution coefficient	0.44

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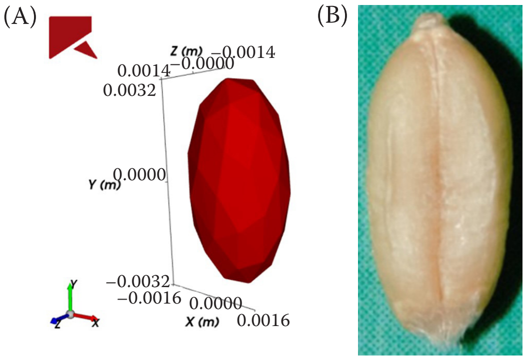

Figure 4. (A) the wheat modeled in Rocky DEM and (B) the wheat grain used in the experimen

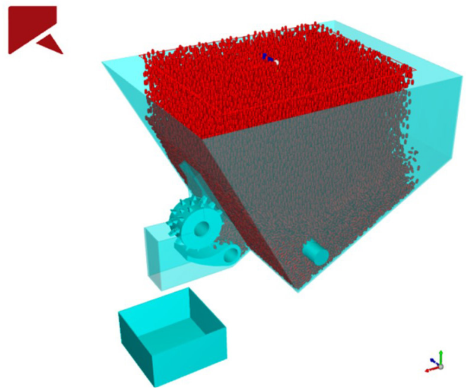

Figure 5. Filling the hopper with wheat seed

Working of the seed drill in DEM simulation. The DEM simulation model was run by giving a rotational speed to the studded feed roller and agitator. The speed of the agitator was the same as the speed of the roller. It was important to include the agitator in the simulation. Because in the real world, there is definitely an agitator in seed drills. Although the use of the agitator in the simulation extended the simulation time, it made the results more reliable.

As the studded feed roller rotated, wheat seeds started to flow through the base flap (Figure 6).

A box was placed just below the seed metering mechanism unit to collect seeds. Thus, the spattering and scattering of seeds are prevented. The total simulation time for running the studded feed roller and for filling the wheat seed model in the hopper is set to 15 s. The measuring zone was placed in the box area under the studded feed roller and the seed flow path (Figure 7). With the help of the measuring zone, flow evenness and seed flow rate were followed in the simulation. Data obtained from the simulation were recorded at 0.05 s intervals.

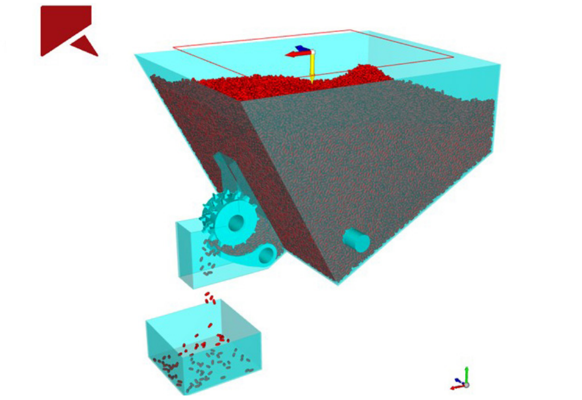

Figure 6. Seed flow from studded feed roller metering unit

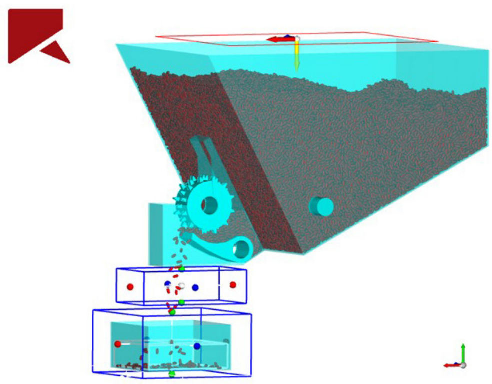

Figure 7. Measurement zones determined in the simulation

RESULTS AND DISCUSSIONS

Experimental results. The flow evenness CV% ANOVA results obtained at different rotational speeds of the studded feed roller in the laboratory are presented in Table 4. According to the ANOVA analysis, the flow evenness of wheat was significantly affected by two experimental factors: the studded feed rollers and the roller speeds. The studded feed roller × roller speed interaction was determined to be non-significant ($P > 0.05$). The flow evenness CV% means values obtained from the studded feed rollers and ground speeds are shown in Figure 8. While the rotational speeds of the studded feed roller increased, the flow evenness became better. While the stud number of studded feed rollers increased, the flow evenness became better. Similarly, Guler (2005) and Boydas and Turgut (2007) stated that the increase in the number of feed roller revolutions caused an improvement in flow evenness. The highest mean value of CV% was obtained at about 12.12% with 1.5 m·s^{-1} ground speeds and

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Table 4. The variance analysis of flow evenness (CV%) values obtained from laboratory experiments

