

STUDY OF GRANULAR FERTILISER DOSING UNIFORMITY USING IMPROVED ROLLER DESIGNS BASED ON DEM MODELLING

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Abstract. Uniform short-term mass-flow behaviour is a critical requirement for precision fertiliser application, yet different helical roller geometries may improve one performance criterion while worsening another. This study statistically analysed an archived ANSYS Rocky DEM dataset together with bench validation for 6-groove rollers at $\alpha = 30^\circ$. The dataset comprised 69 parametric blocks, each with 10 repetitions. The factors were the number of grooves $S = 5, 6, 7, 8$; groove inclination angle $\alpha = 30, 35, 40^\circ$; roller design helical, helical_S, helical_P; and fertiliser type AgroOrg and AgroNPK. Angular discharge non-uniformity was evaluated by an AVEDEV-based relative index CV_φ , while dosing repeatability was characterised by CV_Q and the derived accuracy index $A = 100 - CV_Q$. Quadratic response-surface regression was used to describe the main trends. The lowest CV_φ value was obtained for configuration 6S_30 helical AgroNPK ($CV_\varphi = 7.33\%$), whereas the highest accuracy index was recorded for 8S_35 helical_P AgroOrg ($A = 99.45\%$). On average, the base design helical provided the smallest flow pulsation ($CV_\varphi = 10.92\%$), helical_S occupied an intermediate position (11.65%), and helical_P increased non-uniformity to 13.15% while slightly improving repeatability of the total dose. Bench validation confirmed the main design ranking for the tested subset, with a mean absolute relative deviation of 3.40% for discharged mass and a mean absolute difference of 0.60 percentage points for accuracy index A. Overall, helical rollers with 6-7 grooves are preferable when angular uniformity is the primary criterion, whereas material-specific compromises may differ.

Keywords: granular fertilisers, dosing roller, DEM modelling, discharge uniformity, accuracy, response surface.

Introduction

Precise application of mineral fertilisers is one of the key conditions for increasing yield, improving nutrient use efficiency, and reducing environmental losses. Therefore, modern precision farming systems are aimed not only at maintaining the prescribed average dose, but also at stabilising the instantaneous mass flow through the dosing unit [1-5].

For roller-type dosing devices, the geometry of the working element plays a crucial role. Studies of pin, fluted, screw and helical rollers show that the number of active cells, the groove inclination angle, the length of the working zone and the arrangement of the grooves noticeably affect flow pulsation and the coefficient of variation of discharge [6-12]. Even relatively small geometric changes can alter the cell filling conditions, the frequency of granule collisions and the cyclic character of discharge [10-15]. Recent spiral-discharge studies likewise confirm that geometric optimisation is configuration-specific and must be interpreted together with the material properties of the fertiliser [16].

The Discrete Element Method (DEM) has become the principal tool for analysing such processes because it allows particle motion, contact forces, cell filling and discharge regularity to be observed under conditions where direct experimental measurements are difficult [17-22]. At the same time, published studies show that the physical and mechanical properties of fertilisers, particle shape representation and calibrated contact parameters substantially affect the simulated flow of granular material inside the dosing unit [23-26].

Despite the considerable number of publications devoted to individual types of dosing devices, far fewer studies compare, within one consistent dataset, the number of grooves, their inclination angle, roller design and the fertiliser type simultaneously. Therefore, the objective of this study was to statistically analyse the complete set of ANSYS Rocky simulation results, assess discharge uniformity and dosing accuracy, construct response surfaces, derive regression equations, and formulate practical recommendations for roller selection, and verify representative DEM results by bench tests of 6S rollers at $\alpha = 30^\circ$ for both fertiliser types.

