

**GIOVANI PRATES BISSO DAMBROZ**

**DEVELOPMENT OF A LOW-COST MULTI-HYBRID VARIABLE RATE SYSTEM  
FOR HORIZONTAL DISK PLANTER**

Dissertation submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

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Francisco de Assis de Carvalho Pinto  
Adviser

*This dissertation is dedicated to my parents Tereza Cristina and Paulo Roberto.*

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*God said, "I need somebody strong enough to clear trees and heave bails, yet gentle enough to tame lambs and wean pigs and tend the pink-combed pullets, who will stop his mower for an hour to splint the broken leg of a meadow lark. It had to be somebody who'd plow deep and straight and not cut corners. Somebody to seed, weed, feed, breed and rake and disc and plow and plant and tie the fleece and strain the milk and replenish the self-feeder and finish a hard week's work with a five-mile drive to church. Somebody who'd bale a family together with the soft strong bonds of sharing, who would laugh and then sigh, and then reply, with smiling eyes, when his son says he wants to spend his life 'doing what dad does'." So God made a farmer.*

(Paul Harvey)

# ABSTRACT

DAMBROZ, Giovani Prates Bisso, M.Sc., Universidade Federal de Viçosa, March, 2023. **Development of a low-cost multi-hybrid variable rate system for horizontal disk planter.** Adviser: Francisco de Assis de Carvalho Pinto. Co-advisers: Andre Luiz de Freitas Coelho, Daniel Marçal de Queiroz, Nerilson Terra Santos and Renato Adriane Alves Ruas.

Food security and the environmental issues are two main challenges of modern times. Due to the economic growth of societies, there is an increase of meat consumption. As a result, demand of feed for livestock is drastically increasing. Plant breeding, fertilizer technology, soil biology, and precision agriculture are some of the areas that could contribute to the improvement of agricultural output efficiency, which is imperative. Seeding operations can become more efficient by using precision agriculture technologies such as variable rate seeding and multi-hybrid seeding. However, there are currently no technologies for multi-hybrid seeding compatible with horizontal disk seed meters, which are vastly used in emerging countries. This study aims to develop a low-cost, electric-driven multi-hybrid variable rate system for row crop planters equipped with horizontal disk seed meters, and to compare the developed system's planting performance with that of a ground-wheel-driven seed meter. The multi-hybrid system was developed based on a product design methodology. A prototype of the system was manufactured in PETG using a desktop 3D printer. The multi-hybrid system has three working positions - open for seed type A, open for seed type B, and closed - operated by a servomotor. The controller is composed of a single-board computer and other electronic components, and operates the multi-hybrid system and an electric-driven horizontal disk seed meter in fixed or prescription map-based variable rate. Total cost of the electric-driven multi-hybrid variable rate seed meter (MVSM) was under USD400. Four experiments were conducted to evaluate the MVSM. The first compared the MVSM with a factory-built, ground-wheel driven seed meter (GWSM) at three seeding rates (3, 3.5, and 4.1 seeds per meter) in terms of planting performance. The second compared the planting performance of four positions of the MVSM - open A, B, and closed A, B - at three seeding rates. The third evaluated the transition distance from one seed type to the other at three seeding rates. The fourth evaluated the planting performance of the developed electric-driven variable rate seed meter without the multi-hybrid system (VSM) at three seeding rates. All experiments were conducted at  $4 \text{ km}\cdot\text{h}^{-1}$  with corn seed. Data from the first and fourth experiments show a tendency of decrease in planting performance as seeding rate increased across all systems tested and a higher disper-

sion of seed spacing distribution produced by the MVSM. The GWSM outperforms the MVSM in terms of planting performance. An increase in seeding rate negatively affects planting performance regardless of the system. The open B and closed B positions of the MVSM have the lowest planting performance. An increase in seeding rate negatively affects planting performance regardless of the position. The switch between seed types B to A produces mean transition distances under seven meters. Seed type switching from A to B is unsatisfactory. The multi-hybrid system negatively affects the electric-driven seed meter's performance at all seeding rates. Although seed type switching needs improvement, the MVSM could potentially replace the GWSM with the advantage of on-the-go seeding rate adjustment.

Keywords: Multi-hybrid. Variable rate seeding. Seed spacing.

## RESUMO

DAMBROZ, Giovani Prates Bisso, M.Sc., Universidade Federal de Viçosa, março de 2023. **Development of a low-cost multi-hybrid variable rate system for horizontal disk planter.** Orientador: Francisco de Assis de Carvalho Pinto. Coorientadores: Andre Luiz de Freitas Coelho, Daniel Marçal de Queiroz, Nerilson Terra Santos e Renato Adriane Alves Ruas.

