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## INTEGRATION AND PERFORMANCE EVALUATION OF A VARIABLE RATE SEEDING SYSTEM USING TRIMBLE TECHNOLOGY FOR PRECISION AGRICULTURE

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A variable seed rate system was integrated and evaluated using Trimble technology. Laboratory tests were conducted to assess system performance on a seeder test bench, with seed delivery rates ranging from 180 to 800 seeds per minute. The system was tested using two corn seed plates: a 30-cell Precision Planting plate (PP) and a 40-cell John Deere (JD) plate. The laboratory results showed a cell fill rate of 98.6% for the PP plate and 104.5% for the JD plate. Field performance was evaluated at four sowing densities (100,000; 80,000; 60,000; and 40,000 seeds·ha<sup>-1</sup>) and three travel speeds (6, 8, and 10 km·h<sup>-1</sup>). Results showed no significant differences in dosing uniformity due to sowing density or speed. The system achieved 100% dose uniformity with a coefficient of variation (CV) of just 1.36%, demonstrating high operational reliability. Regarding seed delivery uniformity, an analysis of variance of seed fall timing revealed a significant difference between the plates. The PP plate outperformed the JD plate, with a CV of 10.82% compared to 14.387%, respectively. The system's response time to changes in seeding density ranged from 43 milliseconds (from 100,000 to 80,000 seeds·ha<sup>-1</sup> at 10 km·h<sup>-1</sup>) to 232 milliseconds (from 40,000 to 100,000 seeds·ha<sup>-1</sup> at 6 km·h<sup>-1</sup>). In conclusion, the integrated variable seed rate system demonstrated high operational reliability. However, an average variability of 12.5% in planter performance was observed, highlighting an opportunity for further optimisation and system improvement.

**Keywords:** variable rate seeding; precision agriculture; Trimble technology; seed delivery uniformity; planter performance

Precision Agriculture (PA), also known as site-specific management, is an agricultural production system that integrates a wide range of technologies, from the Global Positioning System (GPS) to specialised automation and control systems, complemented by the use of geographic information systems, data management, and agricultural equipment for various activities. These include monitoring crop development using drones, as well as harvesting, land preparation, seeding, fertilisation, and the application of agrochemicals (He et al., 2019b).

Various authors (Souza et al., 2025; Clarke et al., 2024; He et al., 2019a; Mattetti et al., 2021; Bazzi et al., 2015; Yang et al., 2015) propose a sequence for the application of PA technology that begins with the creation of yield maps at the site-specific level, followed by an analysis of yield variability and the development of diagnostic maps. These maps help identify the chemical, physical, biological, and topographic factors underlying such variability. The analysis and interpretation of these diagnostic maps facilitate the generation of prescription maps, whose objective is to address limiting factors in the short, medium, and long term. These factors include salinity, compaction, soil fertility, and soil depth issues, which restrict productive potential and generate variability in crop yields (López-Castañeda et al., 2022; Campos Magaña et al., 2015).

Identifying and interpreting these factors allows for the definition of specific sites and the application of differentiated management, such as variable rates of seeds and fertilisers, as well as the selective application of agrochemicals (Bhagwan et al., 2025; Videgain et al., 2024).

Globally, various companies have developed technologies for yield monitoring, such as harvesters equipped with yield flow sensors and yield monitors (Getahun et al., 2024), which enable the identification of areas with yield variability. Drones with multispectral cameras are also used (Zhang et al., 2025; Camenzind and Yu, 2024) to identify yield variability through the Normalised Difference Vegetation Index (NDVI), as well as to detect and locate pests and diseases.

To meet the need for variable-rate seeding systems, manufacturers such as Trimble and John Deere (Šarauskis et al., 2022; Ding et al., 2023), among others, have developed integrated solutions. These systems combine yield maps, diagnostic maps, prescription maps, precision planters, control screens, variable-rate specific software, geographic information systems, and hydraulic motors with oil flow control to regulate rotation speed based on prescribed seeding densities (He et al., 2019a).

The purpose of this research was to determine the operation of a variable-rate seeding system, integrating equipment components and software to perform variable seeding based on prescription maps. In addition, the system's performance was evaluated in terms of cell fill percentage, dosing uniformity coefficient of variation, percentage of empty cells, and the system's response to prescription changes (Zolotukhin et al., 2025; He et al., 2019a, 2019b; Torres-Sandoval et al., 2020).

