Development and evaluation of a novel seeding metering system for mechanic seeder toward precision agriculture

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Abstract.

Recent advances in precision and digital agriculture increasingly rely on computational modeling, sensor-based analysis, and data-driven machinery design to improve agricultural operations. Seed metering systems are among the most critical components of precision seeders because they regulate seed delivery accuracy, directly affecting crop establishment, plant uniformity, and input-use efficiency. In conventional agricultural systems, uniform seed spacing is essential for minimizing intra-row competition and ensuring homogeneous crop emergence. In precision agriculture, however, adaptive seeding strategies require accurate and repeatable seed placement under varying operational conditions. Achieving this level of control remains challenging due to the complex mechanical behavior of granular biological materials and the variability in seed size, shape, surface texture, and mass.

In this study, a mechanically driven, vertically oriented seed-disc metering system was developed and evaluated to improve seeding accuracy for precision agriculture applications. The metering assembly was designed using SolidWorks 2025, and four alternative seed-disc geometries with different cell shapes were developed according to seed morphology. Pea and cumin seeds were selected as representative materials because of their substantially different physical and flow characteristics, enabling rigorous evaluation of metering robustness across contrasting seed types.

Numerical simulations were conducted using Altair EDEM 2025. Experimentally determined seed properties, including density, restitution coefficient, and friction parameters, were incorporated into the model to reproduce realistic particle interactions and contact behavior. Each seed-disc geometry was evaluated at rotational speeds of 20, 30, and 40 rpm to investigate the influence of operating conditions on seed delivery performance. Simulation outputs included seed filling

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behavior, particle retention inside the cells, and seed fall rate.

Experimental validation was performed using a custom-built laboratory test bench equipped with high-speed video recording for detailed temporal analysis of seed discharge behavior. Seed fall rate and seed interval were used as the primary performance indicators. The results demonstrated that seed-cell geometry significantly affected seed acquisition stability, particle orientation, and release consistency. Optimization of the disc-cell design improved metering accuracy by 10–30% under different rotational speeds. For pea seeds, the best experimental vertical drop velocities ranged from 0.39 ± 0.02 to 0.41 ± 0.04 m s^{-1}*, whereas simulated values ranged from 0.44 ± 0.02 to 0.49 ± 0.02 m s*$^{-1}$ *when spoon-type cells were used at 20–40 rpm. Furthermore, the optimized metering discs yielded the lowest seed spacing variability at 20 rpm, with coefficients of variation (CV) of 15% for pea and 18% for cumin seeds. These results confirm the effectiveness of combining EDEM-based modeling with experimental validation across varying operating conditions and seed types. The findings demonstrate the effectiveness of combining DEM-based numerical modeling with experimental validation and providing a scientifically grounded framework for the development of intelligent precision seeding systems.*

Keywords.
Seed metering model, simulation, discrete element method, seeding disk.

Introduction

Precision agriculture has evolved rapidly through the integration of digital technologies, sensor systems, computational modeling, and intelligent machinery design. The primary objective of these developments is to optimize crop production by improving input-use efficiency, operational performance, and environmental sustainability (Chen et al., 2025). Among the various field operations, seeding is one of the most critical because crop establishment largely depends on the accurate placement of seeds at the intended spatial locations. Consequently, the performance of seed metering systems directly influences seed spacing uniformity, plant population, crop emergence, and ultimately yield formation (Kachman & Smith, 1995).

Seed metering devices constitute the core component of precision seeders because they regulate the acquisition, transport, and release of individual seeds. An ideal metering system should deliver seeds at uniform intervals while minimizing missed and multiple seed events (Kachman & Smith, 1995). However, achieving consistent performance remains challenging because seeds are biological materials characterized by significant variability in size, shape, density, moisture content, surface roughness, and friction. These variations affect seed flow dynamics within the metering chamber and influence the filling and discharge processes of seed cells (Yan et al., 2022). As a result, seed metering accuracy frequently decreases when operating conditions or seed characteristics change. Previous studies have shown that mechanical metering systems are particularly susceptible to missed seed events, multiple seed release, and seed damage under high-speed operating conditions, although they remain attractive because of their simple structure, low manufacturing cost, and ease of maintenance (Jun et al., 2022).

