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## **Optimizing Seed Placement in Automated Nursery Tray Planting Systems Using Mathematical Modeling**

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**Abstract:** The extent to which current nursery tray planting relies on trial-and-error procedures limits the achievable tradeoff between productivity and accuracy. To overcome this problem, an integrated modeling framework that links planting speed to seed placement accuracy specifically for automated nursery tray planting is proposed. The framework combines a physical model of seed motion with experimentally derived parameters to create an optimization framework using an objective measure of accuracy. This model describes the relationship between the rate of planting and the accuracy of placement based on the objective function that takes into consideration the accuracy of seed placement ( $\sigma$ ) and the efficiency of the process ( $\tau$ ). The main parameters are the mass of the seeds ( $m$ ), the speed of planting ( $v$ ), the aerodynamic component ( $k$ ), and system parameters ( $\omega$ ). Numerical analysis and experimental verification are used to assess the model's validity under the given operational conditions. Analysis of the results shows that the speed of planting can be increased by a maximum of 35% with a planting accuracy of  $\pm 0.5$  mm, thereby establishing the effectiveness of the proposed approach to determine optimal operation conditions. The results further validate the effectiveness of combining motion modeling with accuracy optimization to offer a systematic approach to overcome traditional trial-and-error technique in nursery tray planting.

**Keywords:** Control systems, Dynamic motion analysis, Mathematical modeling, Nursery automation, Precision seeding, Seed placement accuracy, Speed optimization.

## Introduction

Nursery tray planting is mainly used for planting vegetable seeds, such as vegetables like lettuce, tomato, and pepper, and is based on small and light seeds. Such seeds tend to be spherical or nearly spherical in shape, with low weight and poor aerodynamic stability, such that their planting is sensitive to planting speed and vibration (Li et al., 2025a). Considering the small and light physical properties of seeds and their susceptibility to vibrations, as well as the high speed of the process, there is a significant need to develop highly accurate automated seedling planting machines that can accurately control seed placement in the tray and eliminate any loss or duplication of seeds. Therefore, current research has focuses on the development and improvement of tray planting machines and seed cleaning and feeding equipment using various technologies to accurately place seeds in the tray and improve the efficiency of automation (Ding et al., 2024; Wang et al., 2024; Li et al., 2025a). With the increasing reliance on these systems, automating nursery operations is a key advance in modern agriculture. The need for seedlings is especially important for seedling production (Choudhary and Machavaram, 2022). The machine for planting in nursery trays assists in planting the seedlings in the trays automatically (Yao et al., 2024a). This machine is currently essential in seedling production to plant the seeds at the correct positions in the trays (Burton et al., 2022). The challenge, however, is to

ensure the optimal operation of these machines to plant the seeds in the correct positions. The two objectives are typically at odds with each other (Du et al., 2023).

Accuracy in seed distribution is required and impacts the growth of the seedling and final yield (Gallegos-Cedillo et al., 2024). Experimental validation shows that inappropriate seed distribution can decrease the germination process by as much as 15% and can cause unequal plant growth, thus resulting in major losses for the nursery (Vinosh et al., 2021). Conventional methods can improve the accuracy of the distribution often slow down the process, thus affecting the efficiency of production (Hossen et al., 2022). Over the past thirty years, there have been significant advances in nursery planting automation. The first mechanical seeders, which were developed in the 1990s, provided basic automation. However, they only operated at an accuracy level of 5-10 trays per minute (Zheng et al., 2021). Most modern systems are much improved from this. However, they are not under the pressure of time, yet they cannot plant the seeds properly. Recent Research shows that a 10% speed increase leads to a 0.2mm rise in positioning errors. This is a blocking path to productivity improvements (Yao et al., 2024a). Advances in mathematics and control theory provide solutions to optimize planting mechanisms (Shao et al., 2023). The study of Tian et al. in 2023 showed that dynamic motion analysis is able to predict seed paths