A segurança alimentar e a questão ambiental são dois grandes desafios dos tempos atuais. Devido ao desenvolvimento econômico das sociedades, há um aumento no consumo de carne. Como resultado, há um aumento drástico na demanda de alimentos para os rebanhos. O melhoramento genético, a tecnologia de fertilizantes, a biologia do solo e a agricultura de precisão são algumas das áreas que podem contribuir para o aumento da eficiência de produção agrícola, que é essencial. As operações de semeadura podem se tornar mais eficientes utilizando tecnologias da agricultura de precisão, como semeadura à taxa variada e semeadura multi-híbridos. No entanto, não há tecnologias disponíveis para semeadura multi-híbridos compatíveis com dosadores de sementes de disco perfurado horizontal, que são utilizados em larga escala em países emergentes. Este estudo busca desenvolver um sistema multi-híbridos com taxa variada e acionamento elétrico, de baixo custo, para semeadoras equipadas com dosadores de semente de disco perfurado horizontal, e comparar a distribuição longitudinal de sementes do sistema desenvolvido com a de um dosador de sementes acionado por roda de terra. O sistema multi-híbridos foi desenvolvido com base em uma metodologia de projeto de produto. Um protótipo do sistema multi-híbridos foi fabricado em PETG utilizando uma impressora 3D. O sistema multi-híbridos possui três posições de operação - aberto para semente tipo A, aberto para semente tipo B e fechado - operadas por um servomotor. O controlador é composto por um computador de placa única, entre outros componentes eletrônicos. Ele controla o sistema multi-híbrido e um dosador de sementes de disco perfurado horizontal, acionado eletricamente em taxa fixa ou variada, com base em mapa de prescrição. O custo total do dosador de semente multi-híbrido à taxa variada com acionamento elétrico (MVSM) é de menos de USD400. Quatro experimentos foram conduzidos para avaliar o MVSM. O primeiro comparou o MVSM com um dosador de sementes de disco perfurado horizontal acionado por roda de terra (GWSM) em três taxas de semeadura (3, 3,5 e 4,1 sementes por metro) em termos de distribuição longitudinal de sementes. O segundo comparou a distribuição longitudinal de sementes de quatro posições do MVSM - aberto A, B, e fechado após A, B - em três taxas de semeadura. O terceiro avaliou a distância de transição entre os tipos de sementes em três taxas de semeadura. O

quarto avaliou a distribuição longitudinal de sementes do dosador de sementes à taxa variada com acionamento elétrico sem o sistema multi-híbrido (VSM) em três taxas de semeadura. Todos os experimentos foram conduzidos a  $4 \text{ km}\cdot\text{h}^{-1}$  com sementes de milho. Dados dos experimentos mostram uma tendência de redução da uniformidade dos espaçamentos entre sementes com o aumento da taxa de semeadura em todos os sistemas testados, e uma maior dispersão dos espaçamentos entre sementes produzida pelo MVSM. O GWSM supera o MVSM em termos de distribuição longitudinal de sementes. O aumento na taxa de semeadura afeta negativamente a distribuição longitudinal de sementes, independente do sistema. As posições aberto B e fechado B do MVSM apresentam distribuição longitudinal de sementes menos uniforme. O aumento na taxa de semeadura afeta negativamente a distribuição longitudinal de sementes, independente da posição do MVSM. A troca de sementes tipo B para A produz distâncias médias de transição abaixo de sete metros. O desempenho da troca de sementes tipo A para B não é satisfatório. O sistema multi-híbridos afeta negativamente o desempenho do dosador de sementes à taxa variada com acionamento elétrico em todas as taxas de semeadura. Embora o desempenho da troca de tipo de sementes necessite de melhoria, o MVSM poderia substituir o GWSM com a vantagem do ajuste da taxa de semeadura durante a semeadura.

Palavras-chave: Multi-híbridos. Semeadura à taxa variada. Espaçamento entre sementes.

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# SUMMARY

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# 1 INTRODUCTION

The 2020s have been the setting of important events in human history. Although the COVID-19 pandemic has lowered birthrates worldwide (BRICKER, 2021), the human population has hit the figure of 8 billion inhabitants, and is expected to reach nearly 10 billion people by 2050 (UNITED NATIONS, 2022). With that, comes one of the main challenges of modern times: to ensure food security and, simultaneously, to care for the environment. Meat has been an important source of proteins in the human diet, and meat consumption tends to increase as the population grows. It has also been evident that the economic growth of societies leads to an increase of meat consumption (WHITTON et al., 2021), accompanied by a decrease in human consumption of crops (CHEN; LU, 2019; XIE; XU, 2019). Emerging economies such as China and India hold a large share of the human population, and even slight dietary changes in their populations can cause large scale effects in the supply chain of food. As a response, demand of feed for livestock is drastically increasing.

Protein is an essential element in the human diet, and can come from animal-based foods or plant-based foods. While today's population depends heavily on animal protein, a switch to vegetarianism and veganism is trending among environmentally aware communities (WEIS; ELLIS, 2022). Plant-based meat alternatives, for instance, are becoming mainstream, although challenges related to production cost and sensory experience are yet to be overcome (BOUKID, 2021). Nevertheless, an increase in protein-rich food demand puts significant pressure on one of human's most basic practices: crop production. In short, modern agriculture needs to balance a growing demand of grains with a reduction in use of resources such as water, land and fertilizer.

An improvement in agricultural production efficiency is likely to come from breakthroughs in plant breeding, fertilizer technology, soil biology (AASFAR et al., 2021; ANAS et al., 2020; DELLERO, 2020; STEINWAND; RONALD, 2020; ZULFIQAR et al., 2019), as well as precision agriculture. The latter encompasses techniques to identify and manage the spatial and temporal variabilities of the productive system, with a goal of increasing profitability and sustainability. Among the techniques of precision agriculture, there are soil and plant attributes georeferenced identification, and the variable rate application of inputs (MOLIN; AMARAL; COLAÇO, 2015). When referring to the seeding process, precision agriculture might be performed by varying plant population (variable rate seeding), seed depth, hybrid (multi-hybrid seeding), variety (multi-variety seeding), or seed treatment. The optimum seeding parameters can vary continuously within a field or among management zones.

Variable rate seeding is an example of a technology used in precision agriculture. There are row crop planters on the market equipped with the latest variable rate

application systems, and the adoption of these equipment is justified by studies which have demonstrated the economic feasibility of varying plant population in a field (CARCIOCHI et al., 2019; CORASSA et al., 2018). Hörbe et al. (2013) conducted an experiment in a corn area in northwestern Rio Grande do Sul state, Brazil, using three management zones and five different plant populations. Management zones represented different yield classes. These classes were determined using yield maps from previous harvests. In the low yield management zone, there was an increase in corn yield and net income with a decrease of plant population, whereas the opposite occurred in the high yield management zone. Krause et al. (2020) gathered data from 57 site-years in the state of New York where corn and soybean trials were executed, at varying planting rates. It was found that yield variation could be partially explained by the change in plant population, as well as hybrid or variety selection.