## Material and Methods

The equipment used for laboratory evaluation is located at the Agricultural Mechanisation Department of the Antonio Narro Autonomous Agricultural University. It consists of a test bench for single-seed planters, equipped with a Mitsubishi variable frequency drive (FREQROL-A200), which allows adjustment of the seed delivery rate to the selected evaluation rates (180, 520, 650, and 800 seeds·min<sup>-1</sup>). The bench includes a chain and gear transmission system to couple a 1.5 kW three-phase electric motor to the main shaft of the planter (Fig. 1).

For dosing control, the test bench features an automated system for selecting seed rates using a National Instruments data acquisition board (PC-NI-6221) with two logging ports and twelve control ports, installed in a computer. The control software, developed using virtual instruments in the LabVIEW 2009 environment by National Instruments, allows the control of seed quantity recording and drop times, in addition to storing data in .txt files.

The records of actual and expected (ideal) seed discharge times are used to calculate the cell fill percentage (%) using the following formula: (ideal seeds/actual seeds) × 100.

This calculation is performed for each selected seed rate. The dosing uniformity for each treatment (seed plate-seeding speed-seeding density) is determined by calculating the average seed drop time and its standard deviation to obtain the coefficient of variation for the total number of seeds in each subplot.

The experimental design used to evaluate the cell fill percentage in the laboratory was a Randomised Complete Block Design with Split Plot (RCBD-SP), with five replications (Cheng et al., 2021; Zhao et al., 2016). The main plot corresponded to the two metering plates evaluated (John Deere (JD) with 40 cells and Precision Planting (PP) with 30 cells, both for corn), while the subplot consisted of four seed rates per minute.

The analysis of variance (ANOVA) and Tukey's mean comparison tests ( $\alpha \leq 0.05$ ) were conducted to analyse interactions. Additionally, an orthogonal contrast was performed. For these statistical analyses, the software Minitab V19 and InfoStat V2020e were used.

To generate the variable-rate seeding prescription maps, the perimeter of the plot was delineated using the FmX control display and Survey software from Trimble. This survey was carried out with an RTK (Real-Time Kinematics) positioning correction system (Trimble, with a signal range of 2 km and a maximum accumulated positioning error of 2.5 cm). The georeferenced boundary maps of the experimental plot were exported from the control display as multiplane files with a .txt extension.

For the editing of boundary maps and the creation of prescription maps, Trimble's Farmer Basic 2018 software was used. The multiplane.txt file, which contained the corresponding coordinates (Master Bench Point), was uploaded to reconstruct the georeferenced plot. Then, the prescription maps were created for large plots measuring 88 × 64 m, each subdivided into six medium plots of 88 × 11 m, and each medium plot further divided into four small plots of 22 × 11 m. Within each small plot, four seeding densities were randomly assigned, with six replications.

Once edited, the prescription maps were exported in SHP, SHX, and DBF formats, which are required for communication between the FmX control display and the variable-rate equipment, for subsequent upload to the control display.

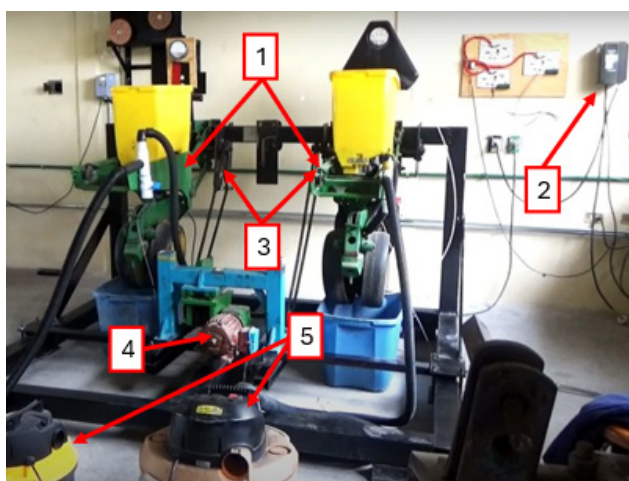
For field evaluation of the cell-filling percentage (%), the dose uniformity variation coefficient (CV<sub>ud</sub>), and the percentages of double seeds and lost cells (following the rules and methodologies of the NMX-O-222-SCFI-2004 standard and other research they have evaluated, Dong et al., 2025; Pandoo et al., 2025; Jiang et al., 2024; Torres-Sandoval et al., 2020; Quanwei et al., 2017; Yang et al., 2015), six prescription maps were generated using the Farmer Basic 2018V software.