under different situations. Some researchs have focused on precision seeders specifically for vegetable trays. Through dynamic kinematic analysis on seeding parts and simulation, a precision seeder for vegetable trays has been improved to optimize design, eliminate motion problems, and enhance seeding performance (Zou et al., 2023). Another research on an automated precision seeder for vegetable crops proved that it could plant individual seeds with a high degree of precision, reaching about 95% efficiency. It can also increase efficiency 3.8 times compared to manual planting, though accuracy varies depending on factors such as vacuum pressure and surface area of the seeds (Zamuco et al., 2023). In search of a uniform seeding pattern, pneumatic distribution systems have been researched. It was found that changing the geometry of the pneumatic distribution parts can reduce the coefficient of variation in seed distribution by more than 50%. This emphasizes that the accuracy of seed distribution depends on the design of the conveying and distribution parts (Albasheer et al., 2023). Sophisticated models based on multi-sensor data, including GNSS and inertial measurement units, were developed to predict seeding locations and account for planting paths. With speeds reaching 3 m/s, seed passing rates were at 99% or higher (Zhao et al., 2018; Sun et al., 2022).

This study seeks to fill the existing gap in the mathematical integration of speed and accuracy in the automated seed tray

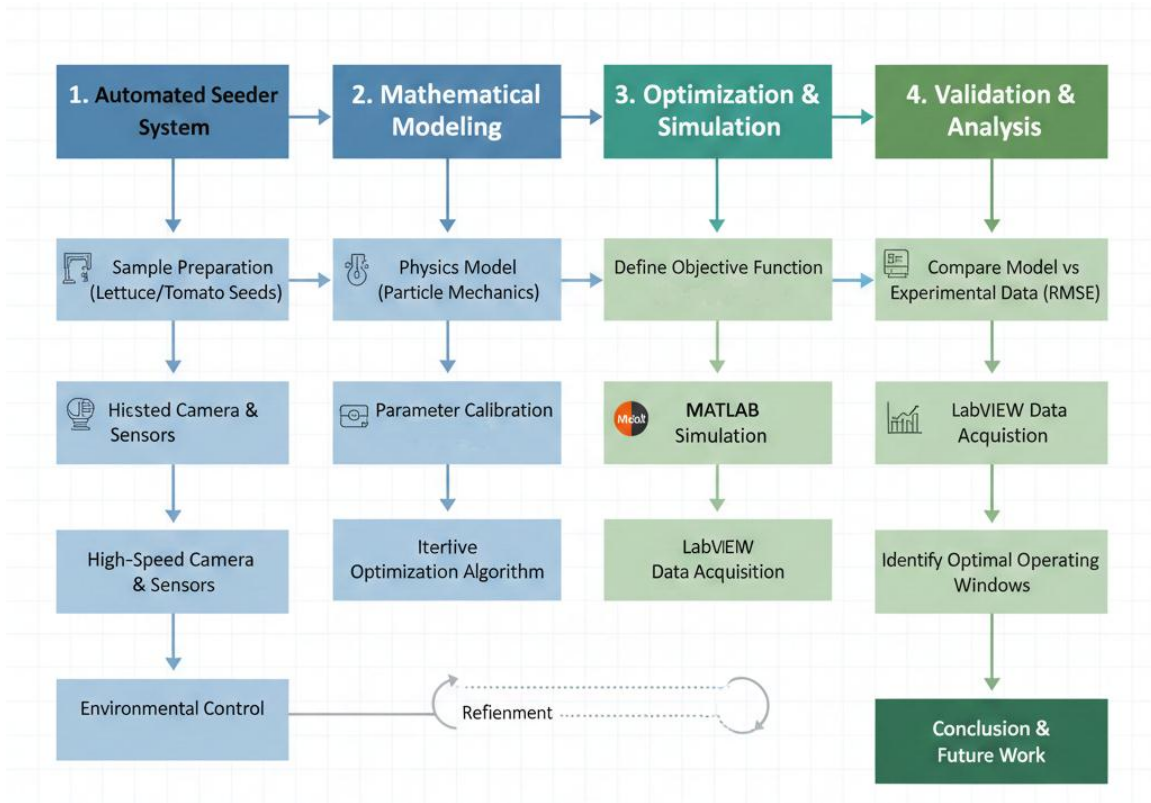
planting system, despite the advancements made in the development of seed drill technology. Currently, there is a lack of an all-encompassing mathematical model that incorporates both physical modeling and optimization techniques to achieve an optimal balance between efficiency and accuracy. The conventional reliance on trial and error methods has limited the achievement of an optimal balance, resulting in germination rates as low as 15%. The need to develop an integrated mathematical model that links the velocity of seeds and accuracy in the automated seed tray planting system has been established. This will be achieved by developing a physical model of the motion dynamics of seeds and analyzing the impact of external factors and mechanical interference. The main goal of this study will be to develop an objective function that equilibrates the operating velocity of the system ( $\tau$ ) and accuracy criteria ( $\sigma$ ). The validity and reliability of the developed mathematical model will be tested by comparing the results obtained using the model with those obtained from the actual system operating under different conditions, with the aim of finding the optimal operating conditions that maximize efficiency while maintaining the qualitative nature of the seed planting process.