Variation sources	*df*	MS	*F*-value	*P*-value
Studded feed roller (*S*)	2	33.9675	118.02	0.000*
Roller speed (*R*)	2	30.7413	106.81	0.000*
Replication	2	0.5384	1.87	0.186
S × *R*	4	0.0908	0.32	0.863
Residual	16	0.2878		
Total	26			

* Significant at *P*-value < 0.001; *df* – degree of freedom; MS – mean square

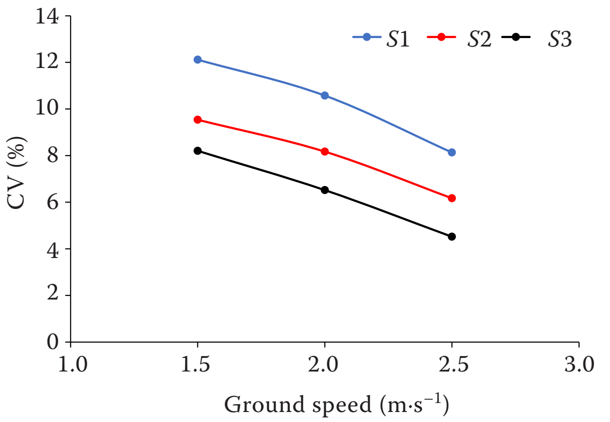

Figure 8. The flow evenness coefficient of variation (CV)% means values obtained from the studded feed rollers and ground speed with laboratory experiments

the 27 studs. The lowest mean value of CV% was obtained at about 4.52% with 2.5 m·s^{-1} ground speeds and the 45 studs. The mean values of CV% were obtained as 12.12, 10.58, and 8.13% with 27 studs of studded feed roller for 1.5, 2, and 2.5 m·s^{-1} ground speeds, respectively. The mean values of CV% obtained from 36 studs of studded feed roller were found to be 9.54, 8.17, and 6.17% for 1.5, 2, and 2.5 m·s^{-1} ground speeds, respectively. The mean values of CV% obtained from 45 studs of studded feed roller were found to be 8.20, 6.52, and 4.52% for 1.5 , 2, and 2.5 m·s^{-1} ground speeds, respectively.

Simulation results. The simulation study was also carried out similarly to the laboratory study. In the box placed under the studded feed roller, seeds were collected at intervals of 0.05 s. Then, the number of seeds in this box was taken from the program of the Rocky DEM software (Version Rocky 4.5) in the form of a table and transferred to the Excel software. So, CV% values were calculated in Excel. The flow evenness CV% ANOVA results obtained at different rotational speeds of the studded feed roller in the Roky DEM are presented in Table 5. According to the ANOVA analysis, the flow evenness of wheat was significantly affected by two experimental factors: the studded feed rollers and the roller speeds, the studded feed roller × roller speed interaction was determined to be non-significant ($P > 0.05$). The flow evenness CV% means values obtained from the studded feed rollers and ground speeds are shown in Figure 9. While the rotational speeds of the studded feed roller increased, the flow evenness became better. While the stud number of studded feed rollers increased, the flow evenness became better. The highest mean value of CV% was obtained at about 11.52% with 1.5 m·s^{-1} ground speeds and the 27 studs. The lowest mean values of CV% were obtained about 4.37% with 2.5 m·s^{-1} ground speeds and the 45 studs. The mean values of CV% were obtained to be 11.52, 9.83, and 8.03% with 27 studs of studded feed roller for 1.5, 2, and 2.5 m·s^{-1} ground

Table 5. The variance analysis of flow evenness (CV%) values obtained from simulations

Variation sources	*df*	MS	*F*-value	*P*-value
Studded feed roller (*S*)	2	31.5077	2 336.15	0.000*
Roller speed (*R*)	2	25.9140	1 921.40	0.000*
Replication	2	0.0186	1.38	0.280
S × *R*	4	0.0314	2.33	0.100
Residual	16	0.0135		
Total	26			

Significant at *P*-value < 0.001; *df* – degree of freedom; MS – mean square

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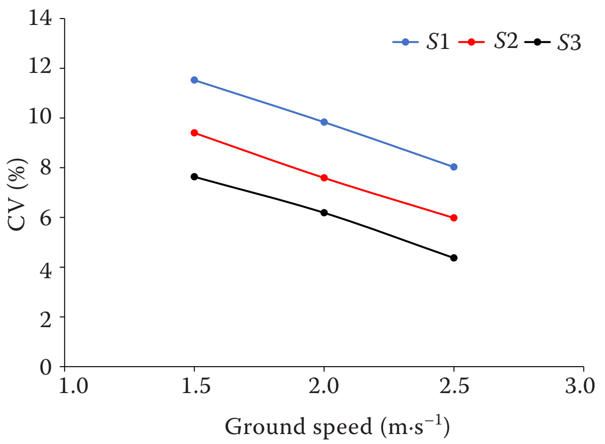

Figure 9. The flow evenness coefficient of variation (CV%) means values obtained from the studded feed rollers and ground speed with simulation