To improve seeding performance, considerable research has focused on the optimization of seed-metering mechanisms, including seed-disc geometry, seed-cell dimensions, filling zones, cleaning devices, and operating parameters (Dun et al., 2022). Recent developments in precision seeding have demonstrated that even small modifications in seed-cell design can significantly affect seed capture efficiency, filling stability, and release consistency (Chen et al., 2024). Furthermore, increasing speed of seeding often introduces additional challenges because centrifugal forces and particle interactions alter seed trajectories and filling behavior, leading to greater spacing variability and reduced metering quality (Jun et al., 2022; Zhang et al., 2025).

Experimental evaluation alone often provides limited information about the internal behavior of seeds within metering devices. Many critical phenomena, such as seed orientation, collision dynamics, contact forces, and particle trajectories, are difficult or impossible to observe directly. Therefore, numerical simulation methods have become increasingly important in agricultural machinery research. Among these approaches, the Discrete Element Method (DEM) has emerged as one of the most powerful tools for analyzing bulk material flow processes (Coetzee, 2017). The method has been successfully applied to investigate seed population movement, optimize metering structures, evaluate filling performance, and predict seed distribution characteristics under varying operational conditions (Li et al., 2021; Baghooee et al., 2023).

Several recent studies have combined DEM simulations with laboratory experiments to improve the design of precision seed-metering devices. For example, DEM-based analyses have been used to optimize hole geometry in soybean metering wheels (Dun et al., 2022), investigate seed-filling mechanisms in maize seeders (Chen et al., 2025), evaluate slotted roller metering systems (Baghooee et al., 2023), and improve high-speed precision planting performance (Jun et al., 2022; Zhang et al., 2025). These studies demonstrated that DEM can reliably predict seed motion and provide valuable information for parameter optimization when properly calibrated using experimentally determined material properties (Coetzee, 2017). Nevertheless, most previous investigations have focused on a single crop species or a specific metering configuration.

Although previous studies have demonstrated the value of DEM for seed-metering analysis, there remains limited information regarding the combined influence of seed-cell geometry, seed morphology, and rotational speed in vertically oriented mechanical seed-disc systems. Furthermore, experimental validation of DEM predictions remains essential for confirming simulation reliability and identifying practical design improvements.

Therefore, the aim of this study was to develop and experimentally validate a mechanically driven vertical seed-disc metering system intended for precision agriculture applications through the combined use of discrete element modelling (DEM) and laboratory-based performance analysis. The originality of the study lies in the integration of numerical simulation, high-speed image analysis, and comparative evaluation of multiple seed-disc geometries. Unlike conventional studies that primarily focus on a single disc configuration or uniform seed type, the present research investigates the dynamic interaction between seed geometry and disc-cell design under varying operational speed.