## **Materials and Methods**

The subject matter under investigation, in both its hands-on and simulated aspects, revolves around tiny vegetable

seeds that include lettuce and tomatoes, which serve as the reference model for greenhouse crops. This selection is not arbitrary; vegetable seeds have unique dynamic characteristics that make them stand out from the rest. They are light and have simple geometries; thus, their free-fall behavior is significantly responsive to factors like seeding rate, machine-induced vibrations, and timing of release. Given that the difference between lettuce and tomato seeds is only minor with respect to physical structure, we began by making a brief physical assessment to determine average mechanical properties, such as mass and size. We then inserted these values into the mathematical model. To account for how the shape of the seeds might affect the airflow, we introduced a correction factor to the disturbance parameters ( $F_x$ ,  $F_y$ ). This ensures that the model remains

valid and capable of predicting behavior while applying to many types of crops with similar physical properties, rather than requiring recalibration for every single type of seed. To ensure that the results could be replicated, the parameters were refined to conform to this class of seeds. This entailed measuring the mass of the seeds and experimentally determining the air damping and disturbance coefficients under the operating conditions. This detailed characterization provides the physics necessary to relate the mechanical properties to the final position of the seeds in the cell. The flowchart in (Figure 1) illustrates the integrated methodological framework adopted in this study, which links the stages of physical characterization, mathematical modeling, and verification and optimization processes.



**Figure 1.** Integrated research methodology framework, illustrating the transition from physical seed characterization and system setup to mathematical modeling and multi-objective optimization.

## Experimental Setup

The aim of the setup was to measure and control seed placement precisely. It also had to apply to industrial applications. This framework enables data collection in controlled settings. It is a simulated nursery, reproducing real-world nursery operations. The seeds were cleaned and sized uniformly using sieves to reduce variation in mass and geometry, ensuring the accuracy of the extinction coefficients ( $k$ ) in the mathematical model. The equipment used for this experiment is a state-of-the-art automatic nursery tray seeder that can place seeds accurately into plug trays.

This seeder has a single-head system that allows for controlled seed delivery, which is necessary for studying the relationship between seeder speed and accuracy.