Data for both:

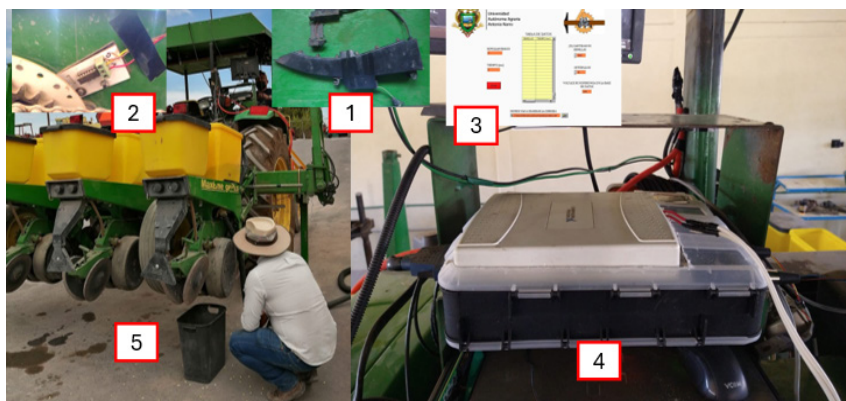
1. actual seeds detected by the optoelectronic sensor;
2. expected seeds recorded by the Hall-effect sensor were collected using the same data acquisition system (PC-NI-6221).

This setup included a National Instruments card and software based on virtual instrumentation. Optoelectronic seed drop sensors (H21A1) and a Hall-effect sensor (SS49E by SEC Electronics Inc.) were used for seed detection, as shown in Fig. 2.

The experimental design used to evaluate field results in terms of cell fill percentage and dosing uniformity was a Randomised Complete Block Design with Split-Split Plots. The main plot corresponded to the two seed metering plates (JD with 40 cells and PP with 30 cells, both for



**Fig. 1** Seed drill test bench  
1 – planter hopper; 2 – mitsubishi variable frequency drive;  
3 – gear transmission system; 4 – electric motor; 5 – seed quantity recording and drop times



**Fig. 2** Data collection in the field  
1 – optoelectronic sensor; 2 – hall-effect sensor; 3 – software; 4 – national Instrument card; 5 – precision planter model 1700

maize). The sub-plot consisted of three seeding speeds (6, 8, and 10 km·h<sup>-1</sup>), and the sub-sub-plot included four seeding densities (100,000, 80,000, 60,000, and 40,000 seeds·ha<sup>-1</sup>). The factorial design was 2 × 3 × 4 with six replications, implemented using a John Deere precision planter model 1700 set at an inter-row spacing of 0.80 m, as shown in Fig. 2.

The ANOVA and Tukey's mean comparison tests ( $\alpha \leq 0.05$ ) were performed, along with orthogonal contrasts to analyse interactions. As with the laboratory analysis, Minitab V19 and InfoStat V2020e software were used for the statistical analyses.

The variable-rate seeding system used in the field evaluation consisted of a John Deere 1700 four-row precision planter, equipped with a Rawson hydraulic motor (model 300499) and an electronic communication module (reference 75070-00). The interconnection between the hydraulic motor, the FmX control display, and the Field IQ system (model 75050-01 from Trimble) was established using specific harnesses (references 66694, 67258, 76941, 77368, 75528-XX, and 75527).

Variable-rate control was managed using specialised Trimble software, while prescription map editing was performed with Farmer Basic software (version 2017.02.0009). Additionally, the system included an RTK antenna (model 96305 AgGPS, frequency 410–470 MHz) to ensure precise positioning correction of the tractor within the plot.

## Results and Discussion

### Flowchart of the integrated system and variable-rate methodology

Figure 3 presents the flowchart of the Integrated System, beginning with the topographic survey of the field perimeter using the RTK positioning correction antenna, and continuing with the use of the FmX control display and its applications: Survey, Field IQ, and variable-rate control.

A map of the plot perimeter was created, generating multiplane.txt data files, which were downloaded and edited using Trimble Ag software to obtain the prescription maps with the desired seeding densities. After editing and generating the SHP, SHX,