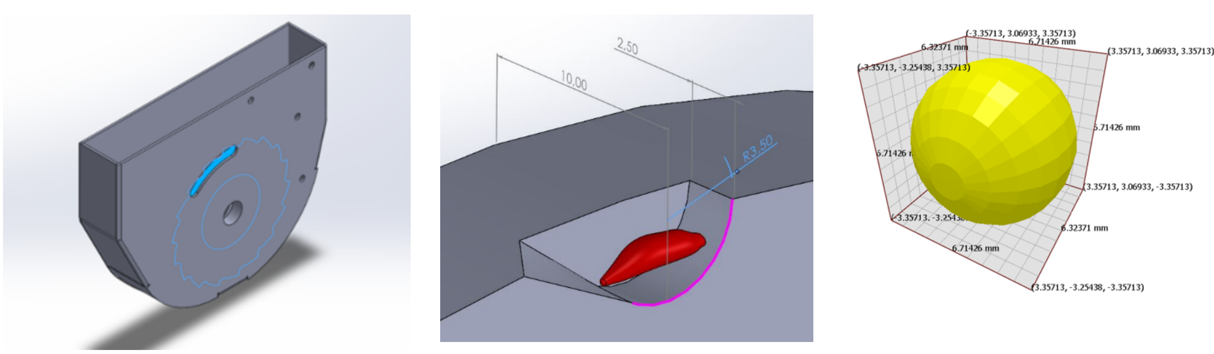
Materials and methods

Seed Metering Unit Design and DEM-Based Numerical Simulation

A seed metering mechanism was designed using SolidWorks 2025 CAD software. The metering system consisted of a hopper, rotating seed disc and seed outlet section (Fig 1a). Several alternative seed-disc geometries were developed to investigate their seed singulation performance. The disc diameter was selected as 130 mm. The first design incorporated hemispherical seed cells distributed uniformly along the disc circumference. Cell dimensions were initially generated according to the average volume of a single pea and cumin seeds. To improve seed pickup performance and facilitate seed entry into the cavity, the cell dimensions were enlarged by approximately 30% (Fig 1b). A tapered outlet profile was additionally integrated into the cell geometry to support smooth seed release at the discharge zone. The second disc configuration employed spoon-shaped cavities positioned circumferentially around the disc surface. The spoon geometry was created according to the same dimensional principles used for the hemispherical-cell design, while modifying the internal cavity shape to improve seed retention during rotation.

All mechanical components, including the hopper and metering discs, were exported in Initial Graphics Specification (.igs) format for subsequent numerical simulation studies. The metering assembly was imported into Altair EDEM 2025 software to simulate particle flow behavior inside the metering mechanism.

Pea and cumin seeds were selected as test material due to their different geometry for precision metering studies. Physical seed dimensions were measured experimentally to define particle properties within the simulation environment. Seed particles were represented using a multi-sphere modelling approach to approximate the irregular external geometry of real pea and cumin seeds (Fig 1c). In the multi-sphere representation, several overlapping spheres were combined to generate a particle shape like the measured seed geometry. Increasing the number of component spheres improved the geometric accuracy of the model but also increased computational demand (Jotautiene et al., 2024).



a) **b)** **c)**

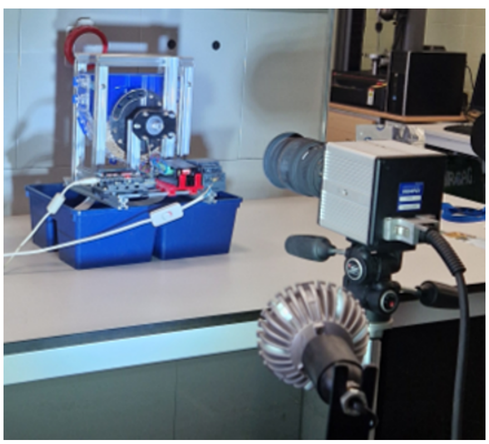
Fig 1. The models: a) metering model; b) cumin seed in the cell; c) pea seed in EDEM software.

The simulation environment included the seed hopper, rotating disc, and discharge section. During the simulations, seed particles interacted with the disc cavities under gravitational and contact-force effects. The Hertz–Mindlin (no-slip) contact model was used to evaluate both seed-to-seed and seed-to-disc interactions. This model is based on Poisson's ratio and is commonly applied for particle contact analysis in DEM simulations. The numerical model enabled observation of seed filling behavior, particle retention inside the cells, and seed fall rate.

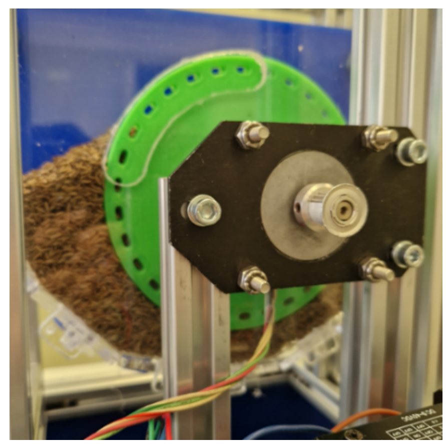
Laboratory Test Bench and Experimental Procedure

Experimental validation tests were conducted using a specially developed laboratory test bench (Fig 2a). The system consisted of a seed metering unit (Fig 2b), electric drive system, rotational speed controller, structural frame, and seed collection section. The metering disc was manufactured using a 3D printer with PLA material. Disc rotation was driven by an HDR-60-24 electric motor controlled through a Microstep Drive operating within a voltage range of 9–40 VDC. The test bench enabled stable adjustment of disc rotational speed during experiments. Pea and cumin seeds were used in the laboratory tests.