Materials and methods

The input data consisted of a grouped set of ANSYS Rocky simulation results for a dosing roller handling granular fertilisers. The complete dataset comprised 69 parametric blocks, corresponding to

690 individual simulations. Each block contained 10 repeated calculations performed at identical factor levels, as well as 8 partial discharge values for angular sectors of 45° over one roller revolution. A full $4 \times 3 \times 3 \times 2$ factorial plan would contain 72 configurations, but during the consistency check of the DEM simulation results and subsequent statistical analysis, three configurations were found to contain output inconsistencies and were therefore excluded from further analysis.

Four factors were analysed: number of grooves S (5, 6, 7, 8), groove inclination angle α (30, 35, 40°), roller design (helical – base design; helical_S – design with a shifted cell distribution; helical_P – design with a more uniform cell distribution) (Fig.1).

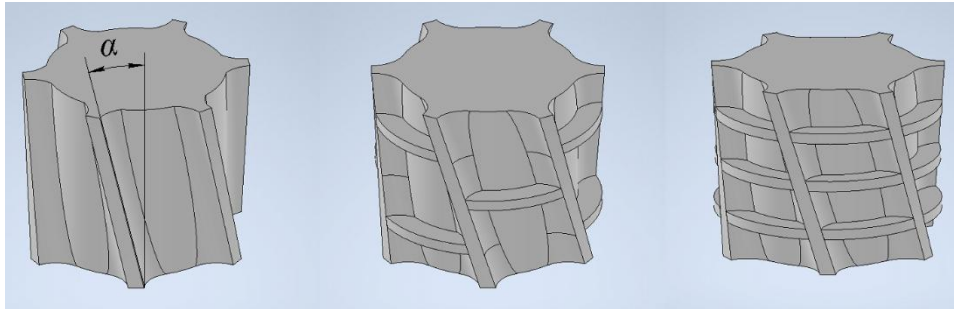


Fig. 1. **Studied dosing roller designs for granular fertilisers:** a – helical; b – helical_S; c – helical_P; α – groove inclination angle

Two granular fertilisers with markedly different physical and granulometric properties were selected for the study: AgroNPK (mineral fertiliser) and AgroOrg (organic fertiliser). AgroNPK is characterised by a higher bulk density ($\approx 1030 \text{ kg}\cdot\text{m}^{-3}$) and a larger mean particle diameter ($\approx 4.29 \text{ mm}$), and its granules have a comparatively regular near-spherical shape. In contrast, AgroOrg has a lower bulk density ($\approx 775 \text{ kg}\cdot\text{m}^{-3}$), a smaller mean particle size ($\approx 3.6 \text{ mm}$), and irregular elongated particles with a higher degree of variability. Particle shape was quantified by the sphericity coefficient φ . AgroNPK particles showed high sphericity ($\varphi \approx 0.89\text{--}0.90$), indicating a geometry close to spherical, whereas AgroOrg particles had much lower sphericity ($\varphi \approx 0.70$), reflecting elongated and anisotropic shapes [27; 28]. Accordingly, different particle representations were adopted in the DEM simulations. AgroNPK was modelled using spherical particles, whereas AgroOrg was represented by multi-sphere (clumped) particles approximating an ellipsoidal geometry.

Material heterogeneity was represented by separate material definitions for AgroNPK and AgroOrg, by their measured particle-size descriptors, and by different particle-shape models. In the DEM model, pellet mass followed from the equivalent particle size and the assigned material density; it was not prescribed independently. Moisture was not introduced as a separate state variable, and no liquid-bridge cohesion model was used; therefore, the present simulations describe dry or laboratory-conditioned fertiliser rather than wet material. The geometry of the dosing system was imported as STL models; the housing was defined as a fixed boundary, while the dosing roller was assigned rotational motion. Particle size was set using the equivalent diameter calculated as the geometric mean of three principal dimensions, and material density was assigned according to experimentally determined bulk density values. Contacts between particles, as well as between particles and machine surfaces, were described by the Hertz-Mindlin model with friction. The model parameters, including coefficients of restitution, static friction and rolling resistance, were selected based on previously published studies [23; 24]. Particles were generated under gravity to fill the dosing zone, and the discharge process was simulated by rotating the roller through a prescribed angular displacement.