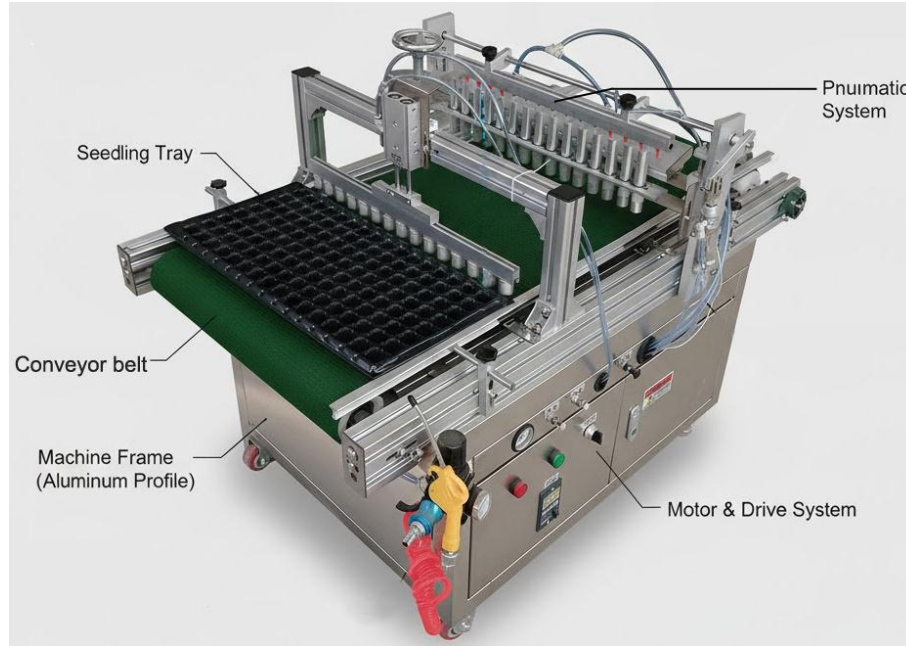
This machine features ample working space to place seedling trays without affecting the movement characteristics. The positioning of the seeds uses a gantry system based on the X-Y mechanism, which is actuated by a servo motor, ensuring the precision of the positions of the released seeds over the range of operating speeds. The real-time feedback control system uses a programmable logic controller. Table 1

shows the specifications of the nursery tray seeding machine.

**Table 1. The specifications of the nursery tray seeding machine.**

<b>Machine Type</b>	SJM-120 Automated single-head nursery tray seeding system
<b>Working envelope</b>	600 × 400mm
<b>Tray specifications</b>	Standard 128-cell nursery trays (16 × 8 configuration)
<b>Seed hopper capacity</b>	500g
<b>Operating speed range</b>	0-2.5 m/s
<b>Moving system</b>	Servo-driven X-Y gantry mechanism
<b>Real-time feedback control system</b>	PLC

A schematic diagram of the experimental seeding machine is shown in Figure 2.



**Figure 2.** Schematic diagram of the automated single-head nursery tray seeding machine used in the experiments.

To accurately evaluate the dynamic process of seed placement, a specialized measurement and data acquisition system was also designed. The system combines visual, positional, and force measurements in order to determine the dynamic properties of the process of seeding. A high-speed industrial camera

(Basler acA1300-200uc, Ace series) was used to capture seed ejection and a brief period of free fall just before seed placement. The camera has a spatial resolution of 1280 × 1024 pixels and a maximum frame rate of 203 frames per second using a region-of-interest (ROI) setting, allowing observation of seed

trajectory and ejection in a time-resolved manner. The motion of the seeding head was measured by optical rotary encoders with a position resolution of 0.01 mm, while the interaction forces were measured by strain-gauge load cells with a resolution of 0.1 N. The data acquisition was synchronized to provide data at 1000 Hz by an industrial PC that has an Intel i7 processor, running scripts written in MATLAB for data processing. The data acquired included time-stamped displacement, force, and trajectory data that can be further analyzed to provide planting accuracy ( $\sigma$ ) parameters.

The electrical energy consumption for the seeding system was determined by means of an inline digital power meter, which was connected to the machine's primary power supply. It was used for calculating the total electrical energy consumption (kWh) for each experiment conducted at a specified speed. The level of vibration was determined through the use of a vibration measurement device that was attached to the primary structural frame of the seeding machine. Vibration sensors were installed as close as possible to the launch nozzle to ensure that disturbances directly affecting the seed's trajectory were recorded. The device was able to measure the frequency of vibration along the major direction of motion, and the vibration level (Hz) is an indication of the average steady-state frequency under a given operating condition.

