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Offset Straight-Tooth Roller Development Using the Discrete Element Method for Applying Granular Mineral Fertilizer

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Abstract. This study aimed to design and evaluate offset straight teeth roller for precise application of granular mineral fertilizer at low rotation speeds. In the first stage, the experiment focused on optimizing the gap length between offset straight-tooth to prevent unintended fertilizer flow and ensure even distribution. In the second stage, additional gaps on the left and right sides of offset straight teeth were compared to a single gap. The results of the comparison showed that adding gaps on the sides improved the discharge rate and the uniformity of distribution. Therefore, offset straight-tooth roller was divided into five sections, each with a length of 12 mm. Discrete Element Method (DEM) simulations showed an actual discharge mass of 148.35 g, producing a slippage rate of 35.9%. Verification using laboratory equipment with offset straight-tooth roller showed a discharge of 150 g of mineral granular fertilizer.

Keywords: Discrete element method; Interaction properties; Mineral granular fertilizer; Offset straight-tooth roller

1. Introduction

The current global tendency is focused on mineral fertilizer applications to meet the precise nutritional needs of plants, maximize yields, and enhance quality. The process is carried out to ensure that crop production contributes to a smooth and healthy food chain, showing the interconnectedness of agriculture, the environment, and human health (Noulas, Torabian, and Qin, 2023). This shows the need to apply granular mineral fertilizer evenly into the soil to promote uniform plant growth, prevent nutrient imbalances, maximize nutrient efficiency, and reduce environmental risks (Bijay-Singh, and Tek, 2022; Petrus *et al.,* 2020; Nukeshev *et al.*, 2024). In drought conditions, applying a small dose of granular fertilizer has a positive effect, while high dose has no positive effect but negative impact (Nukeshev *et al.*, 2023; Wang *et al.,* 2019; Kaur *et al.,* 2017). Applying high doses of granular fertilizer is associated with a significant positive effect when the soil has enough

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water during the vegetation period. Therefore, the even application of granular fertilizer is essential, particularly at a high or a small dose.

Metering device is an integral to precision agriculture practices, allowing accurate application of mineral fertilizer based on field variability and crop requirements (Shafi *et al.,* 2019; Stoorvogel, Kooistra, Bouma, 2015). This enables targeted nutrient application, where fertilizer is applied, leading to more efficient resource use and improved crop performance (Ahmad and Dar, 2020). A well-designed metering device ensures that fertilizer is distributed evenly across the entire field. This prevents uneven nutrient distribution that can cause variations in crop growth and yield (Yeskhozhin *et al.,* 2018; Nukeshev *et al.,* 2017; Zhao, Pengfei, et al., 2024; 2016a; 2016b; Zhaksylykova *et al.,* 2016). To achieve even distribution of granular fertilizer, scientists are designing various metering devices. For example, the pin-roller metering device was designed to apply a high dose of granular fertilizer evenly, where the pins of the pin-roller were in the form of a truncated pyramid (Sugirbay *et al.,* 2023; Nukeshev *et al.,* 2019; Sugirbay *et al.,* 2020). The even distribution or coefficient of variation (CV) for granular fertilizer of the pin-roller metering device was 37%. Meanwhile, the CV of 6 and 12 grooved metering devices were 111.13% and 80.74%, respectively. These pin-roller metering devices distribute granular fertilizer evenly, but to provide experiments were printed by 3D printer.

Manufacturing the pin-roller metering device is complex with machine tools. In this context, a fluted-roller metering device has been proven effective for granular fertilizer due to the easy manufacturing process and adjustment of the working length (Bu *et al.,* 2022; Kuş, 2021; Zeng *et al.,* 2020; Ding *et al.,* 2018; Huang *et al.,* 2018; Minfeng *et al.,* 2018; Su *et al.,* 2015; Lv, Yu, and Fu, 2013). However, fluted-roller metering devices discharge unevenly a butch high dose of granular fertilizer, which can be addressed by decreasing the working length and increasing the rotation speed. Increasing the rotation speed of roller does not allow the metering device with a little electric motor, regarding an unmanned aerial vehicle to discharge granular fertilizer on the soil surface (Al-Gaadi *et al.,* 2023; Su *et al.,* 2022).

