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Design and experimental validation of a real-time feedback control system for precision row seeding

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ABSTRACT

This study addresses the limitations of conventional seed spacing measurement methods, which, although accurate, remain labor-intensive, time-consuming, and unsuitable for real-time field decision-making. The purpose of this research is to develop and validate a real-time closed-loop seeding control system capable of dynamically regulating seed distribution during planting based on in-field feedback signals. The system integrates a mathematical model of the seeding process for inline seeders, incorporating key operational parameters such as tractor speed, mechanical transmission characteristics, and wheel-soil interaction effects. The proposed approach is based on continuous comparison between theoretical and measured seed spacing, enabling automatic correction of seed flow through an embedded actuation mechanism. The methodology combines real-time sensor data acquisition, mathematical modeling, and closed-loop control using a stepper-motor-driven adjustment system. System performance was evaluated using standard error (SE), coefficient of variation (CV), missing seed index (M), multiple seed index (D), and feed quality index (A), along with direct field validation of seed spacing accuracy under different seeding rates and operating speeds. Experimental results demonstrated an 11% reduction in coefficient of variation, a 0.9 cm improvement in mean seed spacing accuracy, a 1.4-point reduction in the missing seed index, and a 0.8-point reduction in the multiple seed index, while the feed quality index improved by 16%. Absolute measurement errors ranged from 0.08 to 0.32 cm, with relative errors between 3.16% and 6.12%, confirming strong agreement between sensor-based and field measurements. The system maintained stable performance across varying tractor speeds, indicating robust adaptive capability. A limitation of the study is that system validation was conducted under controlled field conditions and on a single crop type, which may limit generalization to highly heterogeneous environments. However, the findings demonstrate strong practical potential for low-cost precision seeding systems. The originality of this work lies in demonstrating that real-time seed spacing feedback can be directly used as a control variable for mechanical adjustment without reliance on external positioning systems or prescription maps. This provides a scalable and cost-effective alternative for precision agriculture in resource-limited farming systems, with significant implications for improving seeding efficiency and crop uniformity.

Keywords: dynamic control system, sensors, precision agriculture, real-time regulation, seed distribution, seed spacing.

INTRODUCTION

Seeding is one of the most crucial agronomic operations in cereal cultivation (Dhima et al., 2007), and an appropriate seeding rate can enhance both the production and quality of crop growth (Yadelew et al., 2024). If the seeding rate is lower than the target rate, it can result in land resource waste. On the other hand, an excessive seeding rate can reduce yield due to a shortage of water and nutrients. Therefore, accurate control of the seeding rate is essential to maximize yields.

The main methods of cereal seeding include broadcasting (Edwards, 1998), row planting (Takele et al., 2024), and precision seeding (Dhillon et al., 2022). Broadcasting involves manually scattering seeds over the soil surface and then covering them with soil (Pawelek et al., 2015). While this method is simple to implement, achieving uniform seed distribution is challenging. Row planting, on the other hand, involves creating regular furrows in which cereal seeds are placed. It is primarily used for direct seeding of wheat and rice, maintaining a regular spacing between rows and providing optimal conditions for aeration and sunlight for the seeds. It also facilitates field management, especially for weeding and plant protection operations (Chen et al., 2004; Vaitauskienė et al., 2017). Precision seeding, in contrast, involves placing seeds in holes spaced according to specific parameters, allowing improved field management and fertilization by ensuring uniform seed growth (Dhillon et al., 2022).

Various types of seeding machines have been developed to implement these techniques (Liu et al., 2025; Lin et al., 2015). These machines distribute seeds through dosing devices. However, in conventional machines, a ground-wheel and chain-driven transmission system powers the dosing device, preventing the adjustment of the seeding rate based on factors such as slippage, planter speed, and soil fertility (Liu et al., 2025). Moreover, the working depth of conventional seeders is fixed and depends on the tractor's suspension mechanism, limiting adaptation to soil height and resulting in varying seed depths, thus affecting crop quality (Du et al., 2024). In the absence of a monitoring and control system, these machines cannot adjust their operational parameters according to specific conditions (Barbedo, 2022), which impacts cereal yields and the effectiveness of subsequent agricultural practices. This issue is particularly prominent in many developing countries, including Tunisia, where manual correction of seeding flaws is becoming increasingly rare due to labor shortages, exacerbated by industrialization and urbanization.

To overcome these challenges, it has become essential to develop and adopt advanced control techniques to improve the efficiency of agricultural machinery. Some modern machines incorporate detection, decision-making, and control systems that adjust the seeding rate based on soil fertility and control the position and depth of seeding in relation to the planter's trajectory and descent pressure, allowing for optimal seed placement (Liu et al., 2025; Šarauskis et al., 2022).

Recent studies also emphasize that soil–plant system responses are highly sensitive to environmental variability, where changes in soil-related conditions can significantly influence crop establishment and early-stage development, further highlighting the need for precise and adaptive seeding control strategies (Patah and Othman, 2024).

Studies have explored the differences between variable rate seeding (VRS), based on maps or sensors, and emphasized the importance of data fusion algorithms. For example, Šarauskis et al. (2022) analyzed variable rate seeding methods (VRS) and their efficiency under various field conditions, while Barbedo (2022) reviewed data fusion approaches in agriculture and emphasized their role in resolving ambiguities and closing data gaps for decision-making.

Šarauskis et al. (2022) also examined variable rate seeding technologies and their suitability under field conditions. In a similar study, Kim et al. (2023) developed a seeding rate monitoring system using advanced image processing techniques, such as Hough transform for seed shape detection and Hue-Saturation-Value conversion to improve color distinction. Their work also included image morphology and Gaussian blur to reduce noise and optimize brightness and saturation parameters. Additionally, Dong et al. (2019) designed a real-time monitoring system for hybrid rice seeding, combining embedded machine vision and machine learning to precisely track seeded quantities and optimize process adjustments.

Technological innovation plays a key role in improving agricultural process performance, particularly seeding, by enhancing precision, efficiency, and productivity. The use of advanced technologies, such as machine vision and machine learning, enables real-time monitoring and optimization of agricultural practices, contributing to more efficient resource management and increased yields. As Bongiovanni and Lowenberg-DeBoer (2004) state, precision agriculture allows for more sustainable resource management. Gebbers and Adamchuk (2010) emphasize the role of these technologies in global food security, while Zhang and Kovacs (2012) demonstrate the positive impact of unmanned aerial systems for precision agriculture. Rose and Chilvers (2018) stress the importance of responsible innovation in smart farming. However, in developing countries, access to these technologies remains a major challenge due to their high costs and the small size of farms, which are often scattered. Many farmers, especially those lacking financial resources and training, face difficulties in adopting and implementing these innovations. The development of simple, affordable control systems represents a significant opportunity to overcome these barriers, making these technologies accessible to smallholders and tailored to their needs.

This study addresses the lack of low-cost real-time closed-loop seeding control systems capable of dynamically correcting seed flow based on simultaneous measurements of seed spacing and tractor speed under field conditions.

However, there is still no widely validated low-cost embedded system that simultaneously integrates seed counting, speed sensing, and actuator-based flow correction in a unified closed-loop architecture for small-scale cereal seeders.

Despite advances in precision agriculture and variable rate seeding technologies, there remains a lack of low-cost, real-time closed-loop systems that directly link in-field seed spacing measurements with mechanical actuation for continuous correction of sowing errors under dynamic operating conditions. Existing approaches are often dependent on pre-defined prescription maps, complex calibration procedures, or high-cost sensing infrastructure, which limits their applicability in small-scale farming systems. This study is based on the hypothesis that real-time feedback from seed spacing measurements can be effectively used as a direct control variable to improve seeding uniformity through adaptive mechanical adjustment of seed flow, even under varying tractor speeds and field conditions. It is further hypothesized that a low-cost embedded control architecture can achieve measurable improvements in seed distribution quality without relying on external spatial data or advanced computational platforms. This study aims to propose and experimentally validate a real-time closed-loop seeding control system that couples seed spacing feedback with stepper-motor-driven mechanical adjustment of seed flow, with the objective of enabling continuous correction of sowing errors under variable field speed conditions.