### Mathematical Model Development

The motion of a seed during the release and short free-fall phase in nursery tray

planting is modeled in a two-dimensional plane (X, Y) using a physics-based second-order representation derived from classical particle dynamics. The main parameters are the mass of the seeds ( $m$ ), the speed of planting ( $v$ ), the aerodynamic component ( $k$ ), and system parameters ( $\omega$ ). In the context of automated nursery tray seeding, these governing equations are not presented as a general restatement of Newton's law, but rather as the physical layer of an integrated modeling framework that incorporates experimentally identified parameters and supports accuracy-driven optimization of operating conditions (Ilie et al., 2022). The equations of motion are expressed as (Tian et al., 2023):

$$\begin{aligned}\frac{d^2x}{dt^2} &= -k_1 \frac{dx}{dt} + \frac{F_x(t)}{m} \\ \frac{d^2y}{dt^2} &= -k_1 \frac{dy}{dt} - g + \frac{F_y(t)}{m}\end{aligned}$$

Where  $x(t)$  and  $y(t)$  are the instantaneous coordinates of the seed,  $t$  is time,  $m$  is the mass of a representative small vegetable seed, and  $g$  is the gravitational acceleration. The coefficient  $k_1$  represents an effective aerodynamic damping term associated with the selected seed category and operating environment.

The disturbance terms  $F_x(t)$  and  $F_y(t)$  represent equivalent external forces acting on the seed during the release process. These terms account for the combined effects of (i) the impulse generated during vacuum release, (ii) vibration transmitted from the seeding mechanism, and (iii) localized airflow in the vicinity of the release zone. Similar disturbance-based formulations have been adopted in seed and particle

trajectory modeling under controlled agricultural environments (Tian et al., 2023). In this study, external disturbance terms and the aerodynamic coefficient  $k_1$  are not measured directly as forces. Instead, they are identified experimentally through a synchronized measurement process. Seed trajectories  $x(t)$  and  $y(t)$  are extracted from high-speed camera recordings, while the motion of the seeding head is tracked using optical encoders. Numerical differentiation of the observed trajectories provides the velocity and acceleration profiles, which are used to estimate the parameters by minimizing the discrepancy between the measured and computed seed motion (Yao et al., 2024b).

Root-mean-square error (RMSE) is used as the placement accuracy metric, which is widely used in precision positioning and agricultural automation research (Zhang et al., 2023):

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n [(x_i - x_{\text{target}})^2 + (y_i - y_{\text{target}})^2]}$$

Where  $n$  is the number of trials,  $(x_i, y_i)$  are the measured seed placement coordinates obtained from

To address the tradeoff issue in the placement and speed objectives of the problem, we will introduce the optimization technique to reach a near-optimum placement and speed for the industry scenario. The optimization approach involving two objects accurately describes the criteria of

nursery events, in which accuracy and efficiency are high-priority variables. In relation to production line criteria, the relative importance of such variables can be adjusted via the weight factors  $w_1$  and  $w_2$ .

$$J = w_1\sigma + w_2(1/v)$$

Where  $J$  is objective Function,  $(w_1, w_2)$  are weighting factors,  $v$  is variable.

The operational constraints have been specified based on theoretical values that take into consideration operational experience in related sectors. The operational constraints ensure that the optimized solutions obtained fall within feasible and relevant operational values. The experimental approach was adopted in order to obtain a general validation of the mathematical model in a real life setting in a repeatable way. To calibrate and verify the performance of the measurement and the accuracy of the systems, a detailed calibration process was developed. Optimization aimed at reducing and suppressing systematic error, and thus verifying the standardized performance characteristics at every level within the calibration process. The test procedure has been developed to evaluate performance for different scenarios. Performance requirements related to speed criteria have been identified based on the levels of information deemed relevant, taking into account the levels of accuracy measured as part of the scope of this test.

## Software and Tools

A set of software tools was chosen to support the requirements for modeling, numerical analysis, data acquisition, as well as experimental validation, with emphasis on reliability, reproducibility, and integrative capacity. The MATLAB environment developed by Math Works Inc. was used as a tool for carrying out mathematical modeling, numerical simulations, and optimization analysis. The governing equations for seed motion were implemented in MATLAB, and numerical differentiation and identification methods were used for estimating model coefficients. In addition, MATLAB was used for evaluating the accuracy of seed placement and trade-offs between speed and accuracy. The MATLAB image processing toolbox was used to analyze the high-speed camera recording, which allowed for seed trajectories, centroid movement, and the conversion of these measurements from pixels to physical coordinates via calibration.