The recent trend is to drive metering device of the seeders with electric motors to apply variable rates of granular fertilizer. To decrease the CV or increase the even distribution, the grooves of fluted-roller are designed spirally to replace the conventional straight grooved wheel. Although the spiral grooved wheel showed superior uniformity in fertilizer discharge, the complexity of manufacturing increased due to design modifications. A study was conducted using offset spiral teeth fertilizer discharge device (Fang *et al.,* 2024). It was also reported that decreasing the working length to less than 15 mm of spiral grooved metering device led to the discharge of a batch of granular fertilizer (Wang *et al.,* 2023). Another study was conducted using two fluted rollers or gap squeeze gear-type discharger to dispense granular fertilizer. This was based on the principle of half-cycle superposition of fertilizer discharge curve (Dun *et al.,* 2023a; 2023 b; 2021). Fertilizer apparatus featuring arc gears operates on the principle of releasing fertilizer through clearance within the circular arc discharging gear. This gear maintains a consistent gap, while the teeth spaced move continuously and alternately. The design enhances the consistency of fertilizer discharge flow, preventing common issues such as blockages and intermittent discharge found in conventional fertilizer dispensers. However, increasing the gap between the gears to apply a high dose of granular fertilizer at low rotation speeds is not recommended because of free flow. The use of two rollers also complicates the design of the metering device.

Based on the description, this study aimed to propose a new design featuring a six-grooved roller for discharging high doses. The design was similar to offset spiral teeth fertilizer discharge device but with straight-teeth and a gap between offset. The objective was to effectively use the space between the teeth for evenly discharging high dose of granular fertilizer. To improve the even distribution of granular fertilizer, the six-grooved roller, with a length of 60 mm, was divided into identical left and right parts, offset axially by 30 degrees, with the gap located on the middle side. The first task was to determine the influence of gap located in the middle with various parameters, which was optimized to prevent the free flow of granular fertilizer. The second task was to add more gaps on the left and right sides of roller and compare the results. The discharged granular fertilizer mass, slippage rate (SR), and CV in the discharged mass were used as parameters to compare the influence of different settings.

2. Methods

2.1. The design and parameters of offset straight-tooth six-grooved roller with the gap

The laboratory equipment required for conducting the experiment consists of several components. These include a tank for storing granular fertilizer (1), a casing for the metering device (2), a specially designed six-grooved roller (3), left and right side caps (4), a bottom cap (5), and left and right side discs (6) and bolts (7, 8) (Figure 1a). The casing of the metering device is connected to the tank using bolts and the orifice at the bottom of the tank is in line with the open area of the casing on the top. To direct granular fertilizer, there is a plate inclined at 20 degrees, and the end of the plate is curved along the orifice of the casing (Figure 1b). The middle side view of the metering device casing showed the radius of the casing orifice is 30.25 mm. The metering device casing contained orifices to fix the position of the left and right side caps (4) and the bottom cap (5). The parameters of the disks and caps are showed in Figures 1c and 1d. The inner radius of the disc is fitted into the orifice of the metering device casing, while the outer radius of the disc is connected to the casing. The left and right caps are secured to the metering device casing with bolts, ensuring the positioning of the discs relative to the metering device casing. The parameters of the designed six-grooved roller are shown in Figure 1e.