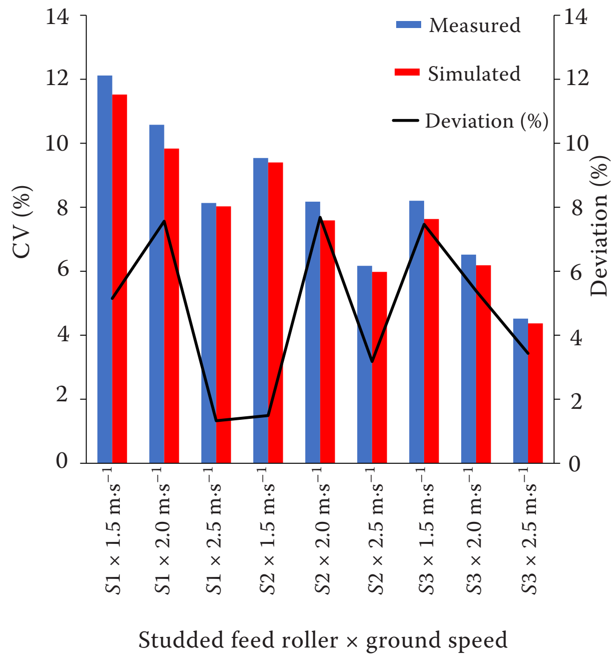

Figure 10. Coefficient of variation (CV%) values of flow evenness and percent deviation values obtained in the laboratory and from the simulation

speeds, respectively. The mean values of CV% obtained from 36 studs of studded feed roller were found to be 9.40, 7.59, and 5.98% for 1.5, 2, and 2.5 m·s^{-1} ground speeds, respectively. The mean values of CV% obtained from 45 studs of studded feed roller were found to be 7.63, 6.19, and 4.37% for 1.5, 2, and 2.5 m·s^{-1} ground speeds, respectively.

The CV% values of flow evenness and percent deviation values obtained in the laboratory and from the simulation are shown in Figure 10. It was determined that the data obtained in the laboratory and the data obtained from the simulation were very close to each other and showed similar characteristics. Huang et al. (2018) studied the parameter optimisation of a fluted roller meter using the DEM both experimentally and by simulation and reported that the simulation and experiment results showed similar trends. In a similar study, Marcinkiewicz et al. (2019) tested the performance of studded feed rollers, which have four different designs, experimentally and with simulation. They found that the experimental study and the simulation study confirmed each other.

It was determined that the data obtained from the simulation were slightly lower than the data obtained from the laboratory. It can be thought that the biggest reason for this is the homogeneous structure of the seed. Because, although the wheat seeds are sieved, it is not possible to eliminate the shape and dimensional differences in the seeds. While the highest deviation between the results obtained from the laboratory and the results obtained from the simulation was 7.68% with 36 studs and 2 m·s^{-1} ground speed, the lowest deviation was obtained to be 1.32% with 27 studs and 2.5 m·s^{-1} ground speed. The research results showed that the increase in the number of studs and the ground speed improves the flow evenness. This result was seen both experimentally and in simulation.

CONCLUSION

A seed drill simulation was set up both in the laboratory and in the DEM model to determine the flow uniformity of wheat seeds from the studded feed roller with different stud numbers. In addition, studded feed rollers were operated at three different speeds in the simulation. Rocky DEM software was used in the preparation of the DEM simulation study. When the results obtained from both laboratory studies and DEM simulation studies were compared, satisfactory results were obtained. The increase in the number of studs and the speed resulted in the improvement of flow evenness in wheat. In laboratory experiments and DEM simulation, the highest mean values of CV% were obtained at about 12.12 and 11.52% with 1.5 m·s^{-1} ground speeds and 27 studs, respectively. The lowest mean values of CV% were obtained at about 4.52 and 4.37% with 2.5 m·s^{-1} ground speeds and the 45 studs. In DEM

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simulation, the highest mean values of CV% were obtained at about 11.52% with 1.5 m·s^{-1} ground speeds and the 27 studs. The lowest mean values of CV% were obtained at about 4.37% with 2.5 m·s^{-1} ground speeds and the 45 studs. It was determined that the results obtained from the laboratory and the results obtained from the DEM model varied between 7.68 and 1.32%. The results obtained were consistent with both the experimental and the DEM model. The use of DEM in the design of seed metering units can help achieve efficiency, appropriate material selection, and faster production. The novelty of this study was the exact modelling of a seed drill simulation system designed under laboratory conditions in the DEM model (machine dimensions, working speed, agitator, and material properties). In the next studies, it is important to examine the seed flow evenness that occurs when a real seed drill is working on the field surface, taking into account the data obtained in this study. It gives successful results in soil-machine interaction analysis using the Rocky DEM software program. Thus, determining the performance of seed metering units in different soil conditions and land slopes without going to the field with the DEM software program will provide an important gain for designers and researchers.

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