Seed discharge behavior was analyzed using a high-speed imaging system. A Photron FASTCAM-1024PCI high-speed camera and Photron Camera Software were used to record seed movement during discharge from the metering disc. The imaging system consisted of a camera, camera controller, personal computer, and external lighting units. Video recordings were captured at a frame rate of 1000 fps to ensure accurate visualization of rapid seed motion. Additional lighting sources were positioned around the experimental area to improve image clarity. Recorded videos were converted into sequential image frames for subsequent analysis of seed spacing behavior and seed falling characteristics.



a)



b)

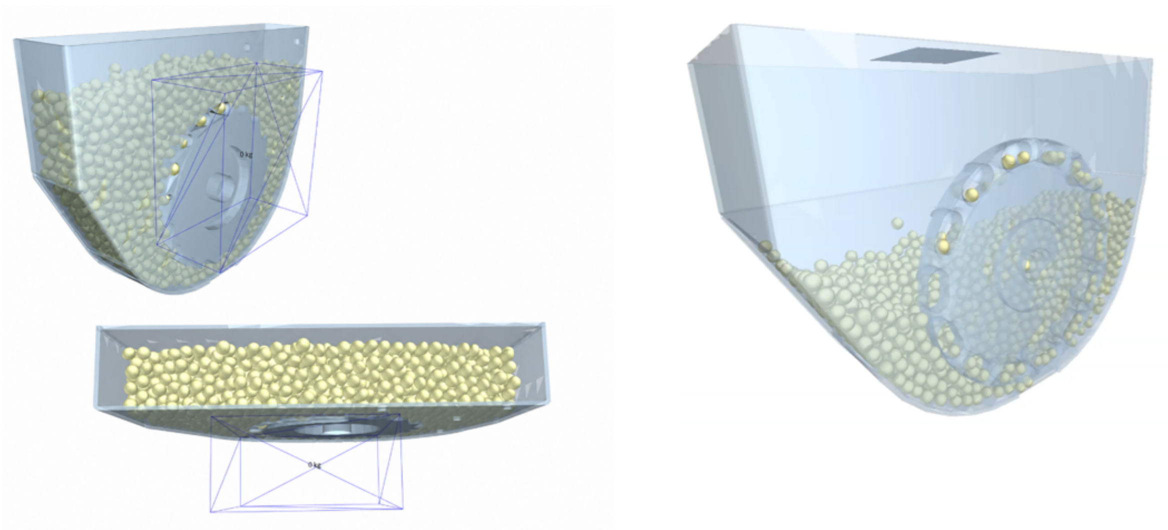
Fig 2. Experimental set up: a) general view of devices; b) seed metering unit with cumin seeds

The metering performance was evaluated under different disc rotational speeds ranging from 20 to 40 rpm with increments of 10 rpm. For each operating condition, three complete disc revolutions were analyzed. All experiments were repeated three times to improve measurement reliability and repeatability. The experimental observations focused on seed pickup behavior and seed fall rate. The coefficient of variation (CV) was determined according to the methodology described by Karayel et al. (2006). Data obtained from the laboratory tests were compared with the DEM simulation outputs to evaluate the capability of the numerical model to represent the physical seed metering process.

Results and Discussion

The measurement sensor added to cover the entire dropout hole for seeds (Fig 3a). Simulation and experimental tests conducted at disc rotational speeds of 20, 30, and 40 rpm demonstrated that seed-metering discs with spoon-shaped holes achieved seed separation efficiencies exceeding 90% (Fig 3b). in mechanical seed metering systems, whereas discs with loop-shaped holes reached efficiencies slightly above 80% (Fig 3a). Missed seed rates were approximately 15%, occurring predominantly in systems equipped with loop-hole discs.

Among the tested seed types, pea seeds exhibited the highest pickup performance, with non-pickup losses remaining below 5%. Cumin seed pickup performance was also improved when using the spoon-hole disc geometry. In contrast, the lowest metering performance was observed for cumin seeds when the disc with slot-shaped holes was used. Therefore, to further enhance seed pickup efficiency under different disc rotational speeds, additional optimization of disc geometry and operating parameters is required.



a) b)

Fig 3. Simulation trials with pea seeds: a) metering system when disk with slots; b) metering system with disk with spoons.