To characterise the dosing process, the same indicators as those used in the original post-processing table were employed. The discharge process was evaluated using two main criteria: angular discharge uniformity and dosing accuracy. For each simulation or experiment, the discharged mass was recorded for eight angular sectors (45° each). The total discharged mass for the i -th repetition was calculated as

$$Q_i = \sum_{j=1}^8 q_{ij},$$

where q_{ij} – mass discharged into the j -th sector.

The mean mass per sector for each repetition was determined as $\bar{q}_i = Q_i/8$. The angular non-uniformity coefficient for each repetition was calculated using the average absolute deviation (AVEDEV):

$$CV_{\varphi,i} = \frac{100 \cdot AVEDEV(q_{i1}, \dots, q_{i8})}{\bar{q}_i}, \quad (1)$$

which characterises the non-uniformity of fertiliser distribution over one revolution.

The overall angular non-uniformity was obtained by averaging over all repetitions:

$$CV_{\varphi} = \frac{1}{10} \sum_{i=10}^{10} CV_{\varphi,i} \quad (2)$$

To evaluate dosing consistency between repetitions, an AVEDEV-based relative variation index of the total discharged mass was calculated:

$$CV_Q = \frac{100 \cdot AVEDEV(Q_1, \dots, Q_8)}{\bar{Q}}, \quad (3)$$

Where \bar{Q} – mean total discharged mass.

Finally, the dosing accuracy index was defined as:

$$A = 100 - CV_Q, \quad (4)$$

where A – accuracy index, higher values of which indicate better repeatability of the dosing process.

In strict statistical terms, CV_{φ} and CV_Q are AVEDEV-based relative dispersion indices, not classical coefficients of variation. Response surfaces were constructed using multiple linear regression models with quadratic and interaction terms for the continuous factors. The centred variables were defined as $x_S = S - 6.5$ and $x_A = \alpha - 35$. The indicator variables were assigned as $I_S = 1$ for helical_S roller design, $I_P = 1$ for helical_P, and $I_{NPK} = 1$ for fertiliser AgroNPK; the baseline level was the combination helical + AgroOrg. Because the design matrix was nearly complete (69 of 72 possible combinations), the surfaces were interpreted as trend estimates within the observed parameter region rather than as exact predictions for the missing combinations.

Bench validation was carried out on the test bench shown in Fig. 2 for all three 6-groove roller designs at $\alpha = 30^\circ$ and for both fertiliser types, using the same eight-sector post-processing scheme as in the DEM study.