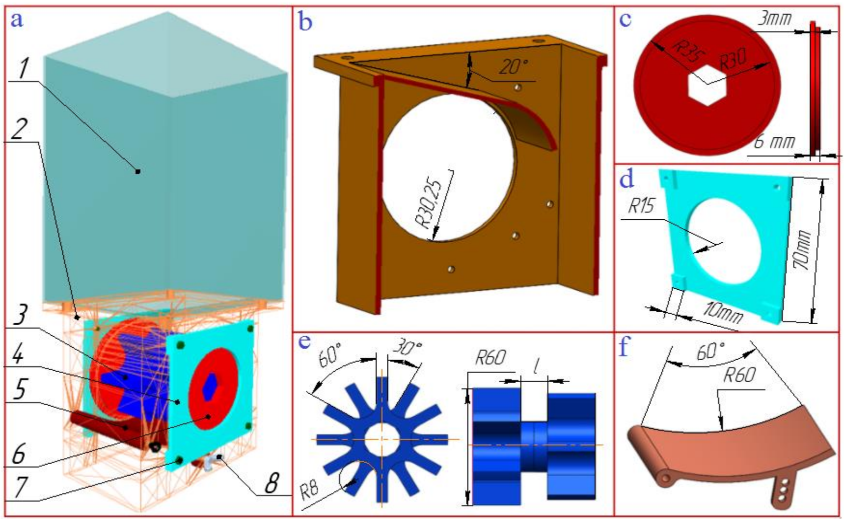

Figure 1 Design and parameters of the of the metering device: a. View of the metering device: 1. Granular fertilizer tank; 2. Metering device casing; 3. Designed six-grooved roller; 4. Right side cap; 5. Bottom cap; 6. Right side disc; 7. Bolt; 8. Bottom cap bolt; b. Metering device case parameters; c. Disc parameters; d. Left and right side cap parameters; e. Designed six-grooved roller parameters; f. Bottom cap parameters

The designed six-grooved roller is axially in line with the discs and metering device orifice, which can freely rotate in both clockwise and counterclockwise directions. The left and right discs are connected to the six-grooved roller and rotate together. The six-grooved roller collar contains identical left and right parts offset axially by 30 degrees. Moreover, there is a gap located on the middle side of the six-grooved roller, which is essential for determining the optimum length (l) of the gap. The bottom cap is shown in Figure 1f, which is fixed to the metering device casing on one side with a cotter pin and on the other side with a bolt.

2.2. The theoretical calculation of the designed six-grooved metering device working volume

The working volume of the designed six-grooved roller per one revolution is calculated by summing the free space of the six-grooved roller and determining the volume of the active layer (equation 1). The active layer volume is considered because of the distance between the six-grooved roller and bottom cap due to the interaction between granular fertilizer. Figure 2 shows granular fertilizer flow inside the metering device and the main parameters for calculating the working volume of the designed six-grooved roller. Granular fertilizer by their gravity move from the tank and fill the free space of the six-grooved roller.

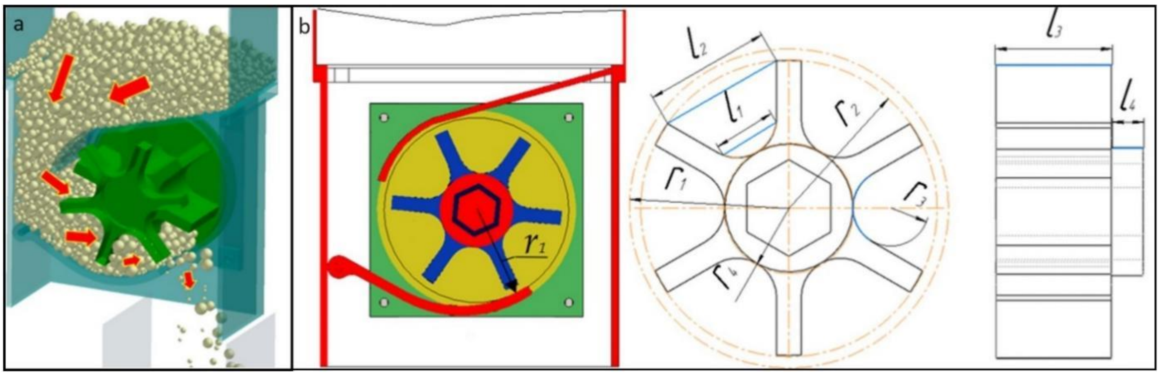

Figure 2 Designed six-grooved metering device: a. The flow of granular fertilizer b

The main parameters to calculate the working volume of the designed six-grooved roller are showed in Equation 1:

$$V_{wv} = V_r + V_{al}, \tag{1}$$

where, $\boldsymbol{V_{wv}}$ – the working volume of the six-grooved roller; $\boldsymbol{V_r}$ – the free space of the six-grooved roller; $\boldsymbol{V_{al}}$ – the active layer volume of the six-grooved roller.

The volume of the six-groover roller free space is determined as (Equation 2):

$$\boldsymbol{V_r = 12 * V_g + 2 * V_o}, \tag{2}$$

where, $\boldsymbol{V_g}$ – the volume of the single groove; $\boldsymbol{V_o}$ –the volume of the gap in the middle of roller.