Although variable-rate seeding, sensor-based monitoring, and closed-loop control have already been reported in the literature, the originality of the present study is mainly engineering-applied rather than purely conceptual. The contribution lies in the integration of a simple, low-cost, and reproducible closed-loop architecture based on an Arduino Mega microcontroller, infrared seed-counting sensors, a tractor-speed sensor, and a NEMA 23 stepper motor coupled to the mechanical flow-adjustment trapdoor of a conventional row seeder. This configuration was designed to provide real-time correction of seed flow without requiring complex machine-vision devices, expensive commercial controllers, or highly specialized calibration procedures. Therefore, the novelty of the work is positioned in the practical adaptation and validation of an affordable control solution suitable for small and medium farms, particularly under resource-limited conditions.

MATERIALS AND METHODS

In this study, the methodology developed to design a real-time seeding control system, aimed at optimizing the efficiency and accuracy of the seeding process, is structured in several key steps. First, a mathematical model was developed that describes the seeding process, focusing on seeding density and seed spacing. This model incorporates various parameters that directly influence the seeding performance, such as the forward speed of the tractor (v), which affects the distance between each seed and the wheel-soil slip coefficient (ε), which modifies the adhesion of the wheel and therefore the precision of seed distribution. The slip coefficient of the tractor wheels is a key factor for real-time control of the sowing process. Under typical field conditions, this coefficient can vary between 8% and 12% (Bulgakov et al., 2021; Zhu et al., 2022). The study by Zhu et al. (2022) measured a slip coefficient of 10.5% for a tractor under loose soil conditions. Similarly, the study by AAl-Dosary et al. (2023) observed a slip coefficient of 9.8% during traction tests on clay-loam soil. Since the experiment was conducted at the École Supérieure des Ingénieurs de Medjez El Beb on clay-loam soil, a 10% coefficient was adopted for real-time control of sowing.

The specifications of the seeder, including the number of seeding units (Z), the spacing between units (a), the diameter of the seeder's wheel (D), and the transmission ratio between the wheel and the distribution system (i) are also considered in the model.

The Chinese national standard GB/T 6973-2005, titled Methods of Testing Precision Seeders (Single-Seeders), specifies testing methods for evaluating the performance of precision seeders. Based on the international standard ISO 7256-1-1984 with certain local adaptations, this standard was developed by the Chinese Academy of Agricultural Mechanization Sciences. It defines the procedures and criteria necessary to assess the efficiency and accuracy of seeders, ensuring uniform seed distribution, which is crucial to optimizing agricultural yields. The standard plays a vital role in ensuring that seeders operate under optimal conditions, thus contributing to better management of agricultural resources and increased crop productivity.

A set of sensors was installed to measure seed deposition at the bottom of the seed tubes and the seeder's forward speed (see the Real-Time Control System section). The data collected by these sensors are processed by a real-time simulation algorithm based on a closed-loop control. The algorithm used in this system is based on a closed-loop control, ensuring dynamic and real-time management of seed distribution. The process begins with data collection through sensors installed on the seed drill, which measure the actual distance between the seeds at the time of deposition while simultaneously recording the speed of the drill. These data are then processed in real-time by the algorithm. At each moment, the algorithm calculates the ideal target distance between the seeds based on the speed of the drill, the number of seeds per hectare, and the working width of the drill. This target distance is compared to the actual distance measured by the sensors. If a significant discrepancy is detected, the algorithm initiates an automatic correction by adjusting the flow rate of the distribution system. This regulation is carried out using a stepper motor, which modifies the feeding speed of the drill to restore the target seed spacing. The system thus operates in a closed-loop, with constant updates of the data from the sensors. This allows for real-time adjustments of seed distribution parameters in response to changes in the speed of the drill, variations in terrain (such as slopes or other obstacles), and soil conditions.

The distribution mechanism consists of a shaft equipped with horizontally arranged splined elements, directly exposed to the drop openings located at the bottom of the seed storage hopper. As the shaft rotates, these splined elements capture and transport the seeds to the bottom of the distribution system. However, variations in the seeding rate may occur when the forward speed increases, mainly due to partial filling of the splined elements, caused by a reduced contact time with the seed mass. To address this limitation, an innovative control of the existing trapdoor has been introduced. Now controlled by a stepper motor, this trapdoor dynamically adjusts the exposure of the splined elements to the seeds. When the trapdoor is articulated upward, the seeding rate decreases. Conversely, when it is articulated downward, the rate increases (Figure 1). This dynamic regulation compensates for variations due to forward speed, ensuring uniform and precise seed distribution regardless of the operating conditions of the seeder.

To evaluate the performance of the control system, tests were conducted on flat terrain at the Medjez El Beb Higher School under specific temperature and humidity conditions. The seeder used is an inline model with a working width of 3.5 meters, equipped with 25 seed tubes, allowing for homogeneous coverage of the land. In this study, selected durum wheat seeds were used, with a bulk density of 750 kg/m^3 and a particle density of 1300 kg/m^3. The tests assessed the effectiveness of dynamic seeding flow control by comparing results with and without the integration of the control system. Details about the seeder's characteristics and the placement of various sensors and actuators of the control system are presented in the Mathematical Modeling of Seeding Control subsection. Standard error (SE), coefficient of variation (CV), missing seed index (M), multiple seed index (D), and feed quality index (A) were used to evaluate the performance of the control system.

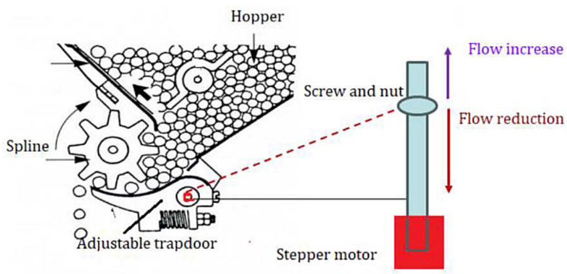

Figure 1. Distribution system equipped with a flow control trapdoor

Mathematical modeling of seeding control

The real-time seeding control model relies on several key parameters, including tractor speed, wheel diameter, and seeder specifications. Calculating wheel rotations is essential for determining the spacing between seeds. The tractor speed, denoted as $v_{tractor}$ (m/s), and the measurement period T (s) are crucial factors. The diameter of the wheel, D (m), allows the computation of the circumference of the wheel C (m).

The distance traveled S (m) by the tractor in one period T is given by Equation 1.

$$S = v_{tractor} \cdot T \quad (1)$$

The number of wheel rotations is calculated by dividing the traveled distance by the circumference of the wheel (Equation 2).

$$n = S/C \quad (2)$$

Considering the wheel slip coefficient (ε), the actual seed metering quantity per minute Q (grains per minute) is calculated by Equation 3.

$$Q = 60 \cdot i \cdot n / [Z \cdot (1 + \varepsilon) \cdot T] \quad (3)$$

In Equation 3, i is the factor between the rotation speed of the seed drill wheel and the seed distribution system, and Z is the number of rows in the seeder.