The allocation of different hybrids, varieties or seed treatments to management zones is a complex task. From an agronomic perspective, there needs to be a deep understanding of how a specific genetic material responds to the environment. To make matters worse, the environment usually presents some form of variability. Zoning is usually performed by means of spatial variability of soil moisture, water holding capacity and soil drainage, disease, insects and weeds incidence, lodging, among other factors (JESCHKE; SHANAHAN, 2015; SEXTON; PRAIRIE; ANDERSON, 2013). However, weather events and temporal variabilities present a significant challenge in zoning prior to planting (STEVENS, 2018).

Research on multi-hybrid, multi-variety, and variable seed treatment seeding has been made, and positive results have been presented. Beck's Hybrids (Atlanta, In.) have published the result of three-year-long trials on multi-hybrid seeding on their annual farm research report. The company reported an increase of yield and economic return when offensive - i.e., high yielding - hybrids of corn were planted on high-productivity soils and defensive - i.e., stress tolerant - hybrids of corn were planted on low-productivity soils, as opposed to planting a single hybrid of corn across entire fields (BECK'S HYBRIDS, 2014). The company also reported positive results for multi-variety seeding of soybeans over two years of trials. Corassa et al. (2019) employed multi-variety seeding in two experimental areas containing three yield classes with six soybean varieties each. In both experimental areas, there was an increase in net return ranging from USD 29  $ha^{-1}$  to USD 50  $ha^{-1}$  when more than one soybean variety was planted in each area.

While seed companies' research focuses mostly on accuracy of hybrid, variety or seed treatment selection, Stevens (2018) made progress on the creation of management zones for multi-hybrid and variable seed treatment seeding. In an experiment with multi-hybrid seeding across two growing seasons, there was no advantage in multi-hybrid seeding in comparison with seeding a single hybrid in previously mapped

zones. However, the collected yield data was used to rearrange management zones, having an estimated positive outcome. Additionally, zoning based on split planter trials might provide more useful insight into hybrid placement as opposed to previous zoning based on soil attributes and yield correlations (STEVENS, 2018). Stevens (2018) also performed a variable seed treatment soybean seeding experiment. The study consisted in placing a high-cost fungicide seed treatment in zones of high disease pressure, and achieved positive economic results.

There are farmers who vary corn hybrids and soybean varieties across whole farms, mostly due to difference in planting date and disease occurrence (VERBETEN, 2015). Still, multi-hybrid or multi-variety seeding could pose a challenge in terms of harvest performance and post-harvest cost management. As pointed out by Ward, Henry & Hock (2016), different hybrids of corn can have significantly variable dry-down performance, which means that grain moisture content could drastically vary within a multi-hybrid field at harvest time. The choice of hybrids for a multi-hybrid seeding strategy must consider the dry-down performance of hybrids, since differences in moisture content of grains within a field can decrease harvest quality and performance, and increase post-harvest drying cost (WARD; HENRY; HOCK, 2016).

From an engineering perspective, multi-hybrid, multi-variety, and variable seed treatment seeding have been partially dealt with by the agricultural machinery industry. Firstly, though, it is necessary to comprehend the machines that are used in the seeding of crops. These machines can be classified by the size of the seeds. For small seeds, such as rice, oats, and wheat, seed drills are used. For large seeds, row crop planters are used. There are significant differences between seed drills and row crop planters, especially when it comes to seed metering systems (BALASTREIRE, 2005). In the case of row crop planters, the most common seed meters are gravity-fed and vacuum-fed. The gravity-fed seed meters, mostly based on horizontal disks, are most common and affordable in Brazil. They are widely used by farmers in emerging markets (Van Loon et al., 2020).

Since 2000, there have been registered intellectual properties presenting solutions for variable seed type seeding, such as in Bender & Flamme (1999). The term variable seed type is used interchangeably with multi-hybrid, multi-variety, or variable seed treatment, but it could also encompass seeding of different species. Back then, the main reason for supporting this technology was based on the information that a single seed type could not efficiently satisfy the naturally occurring spatial variability present in agricultural fields. Additionally, different conditions of soil type, nutrient levels, slope, disease, insects and weed occurrence would benefit from different seed types. Finally, in 2013, Kinze Manufacturing, Inc. (Williamsburg, Ia.) announced the first multi-hybrid concept planter, with two vacuum-fed seed meters per row. The company reported consistent yield gains across trials in multiple years (BAXLEY,

2013).

In the American market, there are readily available solutions for multi-hybrid seeding. The vSet Select (Precision Planting, LLC., Tremont, IL, USA), for instance, is a kit that allows planting of two hybrids. It is compatible with several row crop planter models. This system in particular uses two vacuum-fed seed meters per row, which allows a seamless switch between hybrids (PRECISION PLANTING, 2018). The mSet, also from Precision Planting, uses a selection module for feeding a single vacuum-fed seed meter with two hybrids per row, effectively switching between rows in up to 9 meters (PRECISION PLANTING, 2018). Due to the technological availability, 15% of the farmers in the American Midwest were using multi-hybrid seeding in 2021, an 8-point percentage increase in comparison with the figures from 2017 (ERICKSON; LOWENBERG-DEBOER, 2021). However, widespread availability of such technologies is limited, especially for row crop planters equipped with gravity-fed seed meters.