LabVIEW, from National Instruments, was employed to perform real-time data acquisition as well as synchronization of sensor signals, such as optical encoders and load cells. The software, in essence, enabled the timestamping of signals such as displacement and force at a sampling frequency of 1000 Hz, while also providing integration of hardware and software components.

With regard to documentation, visualization, and post-processing of the experimental results, Microsoft Excel was employed to manage data and create

preliminary figures, whereas final figures were prepared through the use of MATLAB's plotting tools. The overall application of these software tools was useful for an integrated approach to modeling, data collection, and analysis for automated nursery tray seeding systems.

### **Statistical analysis and verification techniques**

The statistical analysis and model validation were performed using MATLAB. Statistical analysis techniques were one of the approaches used in the validation of the mathematical model and the statistical significance of the outputs produced. The confidence level chosen in this validation process is 95% because it represents a significance level in every subject area. To validate the relevance of the model and its optimality, different validation techniques of a model process include cross-validation techniques in proving predictive capabilities and validation of sensitivity analysis in identifying parameters that optimize system performance.

### **Results and Discussion**

In order to verify the effectiveness of the proposed framework, thorough experiments have been conducted to simulate the actual working conditions for the theoretical outputs. In this section, the interactions between the key factors and the seed kinetics will be discussed based on the results, and the reasons for the discrepancy between

speed and accuracy will be explained, as well as the ability of the proposed objective function to identify the optimal working zones for the best crop quality.

From Table 2, results show a consistent relationship between speed and placement accuracy. The system

performed well at lower speeds of 0.5-1.0 m/s with a placement error well within 0.2 mm. A significant drop in placement accuracy was recorded beyond a speed of 1.5 m/s. The success rate of seed placement within an error limit of  $\pm 0.5$  mm remained over 95% at speeds below 2.0 m/s.

**Table 2. Accuracy of Seed Placement across the Speed of Operation**

Speed (m/s)	Mean Error (mm)	Standard Deviation (mm)	Success Rate (%)
0.5	0.12	0.08	99.2
1.0	0.18	0.11	98.7
1.5	0.25	0.15	97.8
2.0	0.35	0.22	95.6
2.5	0.48	0.31	92.3

The result of the experiments on the accuracy of placing seeds corroborates the existence of a speed-accuracy trade-off effect. At a speed of 0.5 to 1.0m/s, a high accuracy was attained, with error mean values of 0.12 to 0.18mm and a success rate of over 98.7%. The high accuracy obtained can be attributed to the lower inertial forces, proper vibration damping, and optimal response of the control system at low speeds (Song et al., 2024). Transition point is at 1.5 m/s, where the mean error increases to 0.25mm, and the success rate is 97.8%. 1.5 m/s is the point beyond which dynamic effects affect placement accuracy, though at this point, the control system is still able to counter these changes. At faster speeds ranging between 2.0 and 2.5 m/s, the performance is greatly affected, with an average error of 0.35–0.48 mm, along with a success rate of 90–95%. This could be attributed to the intensified system vibrations, inertial forces, and

constraints of real-time control (Wu et al., 2025). The experimental results, when examined within the context of the proposed model, indicate that the importance of dynamics becomes greater with increasing speed. In speeds lower than or equal to 1.0 m/s, terms related to disturbances are small, and hence, precision is relatively high. In speeds greater than 1.5 m/s, a transitional region is indicated by the model where dynamics start to have an effect on precision, and yet stability is sufficient for an appropriate balance to be maintained. With higher speeds, i.e., speeds greater than or equal to 2.0 m/s, the experimental results and the model both predict a dramatic escalation in the level of disturbance in the form of vibration, which directly impacts the accuracy of placement. In such a case, to maintain accuracy, a compromise in terms of precision would have to be made, or the systems would have to be upgraded to minimize the effects. The

observed increase in placement error with increasing speed is consistent with the model predictions, which indicate a nonlinear growth in disturbance-related terms beyond a critical operating speed.