The results presented in Fig. 4 show the comparison between the experimentally determined fall vertical velocity and the simulated vertical velocity of pea seeds discharged from the metering hole at different disc rotational speeds (20, 30, and 40 rpm). Both the experimental and simulation results indicate that the pea seed fall velocity increased with increasing disc rotational speed. The experimentally measured vertical velocity increased from approximately 0.39 m s^{-1} at 20 rpm to 0.45 m s^{-1} at 40 rpm. Similarly, the simulation results increased from about 0.44 m s^{-1} to 0.48 m s^{-1} over the same rotational speed range. The simulated velocities were consistently slightly higher than the experimentally measured values at all rotational speeds. The largest difference between experimental and simulated results was observed at 20 rpm, while the differences became smaller at higher rotational speeds.

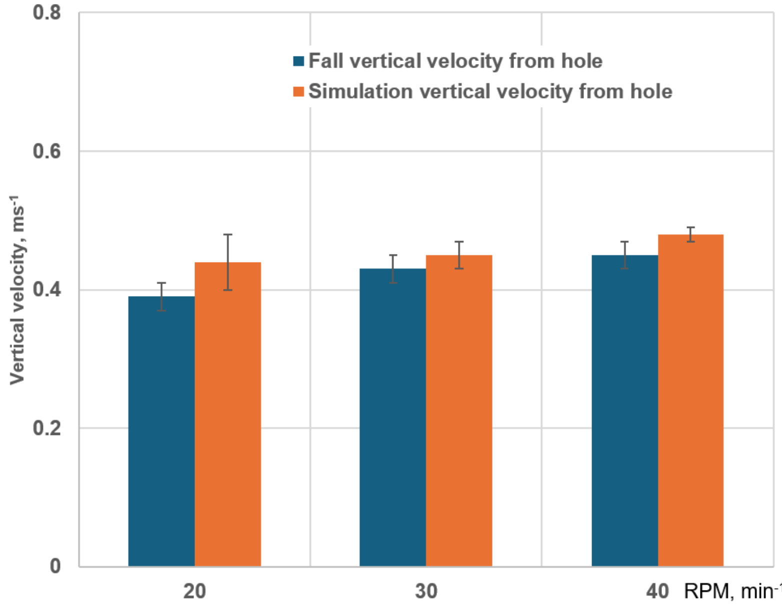


Fig 4. Results of pea seeds fall vertical velocity of seed disk with spoons.

Fig. 5 presents the comparison between experimentally measured and simulated pea seeds fall vertical velocities when disk with slots. The results demonstrate that experimentally measured seed fall velocity increased from approximately 0.41 m s^{-1} at 20 rpm to 0.57 m s^{-1} at 40 rpm. Similarly, the simulated velocities increased from about 0.49 m s^{-1} to 0.62 m s^{-1} as the rotational speed increased. At all tested rotational speeds, the simulated vertical velocities were slightly higher than the experimentally measured values.

The results of cumin seeds fall vertical velocity of seed disk with spoons (Fig. 6) indicate that seed fall vertical velocity increased with increasing rotational speed in both experimental and simulation data. The experimentally measured velocities increased from approximately 0.35 m s^{-1} at 20 rpm to 0.49 m s^{-1} at 40 rpm. Similarly, the simulated velocities increased from about 0.41 m s^{-1} to 0.51 m s^{-1} over the same rotational speed range. The simulation model predicted slightly higher vertical velocities than those obtained experimentally at all rotational speeds. The greatest difference between the measured and simulated values was observed at 30 rpm, while the smallest discrepancy occurred at 40 rpm, where the results showed very close agreement.