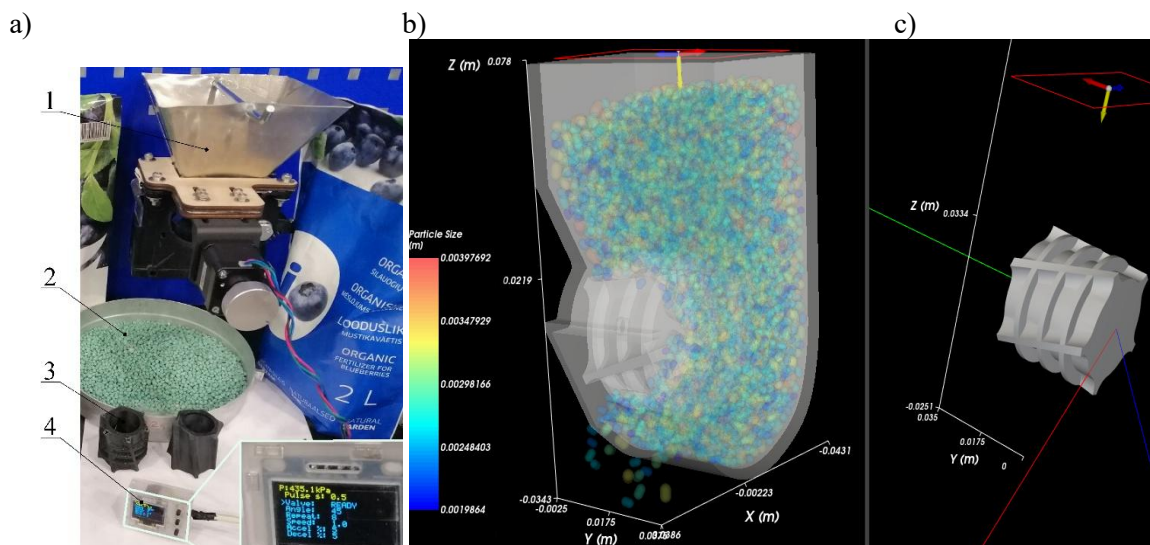


Fig. 2. General view of dosing unit test bench (a) and DEM model of dosing process (b) with current operating position of the roller (c): 1 – test bench; 2 – fertilizer; 3 – rollers; 4 – control unit

Results and discussion

Processing of 69 parametric blocks showed that the mean total discharged mass per block ranged from 15.61 to 31.56 g, the angular non-uniformity coefficient $CV\phi$ ranged from 7.33 to 16.03%, and the accuracy index A ranged from 92.96 to 99.45%. Thus, the investigated factors had a much stronger effect on within-revolution discharge uniformity than on repeatability of the total dose. The best uniformity was obtained for configuration 6S_30 helical AgroNPK ($CV\phi = 7.33\%$, $A = 98.08\%$), whereas highest accuracy was recorded for 8S_35 helical_P AgroOrg ($A = 99.45\%$, $CV\phi = 14.82\%$). Accordingly, the modified geometries cannot be regarded as universally improved across both criteria.

Mean values by roller design and fertiliser type are presented in Table 1. The base helical design provided the lowest angular non-uniformity both overall ($CV\phi = 10.92\%$) and in combination with AgroNPK (9.36%). The modified helical_S design occupied an intermediate position, whereas helical_P showed the highest flow pulsation, especially for AgroOrg. At the same time, both modified designs provided slightly better repeatability of the total discharged mass than helical, indicating a trade-off between local uniformity and total-dose accuracy.

Table 1

Mean indicators by roller design and fertiliser type

Roller design	Fertiliser	n	\bar{Q} , g	$CV\phi$, %	A , %
helical	AgroOrg	12	19.13	12.35	98.02
helical	AgroNPK	11	27.38	9.36	97.89
helical S	AgroOrg	12	18.30	13.22	98.36
helical S	AgroNPK	11	25.10	9.94	98.09
helical P	AgroOrg	12	16.95	14.07	98.58
helical P	AgroNPK	11	20.14	12.15	97.93

A pairwise comparison of variants with identical S , α and fertiliser type showed that the helical_S design increased $CV\phi$ on average by 0.68 percentage points and simultaneously increased A by 0.27 percentage points relative to the base helical design. For helical_P, the corresponding changes were 2.16 and 0.31 percentage points. Therefore, redistribution of the cells can slightly improve repeatability of the total dose, but this is usually accompanied by poorer angular discharge uniformity. This pattern of geometric influence agrees with results reported for fluted and helical metering devices in other studies [7-15].

This application-specific behaviour agrees with recent literature. Xu et al. [5] noted that precision of fertiliser dosing devices depends on joint optimisation of geometry, operating conditions and material properties, while Dun et al. [16] showed that spiral-type fertiliser dischargers achieve improved uniformity only within specific parameter windows. Recent calibration studies likewise emphasise the sensitivity of DEM-based optimisation to particle representation and contact-parameter identification [23-26].