Regarding the analysis of speed optimization guided by the model, the analysis of the optimization test showed

that there were three possible operating speeds with differing levels of speed and accuracy. The "balanced" speed (1.5 m/s) was generally the most suitable operating mode and offered up to 77% greater processing speeds than the prudent mode, while still offering sufficient levels of accuracy.

**Table 3. System Performance Metrics under Different Operating Conditions**

<b>Operating Mode</b>	<b>Speed (m/s)</b>	<b>Trays/Hour</b>	<b>Energy Consumption (kWh)</b>	<b>Vibration Level (Hz)</b>
Conservative	0.8	180	0.45	12.3
Balanced	1.5	320	0.72	18.7
High-Speed	2.2	450	1.15	25.4
Maximum	2.5	520	1.48	31.2

The operating modes summarized in Table 3 correspond to distinct regions of the objective function defined in the optimization framework, where increasing speed improves productivity at the expense of higher  $\sigma$  values and vibration levels. Also, illustrates the outcome of a speed optimization analysis with clear trade-offs that change based on the choice of speed interval. The system has prominent performance behavior offered by four operating modes: conservative, balanced, high speed, and full capacity modes. The lowest throughput of 180 trays per hour is attained at an operating speed of 0.8m/s together with the highest level of energy efficiency of approximately 0.45kWh and the lowest level of vibrations at 12.3Hz. This mode works best when the seeds are considered delicate or when the accuracy of placement counts the most. The balanced

mode, with the velocity at 1.5 m/s, is identified as the most practicable option for commercial applications at the rate of 320 trays per hour with acceptable power use at 0.72 kWh. The level of vibration remains moderate at 18.7 Hz, indicating stable machine performance, as further increases in productivity are associated with diminishing dividends regarding stability and energy efficiency. High-speed performance with a speed of 2.2 m/s brings significant productivity benefits with a productivity of 450 trays/hour, but with increased power consumption of 1.15 kWh and vibration frequency of 25.4 Hz. While this represents a maximum capacity of 520 trays/hour, the energy consumption rises steeply to 1.48 kWh, and the vibration increases to 31.2 Hz. Evidently, a law of diminishing returns applies when this maximum speed is violated. There is no linear relationship between speed and

energy consumption above 2.0 m/s; further speed increases result in dramatically lower efficiency. Overall, the optimum window is between 1.2 and 1.8 m/s, where the movement is restrained, yet productivity remains high; hence, output is enhanced while energy consumption is reduced, and mechanical wear is minimized (Zhang et al., 2023). This gives room for operators to have flexibility in changing settings according to production needs without having to chase peak speeds that drive overconsumption and wear (Liu et al., 2023).

The agreement between the model's predictions and experimental measurements was assessed, thus establishing the role of the mathematical model as a predictive and explanatory tool, not merely a subsequent description of the experiment. The developed mathematical model showed good predictive power: for most parameters, the deviation from the measured values was less than 10%. The largest scatter, which appeared in the placement error predictions, was due to the unmodeled environmental factors around the system, air currents, and mechanical vibrations.

**Table 4. Model Prediction Accuracy**

<b>Parameter</b>	<b>Predicted</b>	<b>Measured</b>	<b>Deviation (%)</b>
Trajectory Time (ms)	145	148	2.03
Impact Velocity (m/s)	0.82	0.85	3.53
Placement Error (mm)	0.28	0.31	9.68
System Response (ms)	22	24	8.33