Currently, in Brazil, there are no row crop planters on the market capable of performing multi-hybrid seeding with horizontal disk seed meters. However, it is possible to find recently registered patents with American ownership. In Adams et al. (2017a), Adams et al. (2017b), Anderson et al. (2021), Sauder, Koch & Plattner (2020), Wendte & Adams (2020), and Wendte & Adams (2021), inventors present methods and systems for distribution and metering of multiple types of seeds. All patents cited encompass pneumatic-based systems for seed distribution and metering, as well as central seed hoppers with fluted-roller meters. Yet, planters presented in the referred patents are conceptually different from row crop planters available in the Brazilian market. Additionally, the owners of these patents don't offer these equipment in Brazil.

Van Loon et al. (2020) presented the development and application of a methodology for evaluating ten types of gravity-fed seed meters commonly used in Asia, Latin America, and sub-Saharan Africa. The experiment was conducted with three types of corn seed, each with different shapes and sizes. During the tests of the seed meters, the horizontal disks were driven at 20 revolutions per minute. When evaluating mechanical damage, longitudinal distribution and seed deposition efficiency, the seed meter from the Brazilian market held the best performance, with an average of 84% adequate seed spacings. Furthermore, in a study conducted by Correia et al. (2020), two models of horizontal disk seed meters were tested. At a planting velocity of  $8.2 \text{ km}\cdot\text{h}^{-1}$ , one of the models presented over 80% adequate seed spacings, which is classified as a good performance. Because of that, it is likely that row crop planters equipped with horizontal disk seed meters will continue to be a viable option in Brazil.

Given the right conditions of field variability, multi-hybrid seeding can be eco-

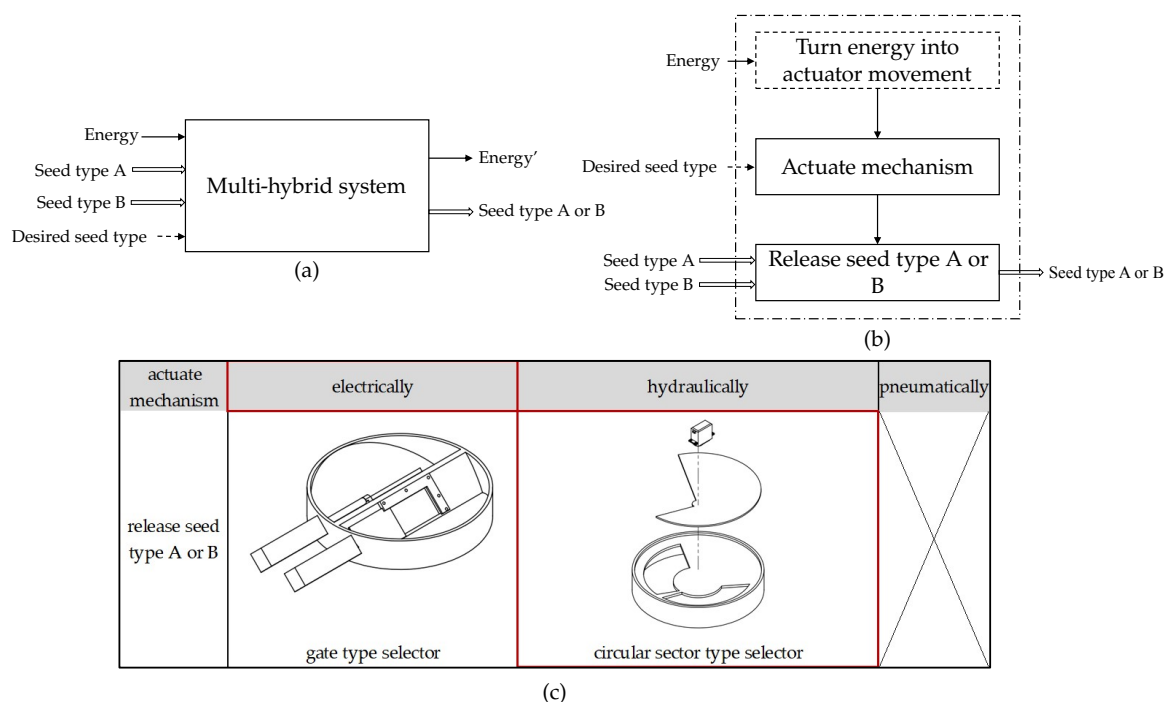
nomically feasible and beneficial within the scope of precision agriculture. However, there is a lack of solutions to enable this practice in horizontal disk planters. This study seeks to fill this gap by (1) developing a low-cost, electric-driven multi-hybrid variable rate system compatible with horizontal disk seed meters; (2) comparing the developed system's planting performance with that of a ground-wheel-driven seed meter.

## 2 MATERIAL AND METHODS

### 2.1 Mechanical design

The multi-hybrid system was developed based on the methodology for product design proposed by Pahl et al. (2007). The development started with the definition of necessary and desired features for the system. After that, a global function for the system was created (Figure 1a). The global function was broken down into two sub-functions whose solutions could be found independently (Figure 1b). Solutions were then combined to form two concepts (Figure 1c). Following technical and economic criteria, one design concept was elected (Figure 1c, highlighted in red) and further developed.

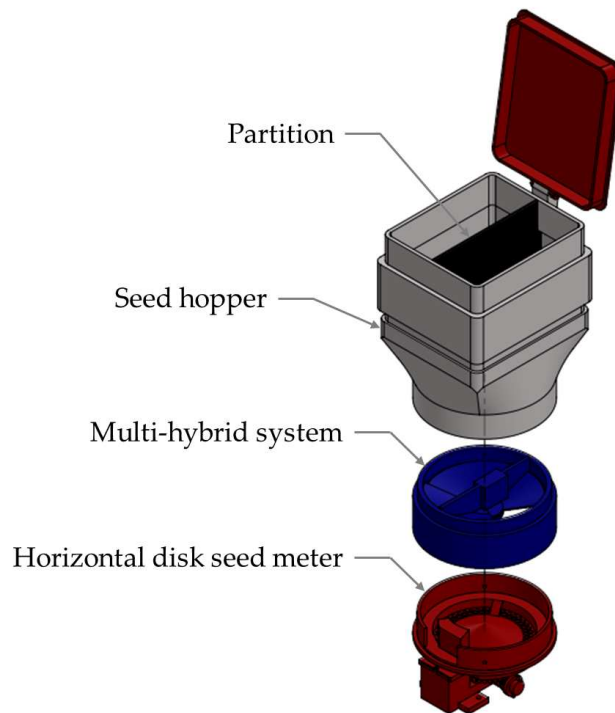
Figure 1 – (a) Global function, (b) structure of subfunctions, and (c) and morphological matrix of the proposed system