The actual seed spacing D'_t (m) is given by Equation 4.

$$D'_t = 360 \cdot N \cdot (1 + \varepsilon) \cdot Z \cdot T / Q \quad (4)$$

Finally, the seeding validation is performed by comparing the actual spacing with the theoretical planting spacing $d_{theoretical}$ (Equations 5–8). If the condition

$$v_{tractor} \cdot D'_t \leq 0.5 \cdot d_{theoretical} \quad (5)$$

is met, the seeding is classified as multiple. If

$$v_{tractor} \cdot D'_t > 1.5 \cdot d_{theoretical} \quad (6)$$

it is classified as missing. Otherwise, it is considered normal. The following relations define the criteria:

$$v_{tractor} \cdot D'_t \leq 0.5 \cdot d_{theoretical} \rightarrow \rightarrow \text{“}\textit{Multiple Seeding}\text{”} \quad (7)$$

$$v_{tractor} \cdot D'_t > 1.5 \cdot d_{theoretical} \rightarrow \rightarrow \text{“}\textit{Missing Seeding}\text{”} \quad (8)$$

Otherwise: “*Normal Seeding*”

The theoretical distance between two seeds, $d_{theoretical}$, can be calculated as follows. First, we calculate the adjusted tractor speed $v_{tractor}$ considering the slippage coefficient ε and the reduction ratio i (Equation 9), and then determine the distance $d_{theoretical}$ between the seeds by Equation 10:

$$v_{tractor} = V_{tractor} / (1 + \varepsilon) \quad (9)$$

$$d_{theoretical} = (L_{working} \times v_{tractor} \times i \times 10^4) / / (D_{sowing} \times 1000 / P_{1000\ seeds} \times N_{seeds/ha}) \quad (10)$$

In Equation 10, $L_{working}$ is the width of the machine working, $V_{tractor}$ is the speed of the tractor, i is the reduction ratio, D_{sowing} is the sowing rate, and $P_{1000\ seeds}$ is the weight of 1000 seeds.

Nseeds/ha represents the seeding density, expressed as the number of seeds sown per ha. It is a key agronomic parameter that directly influences seed spacing, plant competition, and the final crop yield. It is defined as follows:

$$N_{seeds/ha} = \textit{Total number of seeds sown} / / \textit{Sown area} \text{ (ha)} \quad (11)$$

In Equation 11, $N_{seeds/ha}$ is used to determine the theoretical spacing between two seeds ($d_{theoretical}$). A high seeding density ($N_{seeds/ha}$ large) results in reduced seed spacing, while a lower density increases this spacing. This variable is therefore essential for adjusting seed distribution according to sowing conditions and agronomic objectives.

REAL-TIME CONTROL SYSTEM

The control system developed in this study aims to optimize seed distribution through continuous interaction between data acquisition, prediction, and real-time adjustment. This system relies on a combination of integrated sensors and actuators, enabling dynamic monitoring and adjustment of the sowing rate based on real-time working conditions.

The proposed system introduces a feedback architecture in which seed spacing error is continuously estimated and used as a control variable to adjust mechanical seed flow in real time, rather than relying on pre-calibrated or map-based seeding rates.

Six infrared sensors of type IR NB022 were installed to count the seeds at the bottom of the seed tubes. These sensors operate at a frequency of 1 Hz, with an accuracy of ±1 to 2%, and a fast response time of a few milliseconds. This ensures continuous and precise monitoring of the number of seeds sown at each pass, ensuring optimal uniformity of seed distribution. The choice of these sensors is based on their ability to provide reliable real-time data, essential for accurate sowing rate adjustment (Figure 2).

In parallel, the tractor's movement speed is measured using an RCWL-0516 sensor, a microwave radar module utilizing Doppler technology. This sensor, with an accuracy of approximately ±3% and a response time of 1 to 3 seconds, operates in conjunction with magnets attached to the tractor's wheel. Each time the magnets pass in front of the sensor, a signal is generated, the frequency of which is proportional to the wheel's rotation frequency *w*, allowing real-time calculation of the tractor's speed while accounting for the wheel-soil slip coefficient. The use of real-time sensing for continuous monitoring and data acquisition in this system is consistent with recent developments in sensor-based environmental measurement frameworks, where real-time monitoring architectures are increasingly applied to improve accuracy and responsiveness in dynamic physical systems (Amaechi et al., 2026):

$$v_{trac} = w \cdot D \cdot (1 - \varepsilon) / 2 \tag{12}$$

where: v_{trac} is the actual speed of the tractor, w is the wheel's rotation frequency, D is the tractor's wheel diameter, and ε is the wheel-soil slip coefficient.

In typical field conditions, the slip coefficient ε can vary between 8% and 12%. In this study, a slip coefficient of 10% was adopted for real-time control of the seeding process. This measurement is crucial for determining the distance traveled by the tractor (Figure 3).

The data collected by these sensors is processed by an Arduino Mega microcontroller, which handles the acquisition of information and transmits it to the control system. A specific code was developed to compare, in real-time, the actual distance traveled by the tractor to a predefined target distance. The target distance is a function of the tractor's speed and the seeder parameters.

When a difference between the actual and target distance is detected, the system dynamically adjusts the sowing rate to maintain uniform seed distribution, taking into account variations in the tractor's speed.

The adjustment of the sowing rate is performed using a NEMA 23 stepper motor, controlled by a TB6566 driver. The NEMA 23 motor, with a high torque of 1 to 3 Nm and a resolution of 200 steps per revolution (i.e., 1.8° per step), adjusts the sowing rate via a rigid lead screw system coupled to the sowing rate adjustment lever. This mechanism allows for high precision in the adjustment, ensuring a rapid and accurate response to rate variations based on working conditions. The control system operates in a closed-loop configuration, guaranteeing continuous sowing rate adjustment. At each pass, the microcontroller compares the distance traveled to the target distance and, in case of deviation, instantly modifies the sowing rate to compensate for any variation,

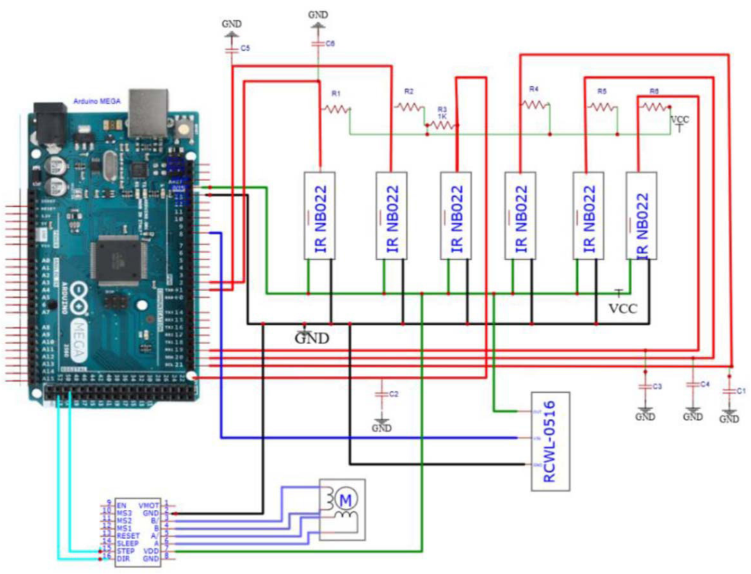

Figure 2. Electrical diagram of the real-time control system

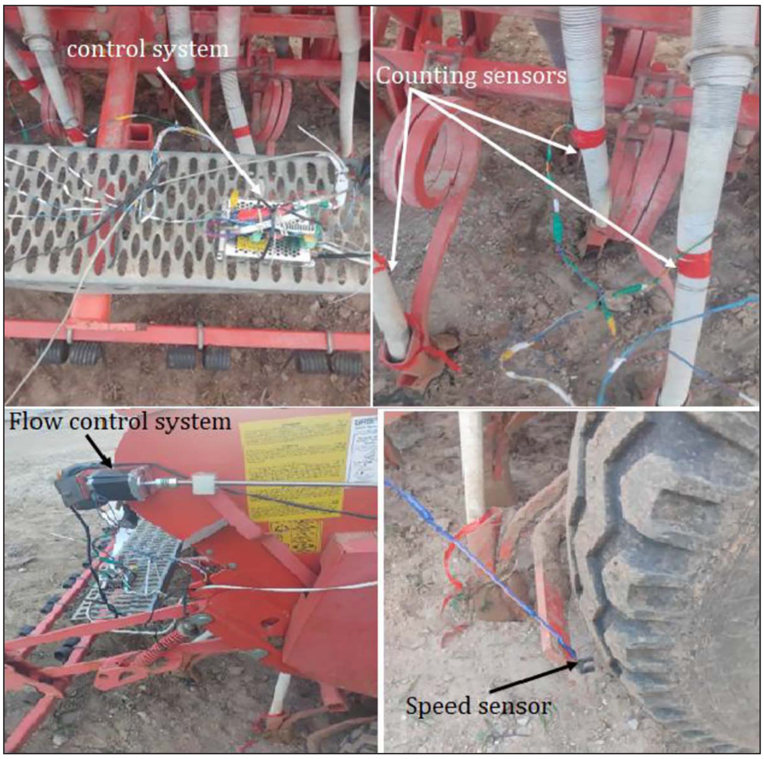

Figure 3. Sensor configuration: counting sensor, speed sensor, and flow control system for real-time monitoring

thus optimizing seed distribution. The control algorithm considers factors such as variations in the tractor's speed and potential disturbances caused by field irregularities, factoring in the wheel-soil-seeder slip (Figure 4).