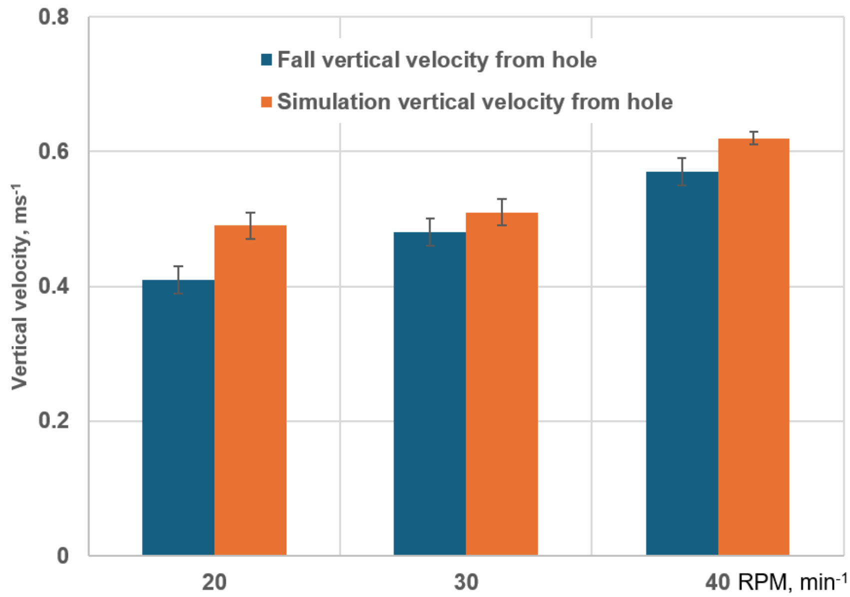


Fig 5. Results of pea seeds fall vertical velocity of seed disk with slots.

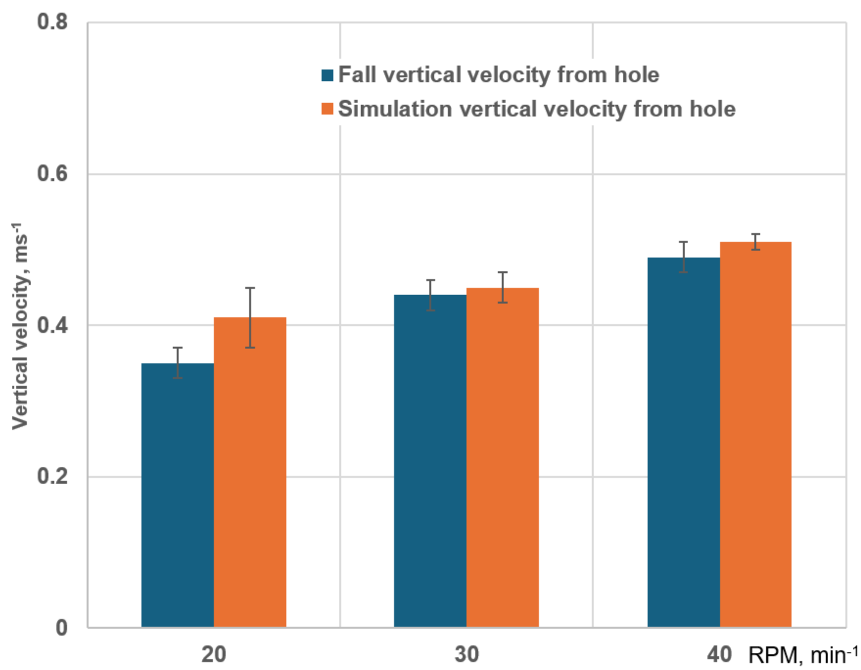


Fig 6. Results of cumin seeds fall vertical velocity of seed disk with spoons.

Fig. 7 presents the comparison between experimentally measured and simulated cumin seeds fall vertical velocities of seed disk with slots. The results show that the seed fall vertical velocity increased with increasing disc rotational speed in both the experimental measurements and the simulation model. The experimentally measured velocities increased from approximately 0.36 m s^{-1} at 20 rpm to 0.45 m s^{-1} at 40 rpm. Similarly, the simulated velocities increased from about 0.42 m s^{-1} to 0.50 m s^{-1} over the same rotational speed range.

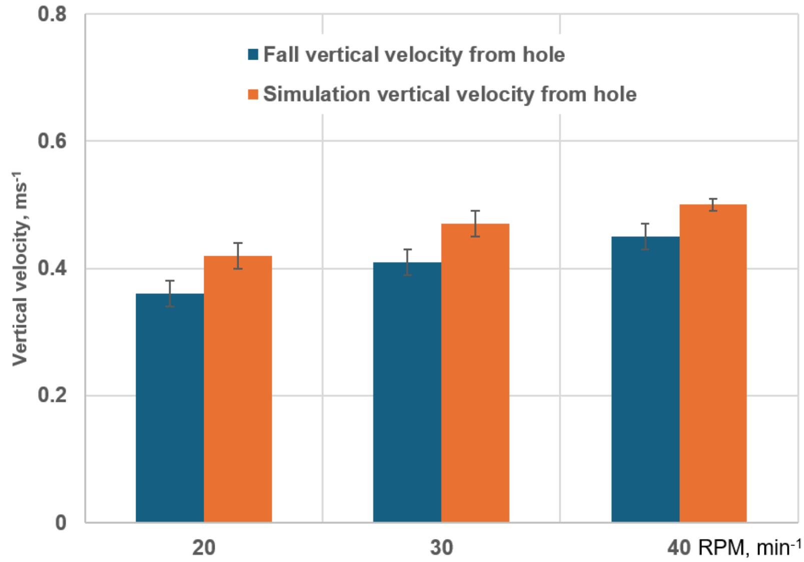


Fig 7. Results of cumin seeds fall vertical velocity of seed disk with slots.