The volume of the single groove is determined as (Figure 3) (Equation 3, 4):

$$\boldsymbol{V_g = (S_1 + S_2 + S_3)l_3}, \tag{3}$$

where, $\boldsymbol{S_1}$ – upper segment area; $\boldsymbol{S_2}$ –bottom segment area; $\boldsymbol{S_3}$ –middle area in the shape of trapezoid.

$$\boldsymbol{V_g = (\frac{1}{2}r_2^2(\frac{\pi\alpha_1}{180^0} - sin\alpha_1) + \frac{1}{2}r_3^2\left(\frac{\pi\alpha_2}{180^0} - sin\alpha_2\right) + \frac{1}{2}(l_1 + l_2)h)l_3}, \tag{4}$$

where, $\boldsymbol{\alpha_1}$ –angle of the groove, 60 degrees; $\boldsymbol{\alpha_2}$ –angle of the chord, 120 degrees; $\boldsymbol{r_2}$ – radius of roller, 30 mm; $\boldsymbol{l_1}$ –the length of the bottom chord, 13.86 mm; $\boldsymbol{l_2}$ – the length of the upper chord, 30 mm; $\boldsymbol{l_3}$ –the length of the groove, mm; $\boldsymbol{h}$ - the distance between the upper and bottom chords, 13.98 mm.

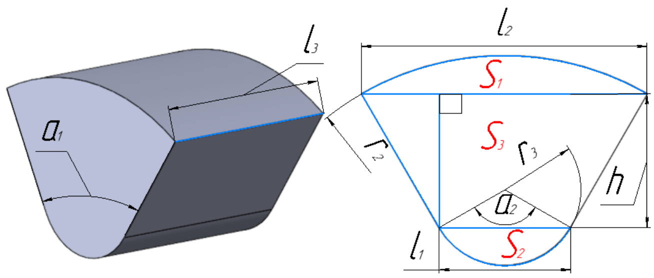

Figure 3 The parameters to calculate the volume of the single groove free space

The volume of the gap is determined as: (Equation 5)

$$V_o = \pi(r_2^2 - r_4^2)l_4, \tag{5}$$

where, r_4 —the distance till the groove bottom; l_4 —the length of the gap.

The volume of the active layer is determined as (Equation 6):

$$V_{al} = 2\pi(r_1^2 - r_2^2)(l_3+l_4), \tag{6}$$

where, r_1 —the distance to the bottom cap, 35 mm.

The overall working volume of the designed six-grooved metering device is determined as (Equation 7):

$$V_{wv} = 12\left(\left(\frac{1}{2}r_2^2\left(\frac{\pi\alpha_1}{180^0} - sin\alpha_1\right) + \frac{1}{2}r_3^2\left(\frac{\pi\alpha_2}{180^0} - sin\alpha_2\right) + \frac{1}{2}(l_1 + l_2)h\right)l_3\right) + 2\pi(r_2^2 - r_4^2)l_4 + 2\pi(r_1^2 - r_2^2)(l_3+l_4), \tag{7}$$

Granular fertilizer weight per one revolution of the six-grooved roller is determined as (Equation 8):

$$Q_{wv} = V_{wv}\,\rho, \tag{8}$$

where, ρ —granular fertilizer bulk density, 946.4 kg m^{-3}.

In this study l_4 is the main parameter to optimize, which influences granular fertilizer weight per one revolution ($l = 2l_4$), The length of the groove (l_3) depends on (l_4) ($l_3 + l_4 = 30$). When the length of the gap is more than optimal, granular fertilizer particles moves on the surface of the bottom cap and fall free. This condition can be prevented by decreasing the free flow of granular fertilizer gap length (l_4). However, a decrease in the gap length may reduce granular fertilizer weight per one revolution. The hypothesis of this study was to determine the optimum length of the designed six-grooved roller gap to increase granular fertilizer flow and improve the even distribution.

2.3. Discrete element method (DEM) model and interaction properties

The simulation was conducted using the DEM model (Siripath, Suranuntchai, and Sucharitpwatskul, 2024). Material properties for the Hertz-Mindlin no-slip numerical model were obtained from existing literature. However, the density of granular fertilizer was determined through experimental data. The shear modulus and Poisson's ratio values for granular fertilizer correlated with the experimental results. The particle size distribution played a significant role in the interaction properties between particles and materials, thereby affecting the overall experimental results. Boundary conditions were not defined, as the primary focus was on particle behavior within the domain. The Euler method was used for time integration in the Hertz-Mindlin no-slip model, with a Rayleigh time-step set at 30%. The simulation grid had an estimated cell radius of 3 mm. Table 2 shows the values for interparticle and particle-material interactions.