Table 4 shows the validation results of the mathematical model, which indicate a strong correlation between the predicted and the measured parameters. The model achieved particularly high accuracy in predicting trajectory time (2.03% from the ratio between predicted (145ms) vs. measured (148ms). This close match not only confirms the basic physics principles that underpin the trajectory calculations but also supports the validity of the model for making predictions about basic motion. The calculated impact velocity was slightly different from the measured impact velocity, with a 3.53% difference between the calculated and measured impact velocities, which were 0.82 m/s

and 0.85 m/s, respectively. Though the experiments were carried out in a lab environment, it was not possible to eliminate the effects of airflow resulting from the movement of mechanical parts, motor cooling systems, and the movement of the seeding head. These airflow effects were not externally imposed but represent low-level, operation-induced disturbances typical of practical nursery tray seeding environments. In the proposed model, such effects are implicitly captured within the effective aerodynamic and disturbance-related parameters. Given the short seed flight duration and limited drop height, the resulting discrepancy remains within acceptable limits and

does not affect the validity of the model for operational optimization purposes (Liu et al., 2022; Li et al., 2025b). The biggest discrepancies in the forecast occurred in the accuracy of placement and the time responses on the system, with 9.68% and 8.33%, respectively. Such discrepancies exist due to the combined phenomenon of the system vibrations. Despite this fact, the model has sufficient accuracy because the combined error on all parameters measured is less than 10%. The outcome of the validation process reveals the relative ability of the model in predicting the primary factors of the system, but there is scope for improvement in the secondary effects and the manner of the system. The future task may involve this, including more complex analyses

regarding the factors of vibration and the environment.

From the perspective of system optimization analysis (the trade-off between speed and accuracy), a detailed analysis of speed-accuracy trade-offs shows specific performance patterns for each production order, as summarized below in Table 5. In the optimization experiment, optimal operational settings incorporating speed-accuracy trade-offs are determined, and there are significant performance enhancements available for three dominant operational settings. When considering the high accuracy specification of 0.8 m/s, this device provides highly accurate performance, having a placement error of no more than 0.15 mm, although its productivity is moderate at 175 trays per hour.

**Table 5. Optimization Results for Different Production Requirements**

<b>Production Priority</b>	<b>Optimal Speed (m/s)</b>	<b>Accuracy (mm)</b>	<b>Productivity (trays/hour)</b>
Maximum Accuracy	0.8	0.15	175
Balanced	1.5	0.25	320
Maximum Speed	2.2	0.42	450

For the balanced operating mode (1.5 m/s) that provides the widest possible operating window, the highest output of 320 trays per hour can be achieved with a level of accuracy measured as 0.25 mm. This setting combines the best of productivity and accuracy by offering a productivity level that is significantly higher than that available in the highest accuracy function while remaining below the threshold that would be deemed commercially unacceptable. To

achieve the maximum speed configuration (2.2 m/s), system capabilities had to be pushed to yield 450 trays/hour, and accuracy decreased (0.42mm). Although this configuration has been optimized for throughput, the resultant placement error indicates that this technology may only be effective in environments or applications where speed is more important than accuracy. And especially at this operational level, it is most clearly observed how speed

and accuracy are non-linear - how even small incremental speed increases have exponential accuracy loss (Xu, 2024; Yang et al. 2024). Such results are crucial in ensuring the system operator chooses the right speed settings in relation to the production process. In general, speed correlates inversely with quality, while the balanced speed generally offers the most economical solution to improve production efficiency while maintaining acceptable quality levels. Hence, the operator should first consider using the balanced speed before resorting to the highest speed achievable.

## Conclusion

The present study discovered that the math model constructed to optimize the rate and accuracy of the automated seedling planting system (CS04) performs very well, with discrepancies between the experiment and the model remaining within 10%. This is a testament to the accuracy of the math model in predicting the performance of the system under various operating conditions. It is proof that the system is operating at the optimal rate of 1.5 m/s, which is the sweet spot for achieving a balance between productivity and accuracy, allowing about 320 trays to pass through per hour while maintaining accuracy within 0.25 mm. The analysis revealed a very distinct non-linear relationship between the variables used

in the process. It was discovered that, beyond a certain point, or speeds greater than 2.0 m/s, accuracy diminishes very quickly, while power consumption increases faster, particularly beyond 2.2 m/s, and mechanical vibrations become a limiting factor at speeds of 2.5 m/s. It is, therefore, evident that the math model is not just a theoretical construct; it is the very basis upon which the design of future agricultural machinery will be based, with the trade-off equations offering the possibility of maximizing the efficiency of agricultural machinery without compromising accuracy and reliability.

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