To improve the reproducibility of the control strategy, the decision-making logic of the algorithm is formalized as follows. At each acquisition step, the microcontroller reads the number of seeds detected by the IR NB022 sensors and the tractor-speed signal generated by the RCWL-0516 module. The actual seed spacing is then estimated from the time interval between two consecutive seed detections and the instantaneous tractor speed. In parallel, the target seed spacing is calculated from the selected sowing rate, working width, 1000-seed weight, reduction ratio, and slip-corrected tractor speed. The control error is defined as:

$$e(t) = d\_measured(t) - d\_theoretical(t)$$

where: d_measured(t) is the measured spacing obtained from the sensor data and d_theoretical(t) is the target spacing calculated from the agronomic and mechanical parameters.

If the measured spacing is lower than 0.5 × d_theoretical, the event is classified as multiple seeding and the controller reduces the seed flow by moving the trapdoor upward through the stepper motor. If the measured spacing is higher than 1.5 × d_theoretical, the event is classified as missing seeding and the controller increases the seed flow by moving the trapdoor downward. If the measured spacing remains within the interval 0.5 × d_theoretical < d_measured ≤ 1.5 × d_theoretical, the spacing is considered normal and no correction is applied. The implemented algorithm can be summarized as follows:

1. Initialize sensors, stepper motor, seeding-rate set point, and mechanical parameters.
2. Acquire seed-counting signals and tractor-speed data.
3. Calculate the instantaneous tractor speed corrected for wheel slip.
4. Estimate the measured seed spacing from detection intervals.
5. Calculate the theoretical spacing corresponding to the target sowing rate.
6. Compare measured and theoretical spacing using the 0.5 and 1.5 threshold limits.
7. Actuate the stepper motor to increase or decrease seed flow when missing or multiple seeding is detected.
8. Store raw sensor counts, detection-derived spacing, calculated indices, and repetition information for post-processing.

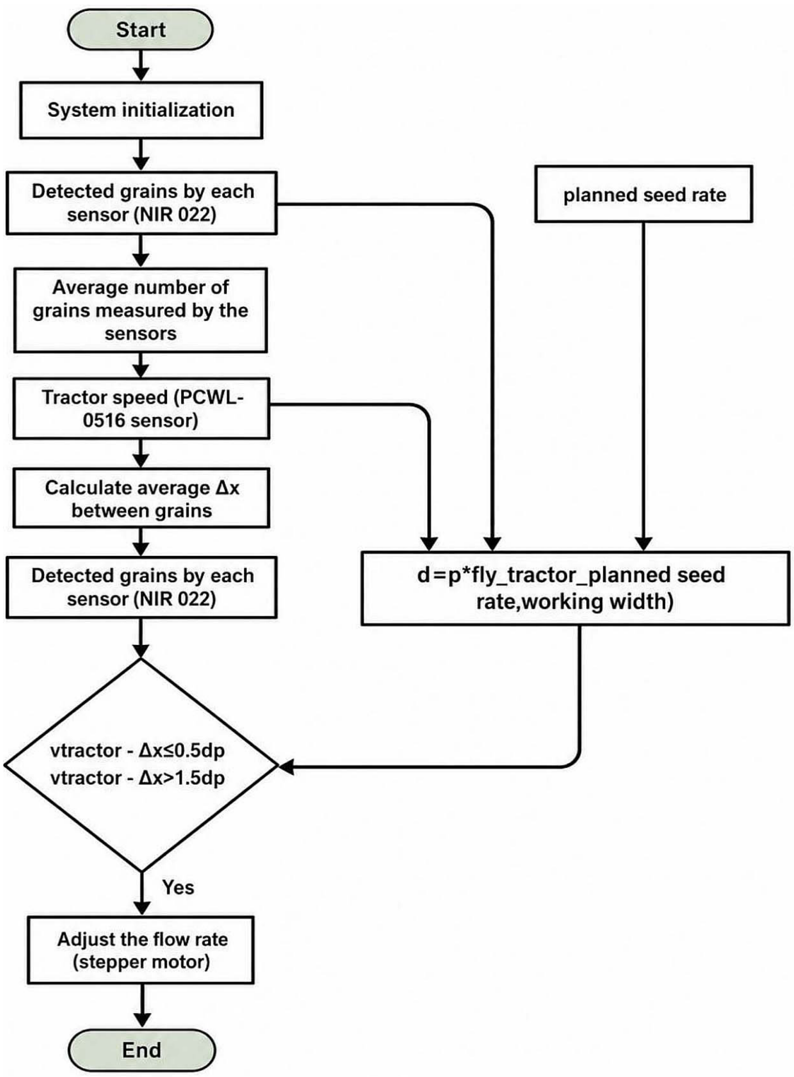

Figure 4. Diagram of the flow control system for real-time monitoring

The main tuning parameters used in the control process were the sensor acquisition frequency of 1 Hz, the slip coefficient fixed at 10% under the tested clay-loam soil conditions, the decision thresholds of 0.5 and 1.5 times the theoretical spacing, and a stepper motor resolution of 200 steps per revolution. These parameters were kept constant during all trials to ensure comparability between repetitions and sowing rates.

Experimentation

This study tested doses of 50, 100, 150, 200, and 250 kg/ha with durum wheat having a bulk density of 750 kg/m³ and a particle density of 1300 kg/m³. Static tests were conducted for the six sensors to assess their accuracy and reliability. Each sensor was tested over some time δt, during which the number of grains collected in the bins located beneath the sowing elements was compared to the count made by the corresponding sensor. These tests aimed to identify the optimal placement of the sensors in the horizontal sections of the drop tubes, allowing for the detection of grains with minimal bouncing. This optimization improved the alignment of the sensors and the efficiency of grain counting.

For each dose, three repetitions were performed, with static tests lasting two minutes per repetition, and three trials for each drop tube. Field experiments were conducted on a flat surface, with a distance of 800 meters covered for each trial. These trials aimed to assess not only the accuracy of the sensors but also the uniformity of seed distribution under real working conditions. Parameters such as tractor speed, sowing rate consistency, and variations due to environmental conditions were considered.

To reduce the influence of uncontrolled field variability, the trials were conducted on the same flat experimental area and under the same machine configuration. For each sowing rat e, three independent repetitions were performed, and the same six seed tubes were monitored throughout the experiment. The order of the tests was alternated between sowing rates to limit the possible effect of progressive changes in field conditions during the experiment. External factors such as tractor speed, soil surface regularity, and wheel slip were monitored or incorporated into the control model. The slip coefficient was fixed at 10%, corresponding to the expected range under the clay-loam soil conditions of the experimental site. All sensor outputs and calculated values were saved as raw repetition-level data, allowing independent verification of the reported results.

To determine the actual grain spacing, we analyzed the time intervals between successive grain detections by the NB022 infrared sensors for each dose and drop tube, taking into account the tractor's forward speed. This method allows for an accurate estimation of grain distribution across the field, reflecting variations caused by the actual seeding conditions.

To measure the seed spacing in the field after sowing, the seed covering components of the six studied tubes were removed from the seed drill to allow seed counting. A direct method based on observation and measurement of the distances between seeds was used. Selected areas of the field were marked, and 10-meter measurement lines were set using stakes. Along these lines, the present seeds were identified, and the distances between each pair of seeds were measured using measuring tapes. This procedure was repeated three times for each sowing rate (50 to 250 kg/ha) and for each seed tube. The average spacing was then calculated by taking the mean of the measured distances between seeds along the entire line and for each seed tube. Finally, the measured spacing in the field was compared with the spacing calculated from the data provided by each seed counting sensor, allowing for verification of the model's accuracy and evaluation of the impact of external factors, such as wheel slippage, on seed distribution.