Table 1 Material mechanical properties

Materials	Shear Modulus (Pa)	Poisson's Ratio	Density (kg m^{-3})
Granular mineral fertilizer	1.24×10^7	0.25	1575
Acrylic material	1.15×10^9	0.35	1385
PLA material	2.42×10^8	0.36	1050

Table 2 Values for interparticle and particle-material interaction properties (Sugirbay *et al.,* 2021)

Friction coefficients	Coefficient
The fertilizer-fertilizer rolling fric.coeff.	0.05
The fertilizer-fertilizer static fric.coeff.	0.30
The fertilizer-fertilizer coeff. of restitution	0.58
The fertilizer-acrylic rolling fric.coeff.	0.08
The fertilizer -acrylic static fric.coeff.	0.266
The fertilizer-acrylic coeff. of restitution	0.531
The fertilizer -PLA rolling fric.coeff.	0.099
The fertilizer - PLA static fric.coeff.	0.294
The fertilizer - PLA coeff. of restitution	0.491

2.4. Designed six-grooved offset straight tooth metering device simulation with various parameters on DEM

The simulation process of the designed six-grooved metering device depending on time is shown in Figure 4. The metering device geometry was inserted into the DEM and the interaction properties were set based on previous parameters. The factory was generated to create granular fertilizer on top of the tank (black one). The box was generated to gather the discharged granular fertilizer under the metering device casing (red one). The top of the box was open.

Initially, the factory started generating 5000 granular fertilizer particles per second. After one second, the six-grooved roller was filled and started rotating counterclockwise on its axis at a speed of 10 rpm. At 2 seconds, some granular fertilizer particles were discharged and had fallen into the box. At 2.3 seconds, 10,000 granular fertilizer particles finished gathering into the tank. It was considered that collecting the discharged granular fertilizer particles during the 8 seconds starting from 2 seconds until 10 seconds would be satisfactory to compare the six-grooved roller with various parameters. The mass flow sensor (MFS), shown by cylindrical green grid on the last figure on DEM, measures the dynamic granular fertilizer mass and exports the data into an Excel file for analysis.

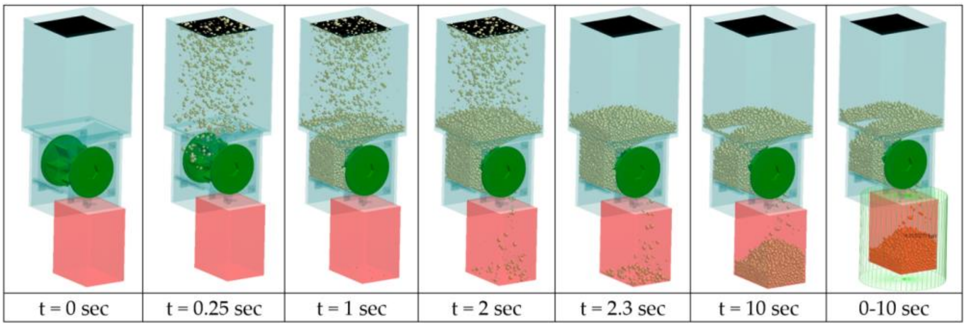

Figure 4 Simulation process of the designed six-grooved metering device on DEM

2.4.1. Measuring the discharged granular fertilizer mass and particle slippage on DEM per revolution

The triplicated simulation of the designed six-grooved roller with various gap lengths ($\boldsymbol{l}$) ranging from 3 mm to 15 mm, in increments of 2 mm, was conducted for seven parameters. The exported data was analyzed using an Excel file and the discharged granular fertilizer mass per revolution of roller was calculated. With roller rotation speed of 10 rpm, data from 2 to 8 seconds was measured to calculate the discharged granular fertilizer mass per revolution of roller. The theoretical calculation of the discharged granular mass ($\boldsymbol{Q_{wv}}$) was compared with the simulation results on DEM ($\boldsymbol{Q_{sim}}$). The comparison was required to determine the slippage between the discharged granular fertilizer particles based on the designed six-grooved roller with various gap lengths ($\boldsymbol{l}$). The SR is determined as follows (Equation 9):

$$\boldsymbol{SR} = \left(\frac{\boldsymbol{Q_{wv}}}{\boldsymbol{Q_{sim}}} - \mathbf{1}\right) * \mathbf{100}\% \quad (9)$$