The presented results are of particular importance for the development of universal precision seeder capable of sowing many plant species. The shape of the seeds has a significant impact on the filling probability, the discharge behavior in the seed cells, and the seed fall rate. This confirms the results obtained by other researchers (Yan et al., 2022). The results demonstrated that disc cell geometry exerted a significant influence on seed acquisition stability, particle orientation, and release consistency. Optimization of the cell design improved metering accuracy by 10–30% across different disc rotational speeds. The best experimental values of the vertical drop velocity of pea seeds ranged from 0.39 ± 0.02 to 0.41 ± 0.04 m s^{-1}, while in simulations they ranged from 0.44 ± 0.02 to 0.49 ± 0.02 m s^{-1} when a disk with spoon cells was used at a rotational speed of 20–40 rpm. Increasing disc rotational speed from 20 to 40 rpm increased the vertical fall velocity of both pea and cumin seeds in all tested disc configurations. This trend was consistently observed in both experimental measurements and DEM simulation results. For pea seeds, the highest seed fall velocities were obtained with slot-shaped hole discs, reaching approximately 0.57 m s^{-1} experimentally and 0.62 m s^{-1} in simulations at 40 rpm. For cumin seeds, maximum experimentally measured and simulated velocities reached approximately 0.49–0.51 m s^{-1} at the same rotational speed. A higher vertical velocity increases the energy of seeds and can be reason for bunching and moving seeds in the furrow. Moving and bouncing the seeds in the furrow is undesirable situation. The optimized metering discs yielded the lowest seed spacing variability at 20 rpm, with coefficients of variation (CV) of 15% for pea and 18% for cumin seeds. These results confirm the effectiveness of combining EDEM-based modeling with experimental validation across varying operating conditions and seed types.

Conclusions

Both DEM simulations and laboratory experiments confirmed that seed-metering performance was strongly influenced by the geometry of the seed-metering disc. Discs equipped with spoon-shaped holes achieved seed separation efficiencies exceeding 90%, while loop-shaped hole discs reached efficiencies slightly above 80%. Missed seed rates were approximately 15% and occurred mainly when loop-shaped discs were used.

Seed type significantly affected metering performance. Pea seeds exhibited the highest pickup efficiency, with non-pickup losses remaining below 5%. Spoon-shaped hole geometry also improved the pickup performance of cumin seeds, whereas the lowest metering performance was observed for cumin seeds when slot-shaped hole discs were used.

The DEM model successfully reproduced the seed discharge behavior observed experimentally. Simulated seed fall velocities were slightly higher than the measured values at all rotational speeds; however, the differences remained relatively small and generally decreased as rotational speed increased, demonstrating good agreement between numerical and experimental results. The best experimental values of the vertical drop velocity of pea seeds ranged from 0.39 ± 0.02 to 0.41 ± 0.04 m s^{-1}, while in simulations they ranged from 0.44 ± 0.02 to 0.49 ± 0.02 m s^{-1} when a disk with spoon cells was used at a rotational speed of 20–40 rpm. The best coefficient of variation (CV) for peas was 15% and for cumin was 18% at a disc rotation of 20 rpm.

The results demonstrate that seed shape and metering-cell geometry jointly influence seed pickup, release behavior, and discharge velocity. Therefore, further optimization of disc geometry and operating parameters is required to improve metering accuracy across different crop species and operating conditions. The validated DEM approach provides a reliable tool for the design and optimization of precision seed-metering systems and contributes to the development of universal precision seed drills capable of accurately sowing seeds with different physical and geometric characteristics. Overall, the findings provide a scientifically grounded framework for the development of intelligent seeding systems and contribute to the advancement of digitally enabled precision agriculture machinery.

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