The objective of the field trials is to evaluate the impact of integrating the control system under real conditions compared to direct seeding. These trials take into account the Chinese standard as a selection criterion for the type of sowing, to determine the effectiveness and relevance of using the control system in practical applications.

In this work, the geometric characteristics of the seeder and the physical properties of the wheat grains used for the experiment are summarized in Table 1.

Statistical analysis

The uniformity of seed spacing in a control system is evaluated in accordance with ISO 7256/1 (1984), which is based on the theoretical seed spacing (*St*). This ideal distance between seeds is determined under the assumption that there are no missing seeds, multiple seeds, or varying seed sizes, and it is typically provided by the planter manufacturer. To evaluate the performance of the planting system in real-time, three indices are used to measure different characteristics of the planting process.

Multiple seed index (D)

The multiple seed index (*D*) quantifies the proportion of intervals where multiple seeds are dropped, which can lead to overseeding and increased competition among plants, negatively affecting the overall planting performance. It is calculated by Equation 13.

$$D = (N_{multiples} / N_{total}) \times 100 \qquad (13)$$

where: $N_{multiples}$ is the number of intervals with multiple seeds, and N_{total} is the total number of intervals.

Table 1. Input variables for the seeding control system

Variable	Description	Value
D	Wheel diameter (m)	1 m
i	Reduction ratio, factor between wheel and seed system speed	1.5
Lworking	Working width of the equipment (m)	3.5 m
P1000 seeds	Weight of 1000 seeds (g)	46
Row spacing	Spacing between rows in the seeder (cm)	18

Missing seed index (M)

The missing seed index (M) measures the proportion of intervals where no seeds are dropped, which can create gaps in planting density and negatively affect yields. It is expressed by Equation 14.

$$M = (N_{missing} / N_{total}) \times 100 \quad (14)$$

where: $N_{missing}$ represents the number of intervals without seeds.

Feed quality index (A)

Finally, the feed quality index (A) evaluates the proportion of intervals where seeds are spaced correctly according to the theoretical spacing, indicating better precision and uniformity in planting. It is calculated by Equation 15.

$$A = (N_{correct} / N_{total}) \times 100 \quad (15)$$

where: $N_{correct}$ is the number of correctly spaced intervals, and N_{total} is the total number of intervals.

These indices allow for the real-time evaluation of the control system's performance, providing critical information to adjust seeding mechanisms and optimize seed distribution. Real-time monitoring helps quickly diagnose potential issues and maximize seeding efficiency to improve agricultural productivity. The interval quantities used to calculate the indicators, such as $N_{multiples}$, $N_{missing}$, $N_{correct}$, and N_{total}, are determined using IR NB022 sensors, which enable real-time seed counting during the experiment. These sensors are integrated into the real-time control system and measure the presence of each seed at specific moments during sowing. The number of seeds detected, along with the detection time, are recorded in a spreadsheet file for each dose and repetition. The PLX-DAQ version 2 interface was used to collect this real-time data, ensuring smooth and accurate data logging. This method allows for rapid and precise measurement of intervals, identifying correctly spaced seeds, missing seeds, and multiple seeds. The collected data is then used to calculate the indices, as illustrated in Equations 13, 14, and 15.

In addition to the calculation of the seeding-performance indices, a statistical analysis was carried out to support the reliability of the results. For each sowing rate and sensor, the three repetitions were used to estimate the mean, standard deviation, and 95% confidence interval of the measured variables. Paired comparisons between uncontrolled and controlled operation were performed across the six monitored sensors for the main performance indicators. Statistical significance was evaluated at $p < 0.05$. Repetition effects were also examined to verify the reproducibility of the measurements. The statistical calculations and graphical outputs were generated from the supplementary dataset using the accompanying analysis code. Specifically, paired t-tests were used for the before/after comparison between uncontrolled and controlled operation across the six monitored sensors, while one-way ANOVA was used to test repetition effects across the three independent repetitions.

RESULTS

Accuracy of seed spacing measurement

The results presented in Table 2 reveal a good agreement between the distances measured in the field and those obtained by the sensors, with absolute and relative errors remaining within acceptable limits, thus demonstrating the accuracy of the real-time control system used. For a seeding rate of 50 kg/ha, the relative error ranges from 3.16% (seeding tube 4) to 6.12% (seeding tube 2), indicating that the sensors provide measurements close to the values observed in the field. As the seeding rate increases, the relative errors slightly increase but remain below 10%. At 100 kg/ha, they range from 4.81% (tube 4) to 5.31% (tube 2), and at 250 kg/ha, they range from 5.81% (seeding tube 1) to 6.51% (seeding tube 2). These results show that the accuracy of the sensors remains acceptable even at high seeding rates.

The discrepancies between the measured distances in the field and those provided by the sensors generally do not exceed 1 cm, and relative errors consistently remain below 10%. Thus, a tractor wheel slippage coefficient of 10% does not significantly affect the difference between the measured field distances and those obtained by the sensors, making this slippage tolerance acceptable for the application.

Furthermore, absolute errors, which range from 0.08 cm to 0.32 cm, reflect minimal differences between field measurements and those provided by the sensors, thus confirming the reliability of the collected data and their ability to provide an accurate assessment of seed distribution.

Table 2. Comparison of calculated and measured seed spacing distances

Sowing rate (kg/ha)	Seed tube	Mean deviation (cm)	Absolute error (cm)	Relative error (%)
50	1	0.15	0.12	3.22
50	2	0.18	0.20	6.12
50	3	0.14	0.13	4.19
50	4	0.10	0.08	3.16
50	5	0.11	0.10	4.21
50	6	0.13	0.14	4.15
100	1	0.16	0.18	5.12
100	2	0.20	0.21	5.31
100	3	0.17	0.15	5.01
100	4	0.18	0.16	4.81
100	5	0.21	0.17	5.16
100	6	0.23	0.20	5.22
150	1	0.25	0.18	5.01
150	2	0.23	0.22	4.92
150	3	0.24	0.19	4.88
150	4	0.21	0.20	4.90
150	5	0.20	0.21	5.10
150	6	0.24	0.22	4.46
200	1	0.26	0.19	5.13
200	2	0.28	0.25	6.01
200	3	0.24	0.20	5.52
200	4	0.28	0.22	5.34
200	5	0.26	0.23	5.62
200	6	0.25	0.26	6.22
250	1	0.30	0.24	5.81
250	2	0.32	0.28	6.51
250	3	0.31	0.25	6.11
250	4	0.29	0.23	5.98
250	5	0.30	0.26	6.21
250	6	0.32	0.28	6.33

Performance of the seed control system

The performance of the real-time control system in this study was evaluated by comparing the results obtained before and after its integration. Before the activation of the control system, only the traditional counting method was used to determine seed spacing. After integrating the control system, the same experimental conditions (speed, product dose) were maintained to allow for a relevant comparison. The results revealed a significant improvement in seeding performance due to the integration of the control system. First, the standard error (SE) of seed spacing significantly decreased after the integration of the control system, indicating a substantial reduction in variability in seed distribution (Figure 5a). Before the integration, the standard error values were relatively high, ranging between 0.149 and 0.184, indicating a less homogeneous seed distribution. After applying the control system, the values stabilized around 0.11 for all sensors, showing a marked improvement in seeding uniformity. This result aligns with previous studies on automated seeding, where real-time control systems have proven effective in improving seed distribution uniformity (Zhang et al., 2023; Liu et al., 2021). Furthermore, the missing seed index (M) experienced a significant decrease after integration of the control system. Before the system was applied, some sensors recorded high indices, reaching up to 11, reflecting areas with no seeds in the rows (Figure 5c). After integrating the control system, these indices decreased significantly, indicating that the system was able to compensate for variations in tractor speed and other environmental factors, thus reducing missing seeds. These results are consistent with the findings of Tang et al. (2022), who observed a similar reduction in the missing seed index in sensor-controlled seeding systems.