2.4.2. Calculation of the CV on DEM

The data exported to the Excel file was analyzed to calculate the CV of the discharged granular mass. This was performed by conducting triplicated simulations of the designed six-grooved roller with various gap lengths (l) ranging from 3 mm to 15 mm, in increments of 2 mm, for seven parameters. Based on each simulation, 198 data points were collected during the 8 seconds from 2 to 10 seconds, with a time interval of 0.04 seconds between each data point. The final data point was subtracted from the previous data point to determine the discharged granular fertilizer mass over 0.04 seconds, leading to 197 data points. To calculate the CV, the standard deviation of these 197 data points was divided by the mean and multiplied by 100.

2.5. Laboratory equipment to verify simulation results

To verify the simulation results, laboratory equipment was constructed, as shown in Figure 5. The equipment included granular fertilizer tank (1), a metering device with offset straight-tooth roller (2), a DC electric motor with a gearbox (CHR-GM37-3429-ABHL) (3), an IRF520 driver (4), an ESP32 DEVKIT V1 microcontroller (5), a laptop (6), and a container (7). Granular fertilizer tank was filled with fertilizer and connected to the metering device with offset straight-teeth roller. The parameters of roller were expected to be validated by the simulation results. The metering device was driven by a DC electric motor powered by a 12V battery through the IRF520 driver.

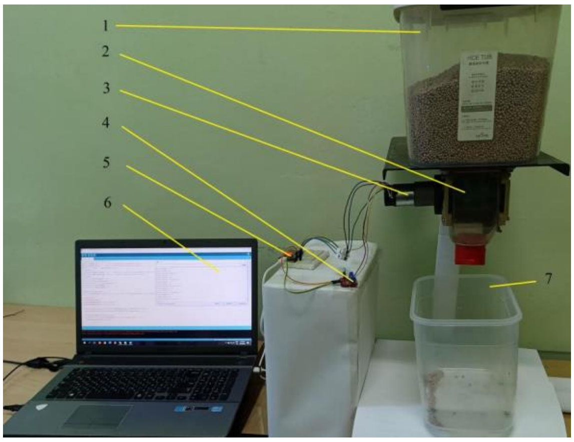

Figure 5 Granular fertilizer discharging equipment: 1. Granular fertilizer tank; 2. Metering device with offset straight tooth roller; 3. DC electric motor with gearbox; 4. Driver; 5. Microcontroller; 6. Laptop; 7. Container

The gearbox had a reduction ratio of 1:450, while the IRF520 driver was controlled by the ESP32 DEVKIT V1 microcontroller. The DC electric motor also included a rotary encoder for PID closed-loop speed control. The rotation speed of the metering device with offset straight-tooth roller was 10 rpm. Subsequently, the discharged granular fertilizer was collected in the container, and the mass was measured with a precision of 0.01 g. The laboratory experiment was conducted five times and the mean mass of the discharged granular fertilizer was determined.

3. Results and Discussion

3.1. The results of the theoretical analysis and simulation on DEM with the gap in the middle

In the first task, designed six-grooved roller with various gap lengths (l) is investigated. The results of the theoretical analysis and three replications of the simulation are shown in Figure 6. The theoretical discharged granular fertilizer mass increased significantly from 125.84 g to 175.29 g, as the designed six-grooved roller gap length rose from 3 mm to 15 mm. However, the simulated discharged granular fertilizer mass increased only slightly when the designed six-grooved roller gap length rose from 3 mm to 15 mm. The mean of three replications of the simulation on DEM is showed in Figure 7. The regression coefficient of the linear trend line of the mean of the three simulations on DEM was found to be 0.9926. This showed a linear increase in the discharged granular fertilizer mass simulated on DEM. The simulated discharged granular fertilizer mass mean increased slightly from 123.35 g to 134.30 g, as the designed six-grooved roller gap length rose from 3 mm to 15 mm. The SR increased from 2.02% to 30.52%, along with the increase in gap length. This shows that increasing the designed six-grooved roller gap length from 3 mm to 15 mm leads to more inefficient use of working due to particle slippage. Therefore, there are particle-particle and particle-material interactions. When roller rotates, the material moves the particles which further adjusts the adjacent particles. As the gap length of the designed six-grooved roller increases, the influence of the material on the particles decreases, causing a rise in particle slippage.