Source: Author's own

The elected concept was designed to be placed between a 260 mm diameter seed hopper and a horizontal disk seed meter (Figure 2). The hopper was modified with an internal partition, creating two separate volumes for seed types A and B inside a single hopper. This modification is also shown in Figure 2.

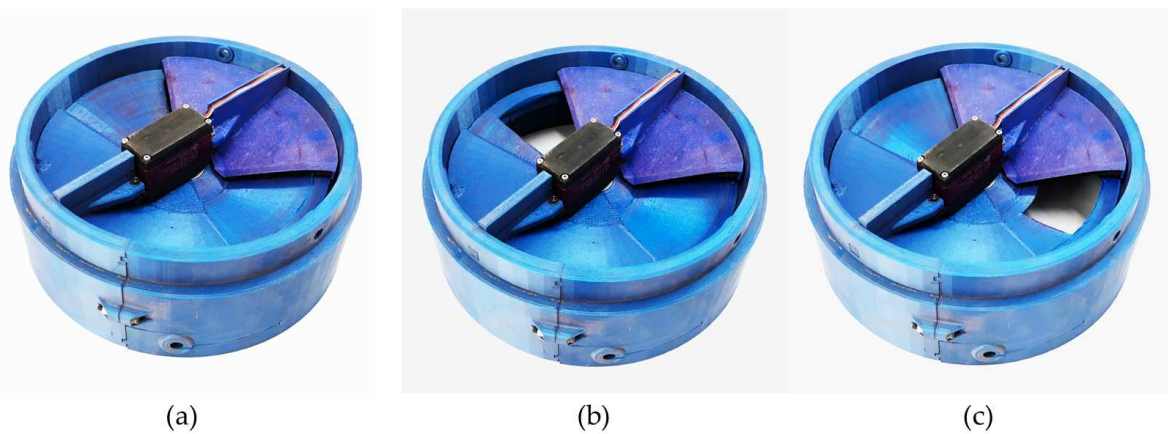
Figure 2 – Modified seed hopper, multi-hybrid system, and horizontal disk seed meter assembly



Source: Author's own

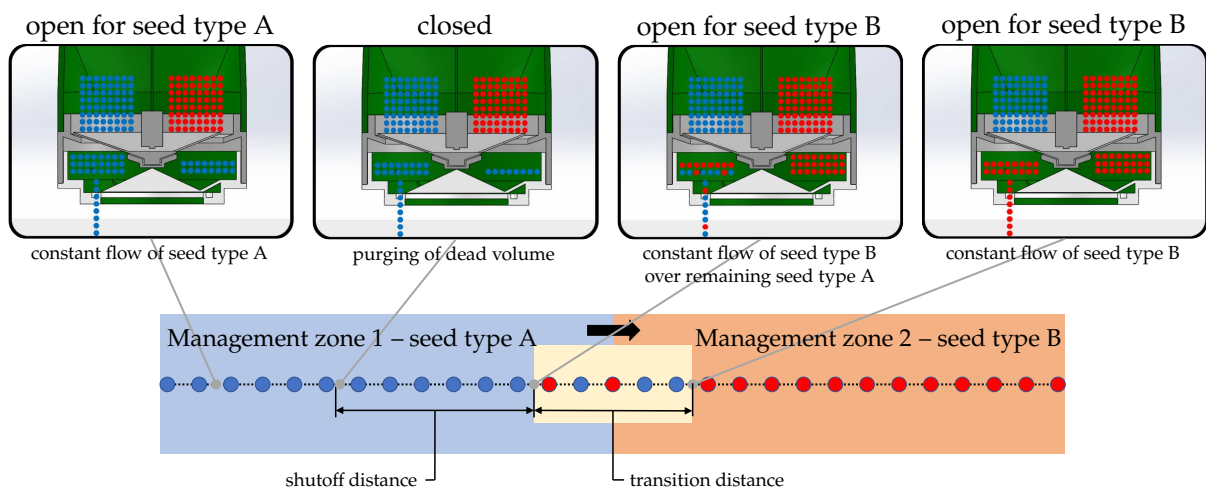
A prototype of the multi-hybrid system was manufactured using a desktop 3D printer and used approximately 1.5 kg of PETG filament. The multi-hybrid system seeks to release a single seed type from the seed hopper to the meter by means of three operating positions: closed (Figure 3a); open for seed type A (Figure 3b); open for seed type B (Figure 3c). A servomotor was used to perform the change in position. The logic behind the workings of the system is illustrated in Figure 4.