The multiple seed index (D) also decreased after the integration of the control system, with values above 20% before the intervention dropping to lower levels, especially for Sensor 2, Sensor 3, and Sensor 4 (Figure 5d). This indicates that the control system effectively reduced multiple seeding, a phenomenon detrimental to crop quality as it causes seed congestion. This result aligns with the work of Liu et al. (2021), who observed that the integration of adaptive real-time controls helped reduce the multiple seed rate in mechanical seeding systems.

Regarding the feed quality index (A), notable improvements were observed, particularly for Sensor 1 and Sensor 5, whose indices dropped from 2.857 and 1.778 to lower values after integration of the control system (Figure 5e). These results suggest better management of seed quality, with more uniform seed distribution throughout the field. These findings corroborate those of Elwakeel et al. (2023), who reported that the integration of dynamic control systems allowed the adjustment of seed speed and quantity in real time, thus improving seed quality.

Finally, the coefficient of variation (CV) showed a significant reduction, indicating improved consistency in seed distribution. Before

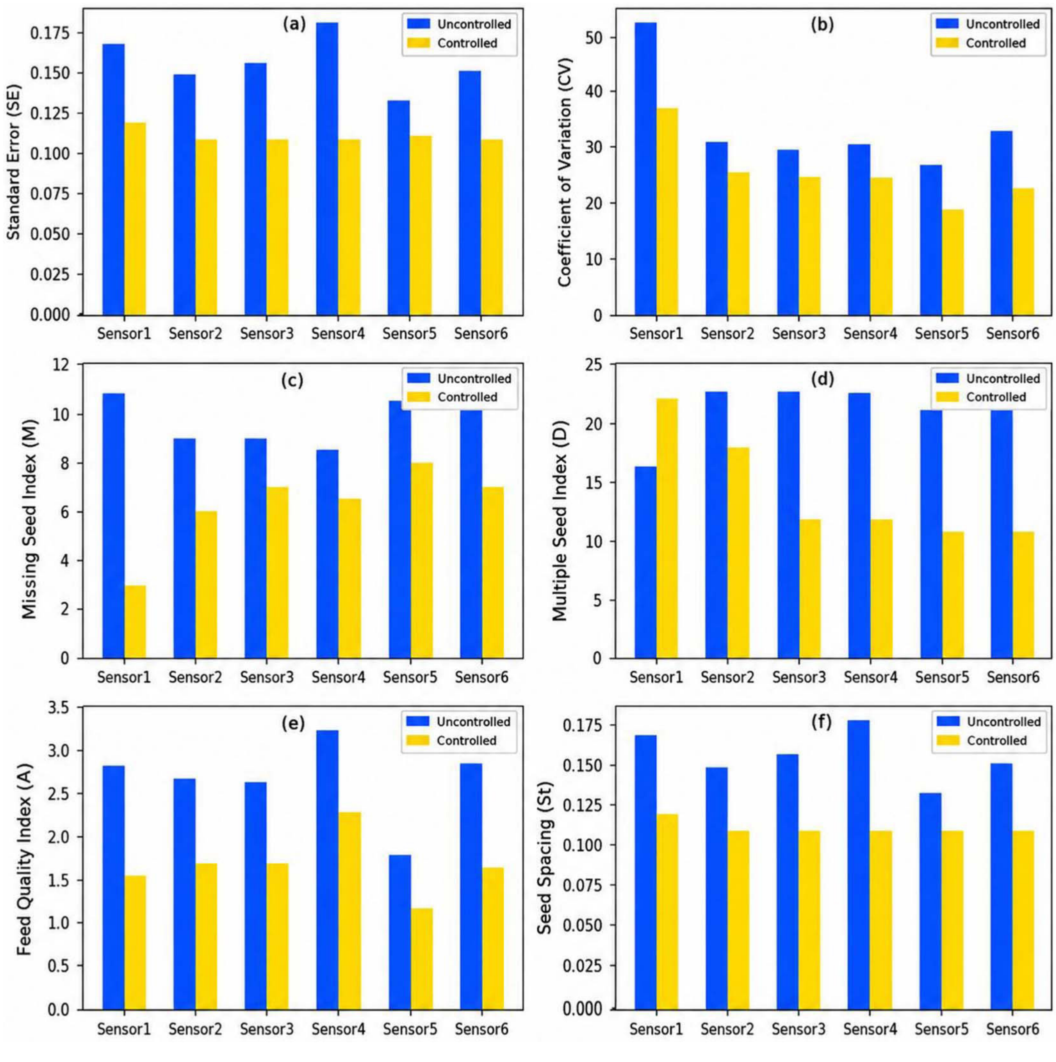

Figure 5. Comparison of seed spacing indicators with and without real-time control: (a) standard error (SE); (b) coefficient of variation (CV); (c) missing seed index (M); (d) multiple seed index (D); (e) feed quality index (A); (f) seed spacing (St)

the integration of the control system, the CV was particularly high, exceeding 50% for some sensors, reflecting irregularities in seeding (Figure 5b). After integrating the control system, the values decreased significantly, indicating greater consistency and precision in seeding. This reduction in CV has also been observed in recent studies, such as that by Zhang et al. (2023), who reported similar improvements in sensor-controlled seeding systems.

The statistical comparison confirmed that the improvements observed after activation of the control system were not only descriptive but also statistically supported. Paired analysis across the six monitored sensors showed a significant reduction in standard error, with a mean decrease of 0.046 and a 95% confidence interval of 0.028 to 0.064 ($p = 0.001$). The coefficient of variation also decreased significantly, with a mean reduction of 8.33 percentage points and a 95% confidence interval of 3.90 to 12.77 percentage points ($p = 0.005$). The missing seed index was reduced by an average of 3.67 points, with a 95% confidence interval of 1.30 to 6.03 points ($p = 0.010$). The feed quality index (A) also improved significantly, with a mean difference of 1.08 and a 95% confidence interval of 0.82 to 1.34 ($p < 0.001$). The reduction in the multiple seed index showed a positive trend, with a mean decrease of 6.42 points, although the confidence interval slightly overlapped zero (95% CI: −0.21 to 13.04; $p = 0.055$). These results indicate that the real-time control system significantly improved seed-spacing regularity and reduced missing events, while the reduction in multiple seeding should be interpreted as a strong tendency rather than a fully significant effect (Table 3). Full numerical results and the analysis code are provided in Supplementary Data S1 and Supplementary Code S1.

The reproducibility analysis further supported the stability of the experimental results. The comparison between the three repetitions showed no significant repetition effect for the coefficient of variation ($p = 0.918$), indicating that the variability observed in the dataset was mainly associated with sowing rate and sensor position rather than uncontrolled repetition-to-repetition fluctuations. The mean relative dispersion of CV between repetitions was 6.21%, ranging from 1.18% to 14.41%, confirming acceptable repeatability under field conditions.

Dynamic regulation: impact on seed distribution across drop tubes

Figure 6 illustrates the significant impact of integrating sensors and a stepper motor, controlled by a continuous adjustment algorithm, on the uniformity of seed distribution within the seed drop tubes of a row planter, with doses varying between 50 and 250 kg/ha. This algorithm adjusts the seeding rate in real-time based on interactions between seed counting sensors and the planter's speed, ensuring precise regulation of the number of seeds planted at each moment.

The peak observed in the probability density curve at 1.3 indicates that the most frequent average deviations are low, suggesting a homogeneous distribution of seeds across the six seed drop tubes for each sampling. The variance of 1.5 reflects moderate dispersion, demonstrating control over fluctuations through the precise adjustment of the stepper motor. This precise control is crucial to avoid variations that could lead to uneven crop growth.