Due to particle slippage, increasing the designed six-grooved roller gap length from 3 mm to 15 mm caused a mass increase of only 10.95 g for the discharged granular fertilizer. The direction of discharged granular fertilizer simulated using DEM is shown in Figure 7. The velocity of the particles increases from the center of roller to bottom cap, changing color from gray to black accordingly (Figure 8a). A hypothesis regarding particle slippage is shown in Figure 8 b. Granular fertilizer particles inside the groove move towards the middle as the particles leave the bottom cup due to bulk angle of repose (Bu *et al.,* 2022), creating free space. After filling the free space, fewer granular fertilizer particles move from the tank to the designed six-grooved roller gap.

The increase in gap length significantly improves the even distribution of granular fertilizer, with the CV decreasing from 63.18% to 38.73% (Figure 9). The trend line of the CV is linearly dependent on the designed six-grooved roller gap length, with a regression coefficient of 0.9626 for the linear trend line of the mean CV across three DEM simulations. Moreover, the designed six-grooved roller gap length should not exceed 15 mm. This is to ensure free flow of granular fertilizer particles from the metering device when the six-grooved roller is not rotating and the seeder is moving in the transport position.

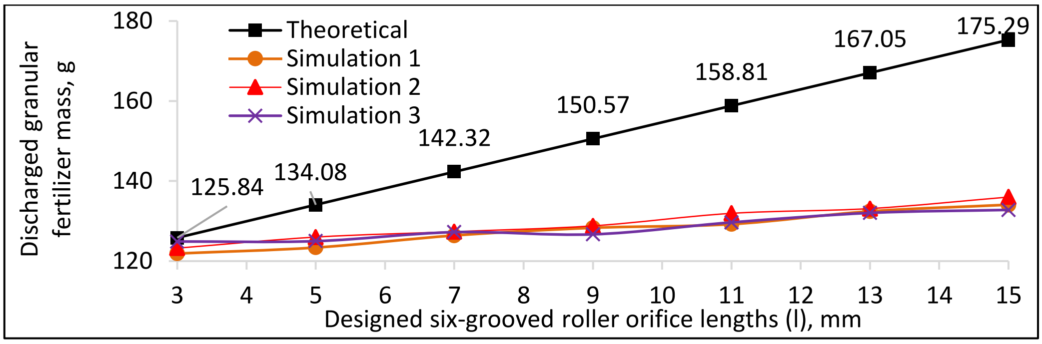

Figure 6 Comparison of theoretical and simulation results of three replications using DEM

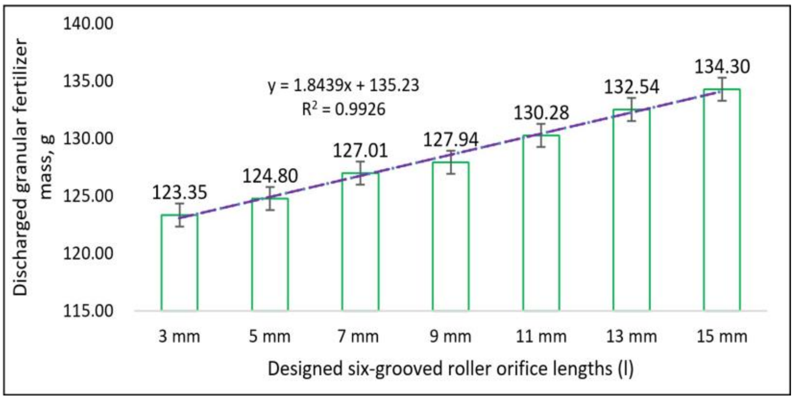

Figure 7 The mean mass of discharged granular fertilizer from three replications simulated using DEM