With respect to the number of grooves, the best average compromise was observed in the range of 6-7 grooves; the lowest mean $CV\phi$ was obtained at $S = 7$ (10.83%), and the highest mean A was also observed at $S = 7$ (98.39%). The effect of groove inclination angle on the average indicators was generally weaker, which is additionally confirmed by the shape of the response surfaces.

The response surfaces for dosing accuracy (Fig. 3) are comparatively flat. The obtained model is described by the equation

$$A = 98.3828 + 0.2778I_S + 0.3205I_P - 0.3316 I_{NPK} + 0.1705x_S - 0.0170x_A - 0.1365x_S^2 - 0.0056x_A^2 + 0.0088x_Sx_A, \text{ adjusted } R^2 = 0.013. \quad (5)$$

The low adjusted R^2 value shows that this surface should be interpreted only as a weak trend description, not as a precise optimisation model for accuracy index A . Within the analysed region, it merely suggests a slight tendency for A to increase with the number of grooves and to decrease for AgroNPK compared with AgroOrg. The positive coefficients for I_S and I_P indicate only small average gains in total-dose repeatability for helical_S and helical_P, and this effect should not be over-interpreted.

The response surfaces of angular non-uniformity (Fig. 4) are much more pronounced than the accuracy surfaces. The following regression equation was obtained for $CV\phi$:

$$CV\phi = 11.4843 + 0.7550I_S + 2.2207I_P - 2.7654I_{NPK} - 0.3204x_S + 0.0090x_A + 0.5335x_S^2 + 0.0041x_A^2 + 0.0660x_Sx_A, \text{ adjusted } R^2 = 0.545. \quad (6)$$

The helical_P design has the greatest positive effect on increasing $CV\phi$, whereas AgroNPK systematically reduces angular non-uniformity. The positive coefficient for x_S^2 confirms that extreme values of the number of grooves are less favourable than the intermediate range of 6-7 grooves. In practical terms, this means that the choice of roller geometry should primarily aim to smooth the instantaneous flow, whereas the indicator A should be used as an additional criterion after selecting variants based on uniformity.