Figure 3 – Physical positions of the multi-hybrid system: (a) closed, (b) open for seed type A, and (c) open for seed type B



Source: Author's own

Figure 4 – Working conditions of the multi-hybrid system

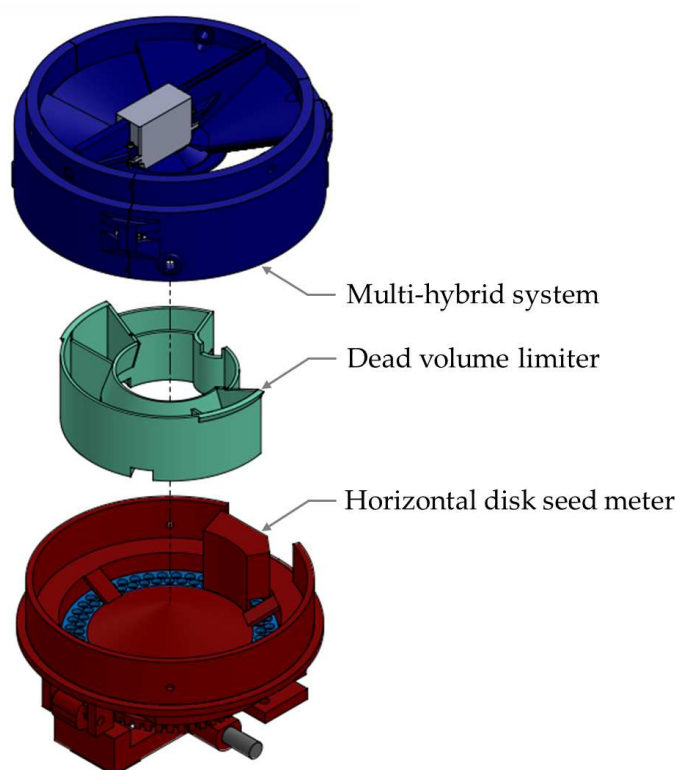


Source: Author's own

A switch between seed types was defined by four events. The first event comprehended the multi-hybrid system open for seed type A (shown in blue in Figure 4) to flow from the hopper to the horizontal disk seed meter. The second event occurred before the change in management zone, at a certain shutoff distance from the transition. Throughout the shutoff distance, the system remained closed (Figure 3a), so that seed from the hopper could not enter the dead volume. The dead volume was defined as the space between the bottom surface of the multi-hybrid system and the top surface of the horizontal disk seed meter. The third event took place before the switch from management zone 1 to management zone 2. At this point, the system allowed seed type B (shown in red in Figure 4) to enter the dead volume, where a small amount of seed type A remained. The fourth event was defined by a constant flow of seed type

B only, after the planter has entered management zone 2. The space between the third and fourth events was named transition distance, and comprehended a random mixture of seed types A and B. In order to reduce the shutoff distance shown in Figure 4, a dead volume limiter was designed and positioned between the multi-hybrid system and seed meter (Figure 5). The dead volume limiter held approximately  $100 \text{ cm}^3$  of each seed type directly above the seed meter's horizontal disk.

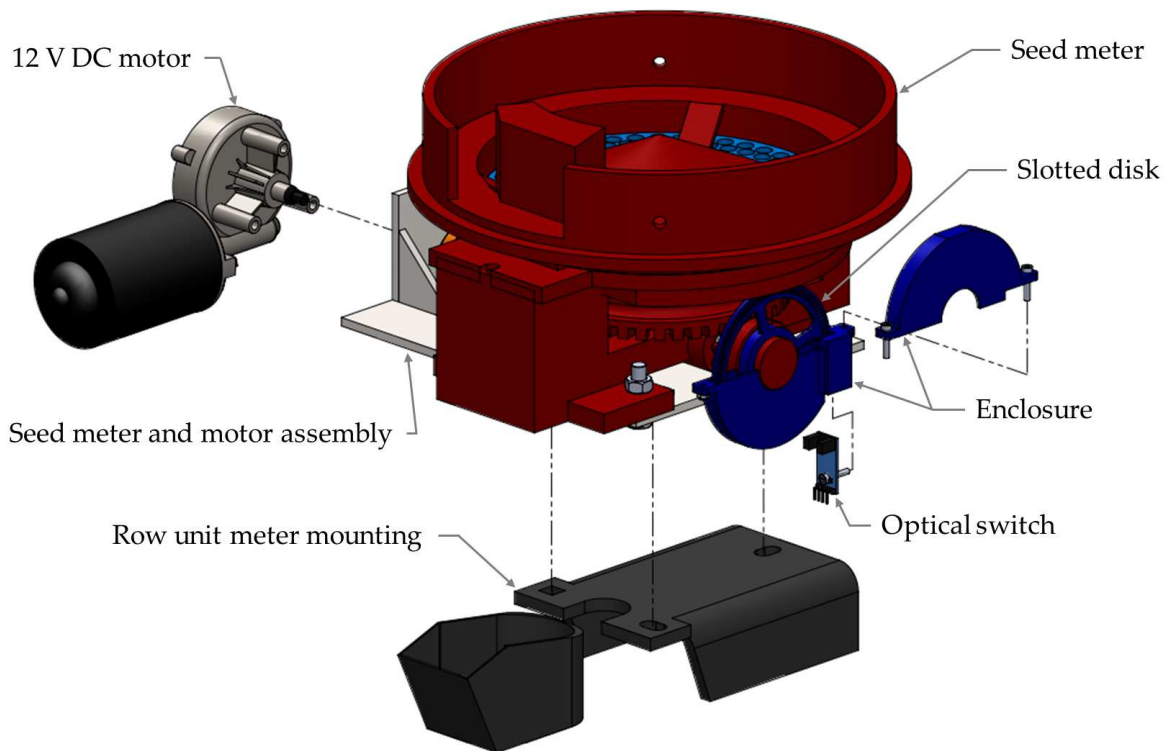
Figure 5 – Multi-hybrid system assembly



Source: Author's own

In order to enable variable seeding rate, the horizontal disk seed meter was driven by a 12 V DC, 38 rpm electric motor. This motor drives a gear set and has a 4:1 gear ratio relative to the horizontal disk. It was necessary to design a support to hold both seed meter and electric motor in place. The support was manufactured in mild steel. It has mounting holes compatible with the row unit of a JM 2570 POP planter (Jumil S/A, Batatais, Brazil). The seed meter and motor assembly also supported an optical encoder which consisted of a disk with 180 slots locked on the motor shaft, an optical switch, and a split body enclosure. The details are shown in Figure 6.