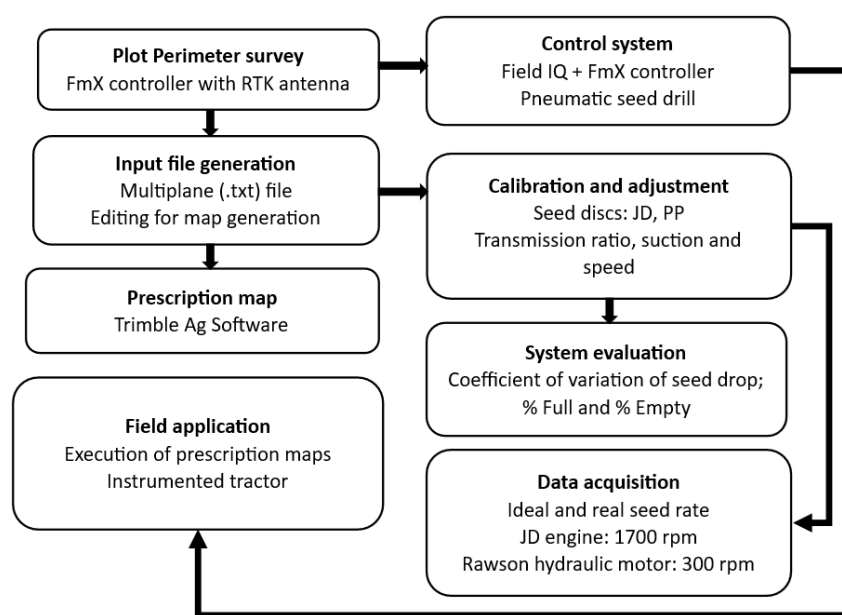
and DBF files, these were uploaded to the FmX control display. Using the Field IQ application, the system was statically calibrated at 300 rpm for the Rawson hydraulic motor and 1700 rpm for the tractor during seeding, using a pneumatic precision planter.

The transmission ratio of the planter was adjusted to achieve the required seeding densities, and the vacuum level was set according to the manufacturer's recommendations (13 inches of water for JD and 15 inches for PP). Once adjustments and static calibration were completed, the prescription was applied in the experimental plot at the selected speeds.

Before starting, the proper functioning of the data acquisition system was verified through preliminary test recordings. The data for ideal and actual seeds from each plot were recorded in .txt files, following the experimental design, for subsequent analysis in terms of coefficient of variation of drop times, cell fill percentage, percentage of double seeds, and percentage of empty cells.

### Laboratory evaluation of the performance of two seed metering plates at four seed delivery speeds

The ANOVA showed significant differences in the performance of the two seed metering plates at



**Fig. 3** Flowchart of the integrated system for variable-rate seed application

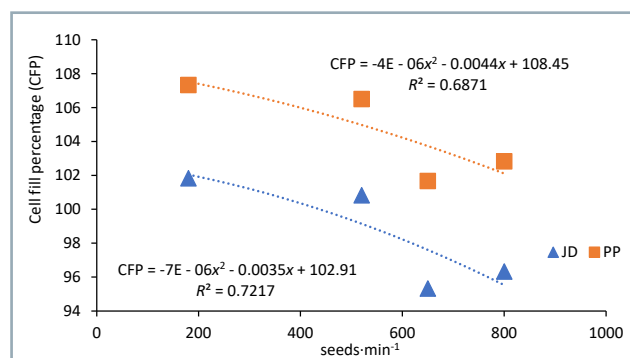
**Table 1** Mean cell fill percentage for two seed metering plates, JD and PP, under laboratory conditions, based on seed delivery rate (seeds·min<sup>-1</sup>)

| SDR (seeds·min <sup>-1</sup> ) | SP            |         |               |         |
|--------------------------------|---------------|---------|---------------|---------|
|                                | JD            |         | PP            |         |
|                                | mean          | SE mean | mean          | SE mean |
| 180                            | 107.33 ±1.97A | 0.803   | 101.83 ±3.06A | 1.25    |
| 520                            | 106.5 ±3.94A  | 1.61    | 100.83 ±3.19A | 1.30    |
| 650                            | 101.67 ±1.03B | 0.422   | 95.33 ±4.32B  | 1.76    |
| 800                            | 102.83 ±1.94B | 0.792   | 96.33 ±4.97B  | 2.03    |

\* SP – seed plate; SDR – seed delivery rate; PP – precision planting; JD – John Deere; SE – standard error; A and B – means with a common letter are not significantly different ( $p > 0.05$ )

the four evaluated seed delivery speeds. The mean cell fill rates were 95.33% for PP and 107.33% for JD (Table 1). These values represent deviations of 1.39% and 1.97% from the ideal fill rate (100%), respectively, with both remaining within the 5% margin of error established by the NMX-O-221-SCFI-2004 standard for pneumatic precision planters.

Figure 4 shows the response curves for the cell fill percentage for the evaluated seed metering plates. Although both exhibit similar behavioural trends, the analysis of variance indicates that there are significant differences between 180–520 and 650–800. The mean fill rates were  $96.33 \pm 4.97\%$  for the JD plate and  $106.5 \pm 3.94\%$  for the PP plate, as shown in Table 1. The data visualisation includes the equations that describe the behaviour of both plates, highlighting that the cell fill percentage tends to decrease as the seed delivery rate increases.