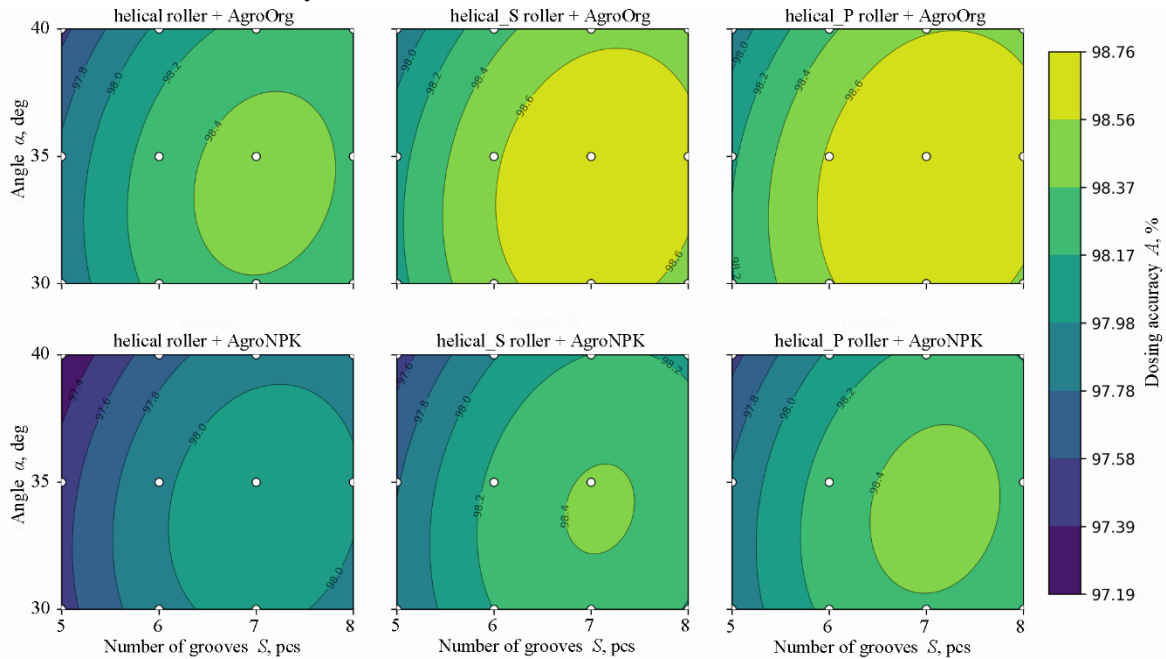


Fig. 3. Response surfaces of dosing accuracy index A : colour field – regression estimate; white dots – simulated configurations

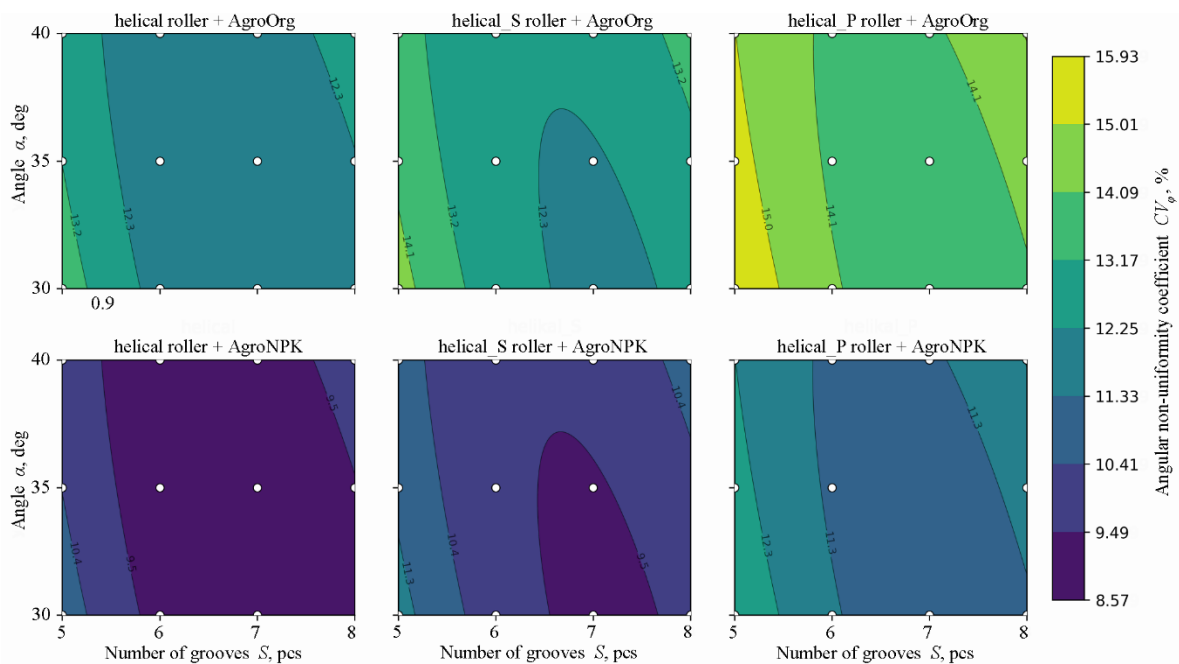


Fig. 4. Response surfaces of the angular non-uniformity coefficient $CV\phi$: colour field – regression estimate; white dots – simulated configurations

From a practical point of view, two levels of recommendation should be distinguished. As an overall trend across both fertilisers, the baseline helical design and 6-7 grooves are preferable when minimising within-revolution pulsation is the main objective. For AgroNPK, 6S_30 helical, 7S_30 helical and 7S_40 helical are the most promising among the analysed variants. For AgroOrg, the best local compromise between $CV\phi$ and A within the tested set was 5S_35 helical_P. Therefore, the modified designs should be treated as material-specific options rather than universally improved solutions.