Figure 6 – Electric-driven seed meter assembly

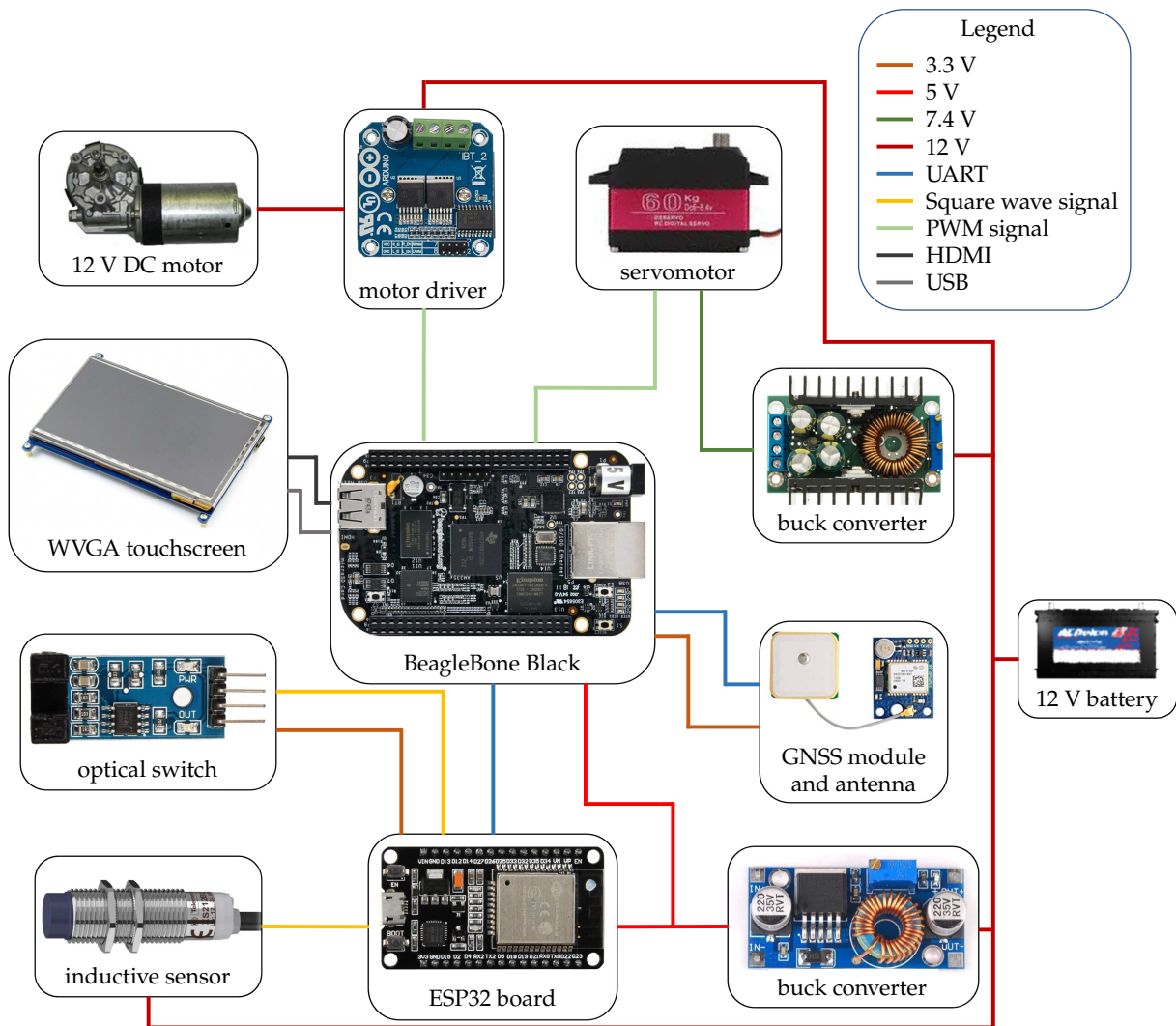


Source: Author's own

## 2.2 Controller design

The controller was based on the variable rate controller developed by Coelho et al. (2020). Figure 7 shows the arrangement of the controller's components. The controller was composed of a BeagleBone Black (BBB) single-board computer (BeagleBoard.org Foundation, Oakland Township, MI, USA), a development board based on the ESP32 microcontroller (Espressif Systems, Shanghai, China), a WVGA touchscreen, a u-blox NEO-6M global navigation satellite system (GNSS) module (u-blox, Thalwil, Switzerland), a BTS7960 motor driver, two buck converters, an optical switch, an inductive sensor, a 12 V DC motor, a 7.4 V DC digital servomotor, and a PCB designed to accommodate the BeagleBone Black and ESP32, as well as discrete components.

Figure 7 – Arrangement of the controller's electronic components



Source: Author's own

The inductive sensor and optical switch sent square wave signals to the ESP32 board. The inductive sensor read pulses from a 19 teeth gear mounted on the planter's ground wheel shaft every one second. The ground wheel had a perimeter of 2.1 meters. This measurement was obtained by averaging the distance traveled by the planter in ten revolutions of the ground wheel with three replications at field condition. The optical switch read pulses from a slotted disk mounted on the electric motor's shaft every tenth of a second. The ESP32 board calculated the horizontal disk seed meter's angular speed and the planter's speed, filtered both variables with an exponentially weighted moving average filter, and sent the filtered data to the BBB via universal asynchronous receiver/transmitter (UART) communication protocol. The filtering was implemented due to the coarse behavior of the square wave signals. The GNSS module also used UART communication protocol to send RMC and GSA sentences from the National Marine Electronics Association (NMEA) standard every one second. The BBB controlled the position of the servomotor through

pulse-width modulated (PWM) signals. The electric motor was controlled by a motor driver, which received PWM signals from the BBB. The BBB was also connected to a WVGA touchscreen in order to exchange data with the operator. A 12 V battery mounted on the tractor powered the controller. Since voltage requirements for some components varied, two buck converters and one voltage divider (placed between the inductive sensor and ESP32 board, not shown in Figure 7) had to be used. The cost of the controller's components is presented in Table 1.