**Fig. 4** The behaviour of seed metering plates across different seed delivery rate ranges (seeds·min<sup>-1</sup>)

Additionally, Table 1 shows that the fill percentage for the PP plate decreases from  $101.83 \pm 3.06\%$  to  $96.33 \pm 4.97\%$  in the seed delivery speed range from 180 to 800 seeds·min<sup>-1</sup>. In contrast, the JD 40-cell plate shows a decrease from  $107.33 \pm 1.97\%$  to  $102.83 \pm 1.94\%$  in the same range of speeds.

### Field evaluation

The field evaluation of the Trimble variable-rate seed system was structured in two phases. The first phase evaluated the system's reliability by measuring the coefficient of variation between the observed and expected records while varying the seeding density and speed. This was done using the ideal seed sensor directly connected to the metering system and prescription maps with four

densities. The second phase employed two seed metering plates (JD 40-cell and PP (720003) 30-cell) with the same prescription maps, varying the seeding rate from 100,000 to 40,000 seeds·ha<sup>-1</sup> in increments of 20,000, at three different seeding speeds 6; 8; and 10 km·h<sup>-1</sup>.

The ANOVA for the records of the ideal seed drop sensor, in response to changes in seeding density and speed defined by the Farmer Basic prescription maps loaded into the FmX display, showed  $p$ -values greater than 0.05 for both variables. This indicates that no significant differences were found in the sensor records due to variations in density and speed, suggesting a high reliability of the Trimble Integrated Variable-Rate Seed System used in this study.

The ANOVA for the coefficient of variation in the cell fill percentage for each evaluated plate at different seeding speeds and densities, as well as the  $p$ -value for the interactions between plate-seeding speed and plate-seeding density, indicated significant differences in these interactions. Table 2 presents the multiple comparisons, showing a significant difference only in the speed-plate interaction for the JD plate at 6 km·h<sup>-1</sup>, where the percentage of double seeds rose to 117%, compared to 100.13% at other speeds. Table 3 illustrates the density-plate interaction, where the JD plate at densities below 60,000 seeds·ha<sup>-1</sup> showed an increase in double seeds to over 110%. In contrast, other plate-density interactions resulted in percentages ranging between 97% and 103%. The ANOVA for the coefficients of variation in the cell fill percentage for each plate evaluated at different speeds and densities yielded significant  $p$ -values for the plate-speed and plate-density interactions, indicating that the effect of the plate type on cell fill depends on both the seeding speed and density.

The mean comparison for the interaction between plate and speed (Table 2) reveals a significant difference only for the JD plate at a speed of 6 km·h<sup>-1</sup>, where the cell fill percentage reaches an average of  $117.69 \pm 5.89\%$  (group 'A'). This value is considerably higher than the average of approximately  $100.53 \pm 5.82\%$  observed for the other plate-speed combinations (group 'B'), suggesting a marked tendency for double seeding with the JD plate at this specific speed.

Regarding the interaction between density and plate (Table 3 and Fig. 4), the results reveal an interesting pattern. The JD plate exhibits significantly higher cell fill percentages (group 'A') at seeding densities below 60,000 seeds·ha<sup>-1</sup>, reaching an average of  $112 \pm 10.29\%$  at 40,000 seeds·ha<sup>-1</sup> and  $108.42 \pm 14.17\%$  at 60,000 seeds·ha<sup>-1</sup>. These values contrast

**Table 2** Mean contrast of cell fill percentage for the plate versus seeding speed interaction

| SP (seeds·min <sup>-1</sup> ) | Cell fill percentage |         |                |         |
|-------------------------------|----------------------|---------|----------------|---------|
|                               | PP                   |         | JD             |         |
|                               | mean                 | SE mean | mean           | SE mean |
| 6                             | 101.25 ±3.83B        | 0.677   | 117.69 ±5.89A  | 1.04    |
| 8                             | 100.53 ±5.82B        | 1.03    | 101.63 ±12.33B | 2.18    |
| 10                            | 97.031 ±5.492B       | 0.971   | 98.5 ±10.29B   | 1.82    |

\* SP: Seed plate; PP: Precision planting; JD: Jonh Deere; SE: Standard error; A and B: Means with a common letter are not significantly different ( $p > 0.05$ )