For subsequent bench validation of the DEM model, it is advisable to compare simulation and experimental results for 6S rollers at $\alpha = 30$ deg for both fertiliser types (Table 2).

Table 2

Comparison of simulation and experimental results for 6S rollers at $\alpha = 30^\circ$

Roller design	Fertiliser	Q_{sim} , g	Q_{exp} , g	ΔQ , %	$CV\phi_{sim}$, %	$CV\phi_{exp}$, %	A_{sim} , %	A_{exp} , %	ΔA , p.p.
helical	AgroOrg	21.47	20.52	-4.45	9.96	12.31	98.66	99.14	+ 0.47
helical	AgroNPK	29.79	29.41	-1.25	7.33	9.83	98.08	99.08	+ 1.00
helical S	AgroOrg	18.58	18.05	-2.83	14.16	14.33	98.56	98.10	-0.46
helical S	AgroNPK	26.04	24.58	-5.59	10.03	13.02	98.55	98.03	-0.53
helical P	AgroOrg	16.66	16.73	+ 0.43	15.36	13.35	98.10	98.64	+ 0.53
helical P	AgroNPK	21.15	19.91	-5.85	11.70	16.02	97.23	97.81	+ 0.59

The experimental data confirmed the main simulated trend for the tested subset: the baseline helical design provided the best angular uniformity for both fertilisers, while the modified designs showed higher within-revolution flow pulsation. Agreement for the mean discharged mass was good, with a mean absolute relative deviation of 3.40%, and the accuracy index A differed by only 0.60 percentage points on average. However, the DEM model generally underestimated $CV\phi$, with a mean absolute difference of 2.39 percentage points. A local ranking mismatch between helical_S and helical_P was observed only for AgroOrg fertiliser. Thus, the present validation supports the model for the 6-groove, $\alpha = 30$ deg subset, while broader validation across the remaining design space should be considered in future work.

Conclusions

1. The analysed dataset of ANSYS/DEM simulation results comprised 69 parametric blocks and showed that roller design primarily affects within-revolution discharge uniformity: $CV\phi$ varied from 7.33 to 16.03%, whereas index A ranged from 92.96 to 99.45%.
2. The best angular uniformity was achieved for 6S_30 helical AgroNPK ($CV\phi = 7.33\%$), whereas the highest total-dose repeatability was recorded for 8S_35 helical_P AgroOrg ($A = 99.45\%$).
3. On average, the base helical design provided the lowest flow pulsation ($CV\phi = 10.92\%$), helical_S occupied an intermediate position (11.65%), and helical_P increased angular non-uniformity to 13.15%, although it slightly improved repeatability of the total dose.
4. AgroNPK exhibited more even angular discharge than AgroOrg (10.48 versus 13.21%). For AgroOrg, 5S_35 helical_P provided the best local compromise between angular uniformity and total-dose repeatability.
5. For practical application, priority should be given to minimising $CV\phi$; therefore, helical rollers and the range of 6–7 grooves are preferable. Experimental validation of the 6-groove rollers at $\alpha = 30^\circ$ demonstrated that the DEM model reliably reproduces the mean discharged mass and overall dosing accuracy. Although angular non-uniformity is predicted somewhat more optimistically than observed in the bench tests; future work should extend validation to other S - α combinations and include moisture, wider particle-size distributions and vibration effects.

Author contributions

Conceptualization, E.P., Y.I. and J.O.; methodology, E.P., Y.I., O.L. and J.O.; formal analysis, E.P., Y.I. and O.L.; investigation, J.O., O.L. and Y.I.; writing – original draft preparation, E.P.; writing–review and editing, E.P., O.L. and Y.I.; project administration, J.O. All authors have read and agreed to the published version of the manuscript.

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