The results obtained are in agreement with the work of Tang et al. (2022) and Jiaze et al. (2022), who also highlighted the importance of integrating sensors and control systems in improving

Table 3. Statistical summary of the effect of the real-time closed-loop control system. Paired t-tests were used for before/after comparisons, and one-way ANOVA was used to evaluate repetition effects

Indicator	Statistical test	Mean difference	95% CI	p-value	Interpretation
Standard error (SE)	Paired t-test	0.046	0.028 to 0.064	p = 0.001	Significant reduction
Coefficient of variation (CV)	Paired t-test	8.33 percentage points	3.90 to 12.77	p = 0.005	Significant reduction
Missing seed index (M)	Paired t-test	3.67 points	1.30 to 6.03	p = 0.010	Significant reduction
Multiple seed index (D)	Paired t-test	6.42 points	-0.21 to 13.04	p = 0.055	Not significant; decreasing tendency
Feed quality index (A)	Paired t-test	1.08	0.82 to 1.34	p < 0.001	Significant improvement
Repetition effect on CV	One-way ANOVA	--	--	p = 0.918	Not significant; acceptable repeatability

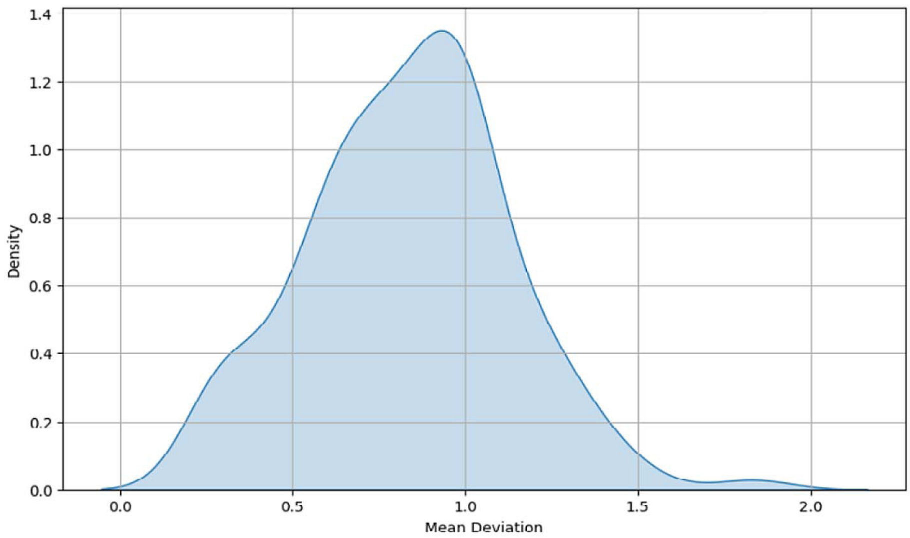

Figure 6. Kernel density of seed distribution across drop tubes as a function of mean deviation, for various seeding rates (50, 100, 150, 200, and 250 kg/ha)

seed distribution and seeding accuracy. These studies emphasize the effectiveness of modern technologies in the dynamic regulation of seeding, ensuring uniform distribution and reducing seeding inconsistencies.

Dynamic regulation: impact on seed spacing

The results presented in Figure 7 demonstrate the control system's effectiveness based on real-time acquisition, simulation, and adjustment. Figure 7 shows that for doses of 50, 100, and 150 kg/ha, the distribution of the number of grains remains stable, with respective medians of approximately 4.5, 7.5, and 9.5 grains. This stability suggests that the dynamic regulation system effectively adjusts the flow rate for these doses, minimizing variations. However, at higher doses of 200 and 250 kg/ha, a slight increase in the variability of the number of grains is observed, with medians of about 12 and 14 grains respectively, indicating slight fluctuations in the flow rate. Despite this variation, the system remains efficient, as the interquartile ranges (IQR) are relatively narrow (around 3 to 4 grains), indicating precise regulation.

These observations align with the findings of Elwakeel et al. (2023), who designed and validated a variable rate dosing mechanism for a high-precision sugarcane transplanter. Their study demonstrated that using a stepper motor allows for adjusting the seed distribution speed according to the travel speed, ensuring high accuracy in dose application.

Additionally, a review by Zhang et al. (2023) highlighted the importance of smart sensors and intelligent data in precision agriculture, emphasizing that the integration of these technologies can improve the accuracy and efficiency of dynamic regulation systems.

Compared to similar systems, the results of this study suggest reliable regulation, with maintained performance even at doses of 250 kg/ha. However, the regulation algorithm could be refined to slightly reduce flow rate variations at higher doses. These findings are consistent with the recommendations of Elwakeel et al. (2023), who proposed improving the stability of regulation systems at higher flow rates by adjusting dynamic control parameters for better accuracy.

Impact of tractor speed on grain distribution using a real-time control system

Figure 8 shows the impact of seeding dose and tractor speed on the total number of grains detected, using a real-time control system for dynamic flow adjustment. The data reveal a proportional increase in the number of grains detected with increasing dose, regardless of speed, which corroborates the findings of Šarauskis et al. (2022) on the efficiency of variable rate seeding systems in ensuring uniform seed distribution. Additionally, the analysis of intermediate speeds (2.5 to 3.0 m/s) shows that the system maintains a stable flow despite speed variations,

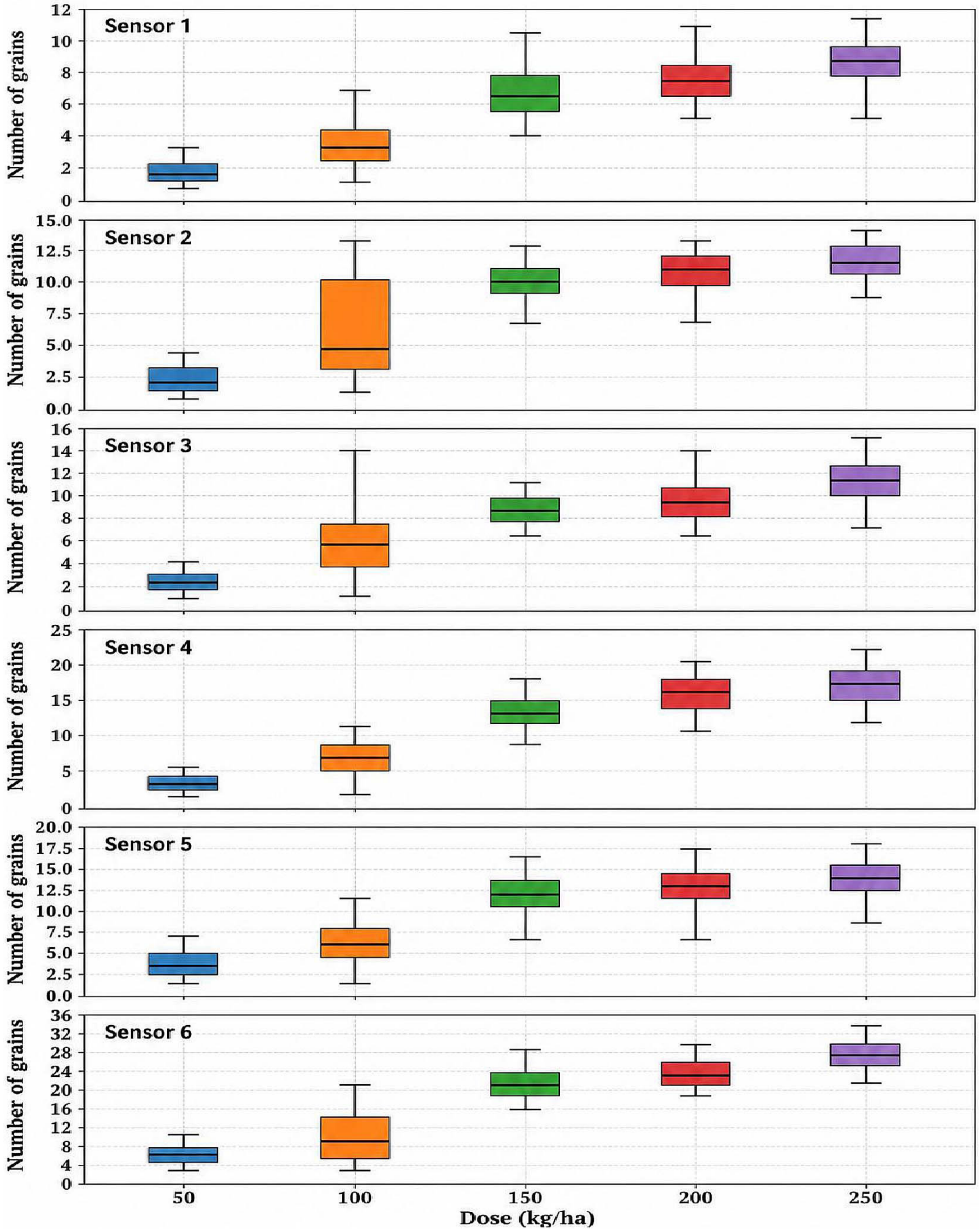

Figure 7. Effect of dynamic regulation on seed spacing for different durum wheat doses