**Table 3** Mean contrast of cell fill percentage for the plate versus seeding density interaction

| SDT | Cell fill percentage |         |                 |         |
|-----|----------------------|---------|-----------------|---------|
|     | PP                   |         | JD              |         |
|     | mean                 | SE mean | mean            | SE mean |
| 40  | 99.92 ±5.83CD        | 1.19    | 112 ±10.29AB    | 2.1     |
| 60  | 100.92 ±5.65CD       | 1.15    | 108.42 ±14.17A  | 2.89    |
| 80  | 100.33 ±4.76CD       | 0.972   | 103.71 ±12.71BC | 2.59    |
| 100 | 97.25 ±4.839D        | 0.988   | 99.63 ±11.39CD  | 2.32    |

\* SDT – seeding density in thousands; PP – precision planting; JD – Jonh Deere; SE – standard error; A, B, C and D – means with a common letter are not significantly different ( $p > 0.05$ )

**Table 4** Mean contrast of the coefficient of variation for seed drop times of the PP and JD plates

| Plate | VSDT           |         |
|-------|----------------|---------|
|       | mean           | SE mean |
| PP    | 10.82 ±5.73B   | 0.585   |
| JD    | 14.387 ±7.508A | 0.766   |

\* VSDT – variation for seed drop times; PP – precision planting; JD – Jonh Deere; SE – standard error; A and B – means with a common letter are not significantly different ( $p > 0.05$ )

with the cell fill range for the PP plate, which generally falls between  $97.25 \pm 4.839\%$  and  $100.92 \pm 5.65\%$  for all evaluated densities (mainly group 'D' and 'CD'), and also for the JD plate at higher densities (40,000 and 60,000 seeds·ha<sup>-1</sup>, groups 'AB' and 'A', respectively). Figure 3 clearly visualises this trend, showing how the JD plate curve significantly rises at lower densities compared to the PP plate curve.

Figure 5 illustrates the interaction between seeding type and density on the percentage of cell fill. A general trend is observed where cell fill percentage decreases as seeding

density increases for both plate types; however, a notable difference between the plates remains. The PP plate shows a cell fill range approximately between  $97.25 \pm 4.839\%$  and  $100.92 \pm 5.65\%$ . In contrast, the JD plate displays a wider range, from around  $99.63 \pm 11.39\%$  up to a maximum near  $112 \pm 10.29\%$ . This higher fill percentage for the JD plate, particularly at lower seeding densities, suggests a greater incidence of double seeding under these conditions.

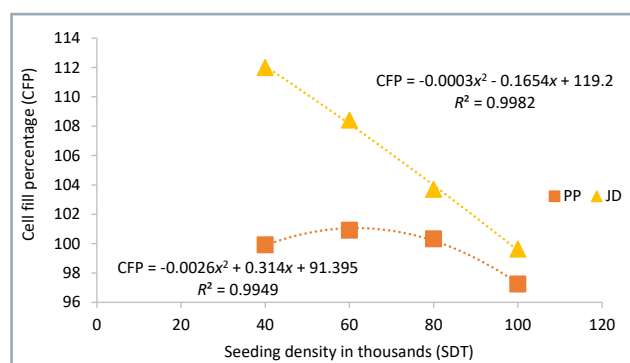
The ANOVA of seed drop times revealed a significant difference in plate performance ( $P$ -value  $< 0.05$ ). The PP plate demonstrated superior performance, with a coefficient of variation (CV) of  $10.82 \pm 5.73\%$ , compared to  $14.38 \pm 7.51\%$  for the JD plate (Table 4). This higher uniformity in seed release from the PP plate suggests improved seed spacing uniformity under field conditions.

The ANOVA did not detect any significant differences in the plate-density ( $P$ -value = 0.339) and plate-seeding speed interactions ( $P$ -value = 0.521), suggesting that the type of plate used has a more pronounced effect on the uniformity of seed release than the variation in seeding density or speed.

From above, the PP plate demonstrated better consistency in seed drop times, which is crucial for ensuring uniformity in the seeding process and spacing between seeds.

The percentage of empty cells did not show a significant difference ( $P$ -value  $> 0.05$ ) in the interaction for the JD plate at a density of 60,000 seeds·ha<sup>-1</sup> ( $12.179 \pm 4.851\%$ ), according to the multiple comparison of means. This value was notably higher than the  $9.784 \pm 4.612\%$  average recorded for the PP plate across the full range of seeding densities. On the other hand, the significant differences ( $P$ -value  $< 0.05$ ) were detected in the interaction between the plates and the seeding speeds (Table 5).