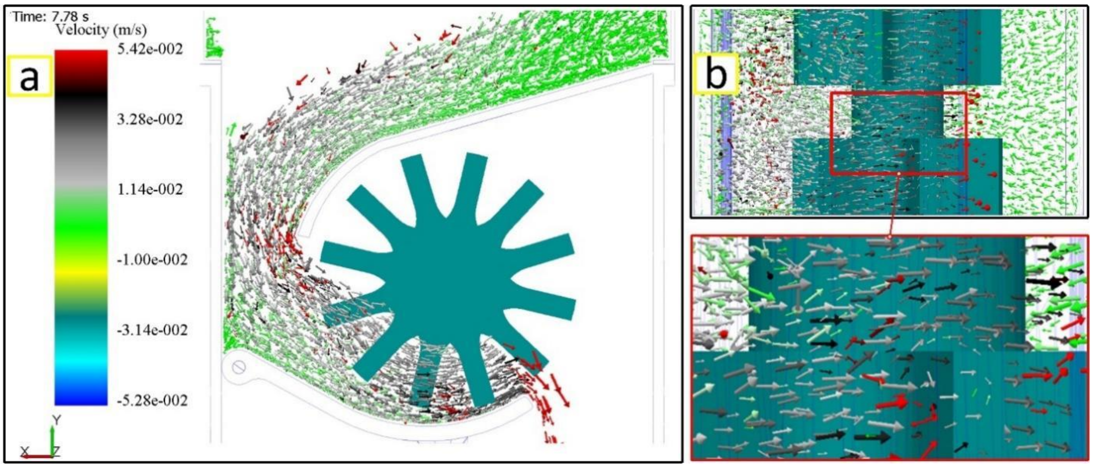

Figure 8 The direction of discharged granular fertilizer simulated using DEM: a. Left side view; b. Bottomview

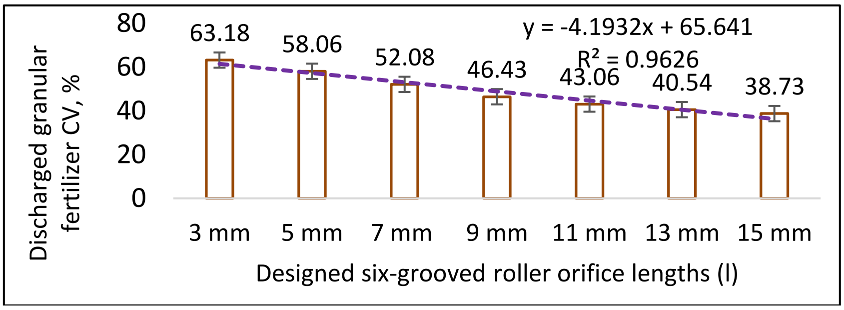

Figure 9 The mean CV of discharged granular fertilizer flow from multiple replications simulated using DEM

3.2. The influence of the additional gaps on the left and right sides

Additional gaps were added on the left and right sides of roller after determining gap influence in the second task. The comparison of the grooved roller with a gap in the middle, left, and right sides is shown in Figures 10a and 10b. In this case, roller length was divided into five parts to ensure symmetric section of left and right. Therefore, the length of each gap was 12 mm. The theoretical discharged granular fertilizer mass of the grooved roller with gaps in the middle, left, and right sides was calculated according to the equation shown in Figure 6, leading to 201.61 g. The simulation results using DEM showed that the discharged granular fertilizer mass was 148.35 grams and the SR was 35.9%, with CV of 30.94%.

a b

Figure 10 The position of roller gap: a. In the middle; b. In the middle, left, and right sides.

The advantage of offset straight-teeth roller is universal, allowing measurement of granular and cylindrical granulated organic fertilizer with bigger sizes. Organic fertilizer significantly increases the drought resistance index of barley and millet compared to mineral fertilizer in both current and warmed climate conditions. Verification using laboratory equipment with offset straight-tooth roller confirmed a discharge of 150 g of mineral granular fertilizer.

4. Conclusions

In conclusion, this study aimed to design and evaluate offset straight-teeth roller for precise granular mineral fertilizer application. The innovative roller design was tested in different configurations, namely a single gap in the middle with additional gaps on the left and right sides. The addition of side gaps significantly improved the uniformity and mass of the discharged fertilizer. The theoretical discharge mass was calculated to be 201.61 g, while the actual mass measured through DEM simulation was 148.35 g, producing a SR of 35.9%. The results showed that increasing the gap length led to a rise in particle slippage. This caused an improvement in the even distribution of fertilizer, as shown by a decrease in the CV from 63.18% to 38.73%. Verification using laboratory equipment with offset straight-tooth roller confirmed a discharge of 150 g of mineral granular fertilizer. The results showed the importance of optimizing gap parameters to balance discharge efficiency and uniformity. This suggested that the proposed grooved roller design could enhance the precision of fertilizer application, contributing to more sustainable and efficient agricultural practices.

Acknowledgments

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Conflict of Interest

The authors declare no conflicts of interest.

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