aligning with the results of Zhang et al. (2023) on the importance of adaptive control systems for seeding precision. The system's performance is demonstrated by the low variability in the number of grains for a given dose, even with speed changes, supporting observations on the benefits of precision technologies. However, a slight dispersion of data is noted at high speeds or maximum doses, suggesting potential limitations under extreme conditions, as reported in studies on optimizing seeding flow under various conditions.

DISCUSSION

This study highlights the effectiveness of a simple and cost-effective dynamic control system for improving seed distribution in agriculture. The system allows for the adjustment of seed distribution by comparing the theoretical spacing, based on the target dose, with the actual distance measured by optical sensors. This adaptability ensures a more homogeneous distribution, contributing to better uniformity in crops. The integration of real-time control led

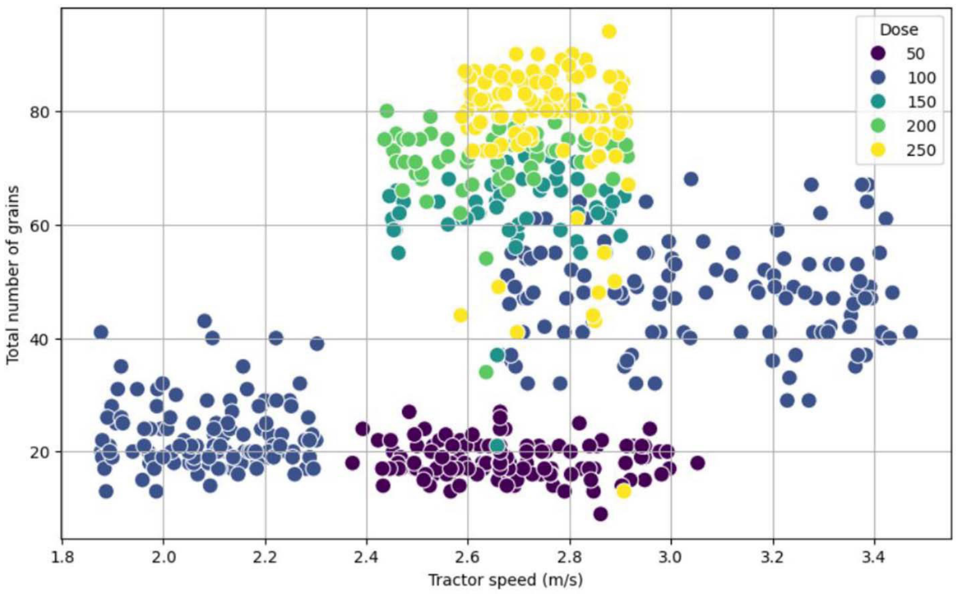

Figure 8. Impact of tractor speed on grain distribution using a real-time control system

to a significant reduction in the standard deviation of seed spacing, from 0.149–0.184 to 0.11, and a decrease in the missing and multiple seed indices. Specifically, the multiple seed index decreased by more than 20% for certain sensors. Dynamic regulation maintained stable median grain numbers for different seed doses, with a slight increase in variability but with precise regulation. Compared to PID control systems and variable rate seeding (VRS) technologies, this solution is simpler, requiring less calibration and technical expertise.

The statistical results strengthen the interpretation of the system performance by showing that the improvements were supported by confidence intervals and p-values rather than only by visual or descriptive comparisons. The significant decreases in standard error, coefficient of variation, and missing seed index confirm that the closed-loop correction was effective in reducing seed-spacing variability under the tested conditions. However, the multiple seed index showed only a near-significant trend, suggesting that the mechanical response of the trapdoor and the inertia of seed flow may still limit the correction of clustered seed events. This point represents an important direction for further tuning of the control parameters, particularly at higher sowing rates and higher tractor speeds.

The main contribution of this work is demonstrating that closed-loop seed spacing control can be achieved using low-cost embedded hardware without sacrificing measurement accuracy or field-level stability compared to more complex VRS and PID-based systems.

Unlike VRS and PID-based systems that rely on pre-defined setpoints or external prescription maps, the proposed approach derives control actions directly from real-time physical measurements of seed deposition, eliminating dependence on external spatial datasets.

Importantly, the system demonstrated robust performance across varying tractor speeds. Despite changes in speed, the control system was able to maintain stable seed distribution, ensuring consistent spacing and improved accuracy. This adaptability to speed variations highlights the system's potential for use in diverse field conditions, making it especially useful for real-time adjustments in areas with fluctuating operating speeds. The system's performance across different speeds was consistent, further supporting its efficiency in practical agricultural settings.

In Tunisia, where farms are often small and fragmented, this system is particularly well-suited as it meets the needs of small-scale mechanization at a low cost. The affordable cost of components, such as the Arduino board and sensors, makes this technology accessible to farmers, even in resource-limited areas. The acceptability of the system is strengthened by its results in terms of seed distribution regularity and the reduction of missing and multiple seed indices. In conclusion, this simple and affordable system could enhance agricultural practices, promote the adoption of more precise seeding technologies, and stimulate innovation and productivity in the agricultural sector. Future research could focus on optimizing this system and adapting it to various agricultural contexts to maximize its benefits.

The observed robustness of the proposed control approach under varying operating speeds is consistent with recent findings emphasizing that adaptive control and real-time feedback mechanisms are critical for maintaining performance stability in agricultural systems exposed to dynamic field conditions (Wuyep et al., 2026).

A limitation of this study is that the validation was conducted during one experimental campaign and on one field site. Although the trials included several sowing rates, six monitored seed tubes, three repetitions, and variable tractor speeds, independent validation under another season, soil moisture condition, or field type would further strengthen the generalization of the results. Therefore, the present findings should be interpreted as a reproducible field validation of the proposed low-cost control architecture under the tested conditions. Future work will include multi-season and multi-site experiments, together with adaptive tuning of the decision thresholds and motor actuation parameters.

Future research should focus on further optimizing the system by incorporating advanced algorithms for real-time seeding adjustments based on environmental parameters such as soil moisture and temperature. Improving the system's responsiveness to field-specific conditions would maximize its benefits for farmers, fostering the transition toward more efficient and sustainable agricultural practices.

CONCLUSIONS

The experimental results indicate that the proposed hypotheses are supported by the findings. The real-time use of seed spacing feedback as a control variable demonstrated measurable improvements in seeding uniformity, while the low-cost embedded architecture was able to maintain stable performance under variable tractor speeds and field conditions.

The study provides a novel contribution by demonstrating that closed-loop seeding correction can be achieved through direct coupling of in-field seed deposition measurements with mechanical flow adjustment, without reliance on prescription maps, external positioning data, or high-cost industrial control platforms. This bridges an important gap between high-precision but expensive variable rate technologies and simplified open-loop mechanical seeders commonly used in resource-limited agricultural systems.

In addition, the results show that real-time correction of seeding errors is feasible using only onboard sensing and actuator feedback, while maintaining acceptable accuracy across a wide range of seeding rates. This confirms the practical viability of a simplified feedback-driven architecture for precision seeding applications.

The study opens new perspectives for the development of scalable, low-cost precision agriculture systems that rely on embedded control rather than external data infrastructure.

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