The ANOVA revealed significant differences in the percentage of double cells for both the plate-speed

**Fig. 5** Mean contrast of cell fill percentage for the plate vs seeding density interaction

**Table 5** Mean contrast of the percentage of empty cells for the plate vs seeding density interaction

| SP<br>(seeds·min <sup>-1</sup> ) | EC              |         |                 |         |
|----------------------------------|-----------------|---------|-----------------|---------|
|                                  | PP              |         | JD              |         |
|                                  | mean            | SE mean | mean            | SE mean |
| 6                                | 7.275 ±3.243C   | 0.573   | 8.548 ±2.729C   | 0.482   |
| 8                                | 11.821 ±3.633B  | 0.642   | 11.954 ±4.459AB | 0.788   |
| 10                               | 12.501 ±3.324AB | 0.588   | 14.4 ±2.988A    | 0.528   |

\* EC – empty cell; SP – seed plate; PP – precision planting; JD – John Deere; SE – standard error; A, B and C – means with a common letter are not significantly different ( $p > 0.05$ )

**Table 6** Mean contrast of the percentage of double cells for the plate vs seeding speed interaction

| SP<br>(seeds·min <sup>-1</sup> ) | DC              |         |                |         |
|----------------------------------|-----------------|---------|----------------|---------|
|                                  | PP              |         | JD             |         |
|                                  | mean            | SE mean | mean           | SE mean |
| 6                                | 7.888 ±4.337BC  | 0.767   | 5.624 ±2.673C  | 0.473   |
| 8                                | 10.392 ±3.767A  | 0.666   | 8.972 ±3.669AB | 0.649   |
| 10                               | 10.145 ±2.455AB | 0.434   | 11.138 ±3.08A  | 0.544   |

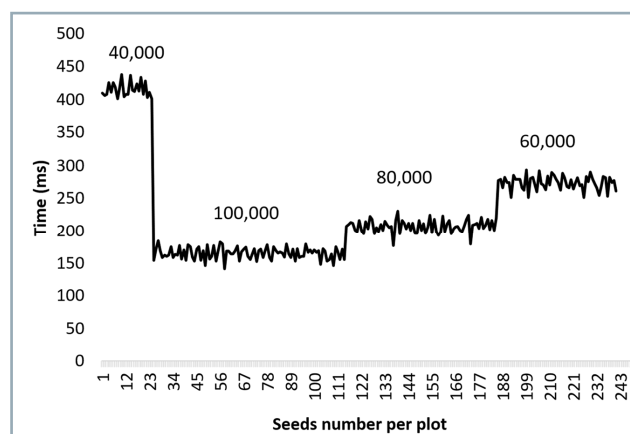
\* DC – double cells; SP – seed plate; PP – precision planting; JD – John Deere; SE – standard error; A, B and C – means with a common letter are not significantly different ( $p > 0.05$ )

**Table 7** Mean contrast of the percentage of double cells for the plate vs seeding density interaction

| SDT | DC             |         |                |         |
|-----|----------------|---------|----------------|---------|
|     | PP             |         | JD             |         |
|     | mean           | SE mean | mean           | SE mean |
| 40  | 11.145 ±4.181A | 0.853   | 8.522 ±3.541AB | 0.723   |
| 60  | 7.882 ±3.292B  | 0.672   | 8.818 ±3.912AB | 0.799   |
| 80  | 10.366 ±3.253A | 0.664   | 8.086 ±3.82B   | 0.78    |
| 100 | 8.508 ±3.411AB | 0.696   | 8.885 ±4.38AB  | 0.894   |

\* SDT – seeding density in thousands; DC – double cells; PP – precision planting; JD – John Deere; SE – standard error; A, B, C and D – means with a common letter are not significantly different ( $p > 0.05$ )

( $P$ -value = 0.020) interaction and the plate-density interaction ( $P$ -value = 0.017). In the plate-speed interaction (Table 6), the percentage of double seeds increased from an average of 5.624 ±2.673% to 11.138 ±3.08% as the speed increased from 6 to 10 km·h<sup>-1</sup> for JD and 7.888 ±4.337% to 10.145 ±2.455% for PP.

**Fig. 6** Response time (ms) of the variable-rate system to density changes at 6 km·h<sup>-1</sup> (PP plate)

Regarding the plate-density interaction (Table 7), the percentage of double seeds increased from 7.882 ±3.292% to 11.145 ±4.181% only for the PP plate when the density was reduced from 60,000 to 40,000 seeds·ha<sup>-1</sup>. In contrast to the results of Torres-Sandoval et al. (2020) who obtained feeding quality indices >90%, seed loss and double seeds <6%, and precision <18% in a variable-rate system, the differences observed in Table 1 suggest that the performance of the metering plates evaluated was a more influential factor than the variable-rate system itself.

Figure 6 illustrates the response of the variable-rate system (PP plate) to sequential changes in seeding density across a 21.80-meter field. Four distinct blocks corresponding to the prescribed densities of 40,000, 100,000, 80,000, and 60,000 seeds·ha<sup>-1</sup> are clearly identified. The seed-to-seed interval graph shows rapid transitions in response to these density changes, with adjustment times ranging from 43 ms (for the transition from 100,000 to 80,000 seeds·ha<sup>-1</sup> at 10 km·h<sup>-1</sup>) to 232 ms (for the transition from 40,000 to 100,000 seeds·ha<sup>-1</sup> at 6 km·h<sup>-1</sup>).

The records from the seed sensor did not exhibit any substantial variations across different densities or speeds, indicating that the integrated variable-rate seeding system – based on RTK and the FmX monitor – operates with

high reliability. These results are consistent with previous research indicating that electronic and hydraulic variable-rate systems are highly accurate when properly calibrated (Büdi et al., 2025; Šarauskiš et al., 2022; Pedersen & Lind, 2017). This confirms that the control system responded appropriately to real-time requirements. Furthermore, its suitability for precision agriculture applications is supported by its rapid response to sequential density changes (43–232 ms).

Ultimately, the findings suggest that the dosing plate type was the primary factor influencing final sowing quality. The JD plate exhibited a higher cell-filling percentage, particularly at low speeds and densities, which indicates a higher occurrence of double seeds. Conversely, the PP plate demonstrated lower variability in seed drop times and greater overall stability. This behaviour aligns with results reported by Virk et al. (2020) and Olomitutu et al. (2025), who noted that spacing uniformity and the reduction of double seeds depend more significantly on the design of the dosing device than on the control system. In conclusion, while variable-rate technology proved to be dependable, achieving optimal seeding uniformity and efficiency requires the selection of an appropriate dosing plate.

### Conclusion

This comparative study investigated the performance of PP and JD seed-metering plates using a Trimble variable-rate system under controlled laboratory and field conditions. Laboratory analyses revealed significant differences in cell-fill percentage between the plates across varying seed delivery speeds. While both remained within the standard error margin, the JD plate consistently exhibited a tendency toward a higher average fill. Initial field evaluations demonstrated the high reliability of the Trimble variable-rate system in accurately delivering prescribed seeding rates.

However, an in-depth analysis of the interactions between metering-plate type and crucial operational variables, such as seeding speed and density, unveiled complex, plate-specific behaviour patterns. Notably, the JD plate displayed a greater propensity for double-seeding, particularly under lower-speed and reduced-density scenarios, which has direct implications for seedling emergence uniformity. Conversely, the PP plate demonstrated superior uniformity in seed drop times, as indicated by a lower coefficient of variation, suggesting potential for improved in-furrow spacing.

Furthermore, the study identified a significant difference in the percentage of empty cells between the plates, with the JD plate exhibiting a higher incidence at a specific seeding density (60,000 seeds·ha<sup>-1</sup>), highlighting the operational sensitivity of its performance. The incidence of double seeds was also influenced by seeding speed in both plate types and by seeding density in the PP plate. The observed differences in seeding quality compared to existing literature suggest that the intrinsic performance characteristics of the evaluated metering plates had a more substantial impact on the results than the capabilities of the variable-rate system itself. The variable-rate system, when used with the PP plate, demonstrated a rapid response capability to changes in prescribed seeding density, with adjustment times ranging from 43 ms to 232 ms depending

on the magnitude of the change and the seeding speed. These findings underscore the critical importance of selecting the appropriate metering plate to optimise seeding precision across diverse operating conditions.

This study evaluated only two metering-plate types (Precision Planting and John Deere), limiting the generalisability of results to other designs. Tests were conducted under controlled conditions, which may not fully capture field variability such as soil types, residue levels, or weather. The focus was on seeding speed and density, overlooking other factors like vacuum pressure, seed type, and component wear. Key performance metrics included cell-fill percentage, coefficient of variation in seed drop, and percentages of double seeds and empty cells, but agronomic outcomes like seedling emergence, spacing uniformity, and yield were not assessed. Future research should explore a wider range of plates, operational variables, and field conditions. Long-term studies could evaluate durability and consistency. Predictive models based on collected data could guide plate and parameter selection. Integration with other precision-agriculture tools may enhance overall planting precision and crop performance.

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