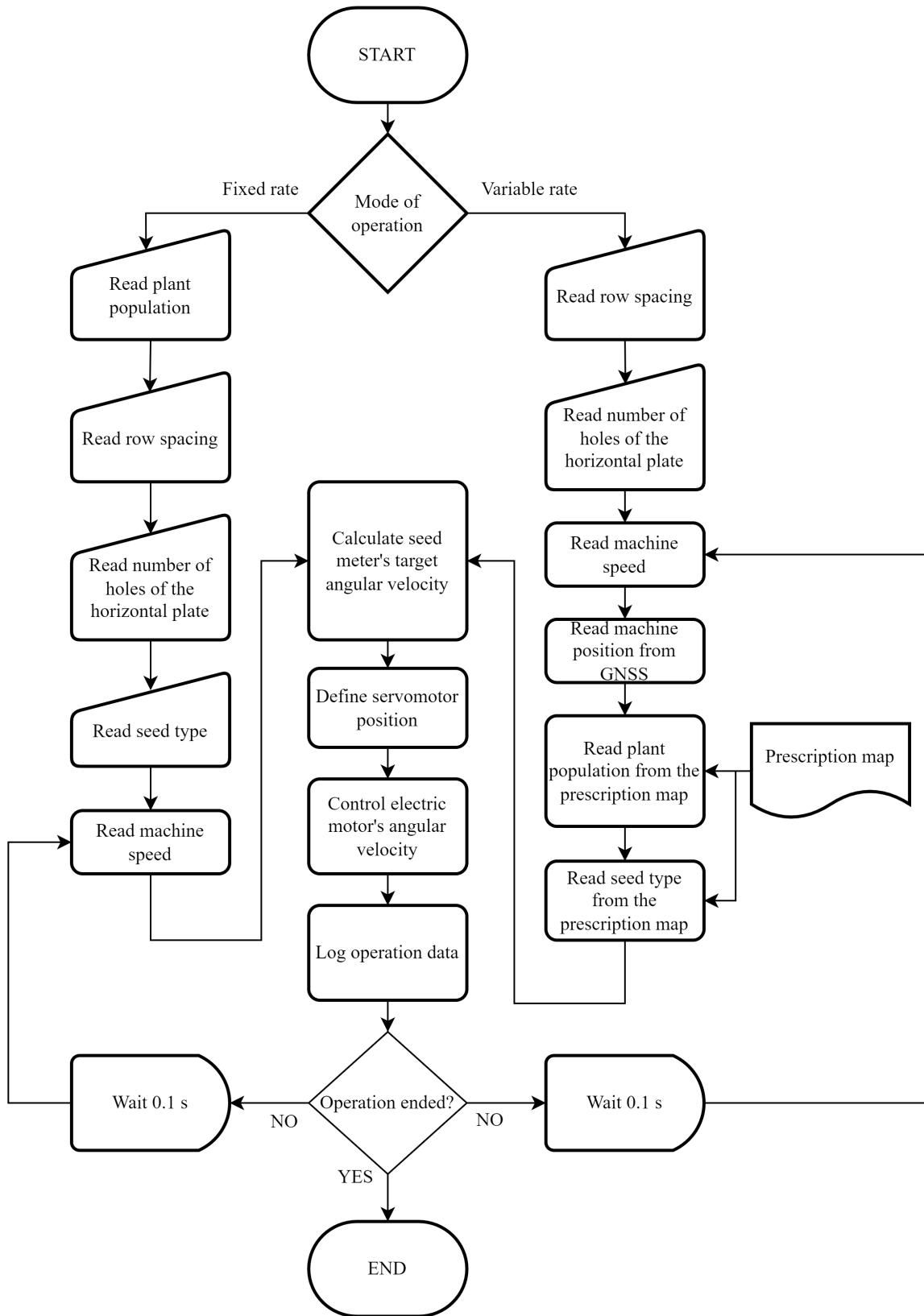
Table 1 – Cost of development of the multi-hybrid variable rate system

Quantity	Description	Total cost (USD) <sup>a</sup>
1	BeagleBone Black rev C	84.99
1	ESP32 WROOM 32	10.19
1	7" WVGA touchscreen	63.99
1	Optical switch	1.26
1	Inductive sensor	6.00
2	Buck converter	21.98
1	u-blox NEO-6M GNSS module	12.59
1	DS5160 servomotor	35.99
1	BTS7960 motor driver	10.99
1	12V DC 38 rpm motor	59.88
1.5	1.75 mm PETG filament (1 kg)	29.99
1	Additional components	50.00
Total (USD)		387.85

<sup>a</sup> Prices obtained at amazon.com on Jan. 5. 2023

The controller's software operated based on the flowchart in Figure 8. The software covered fixed and variable rate modes of operation. The operator was responsible for entering machine parameters, namely row spacing and number of holes of the seed meter's horizontal disk, for both modes of operations. When operating on fixed rate, the operator also needed to enter target plant population and seed type. A prescription map in shapefile format was used when operating with variable rate. In this case, the GNSS module provided real-time machine position and the software detected if the position sat within a management zone. When true, the software extracted plant population and seed type as attributes of the prescription map.

Figure 8 – Controller’s operating logic



Source: Author’s own

The information provided thus far was used to calculate a target seed meter angu-

lar speed, as shown in Equation 1.

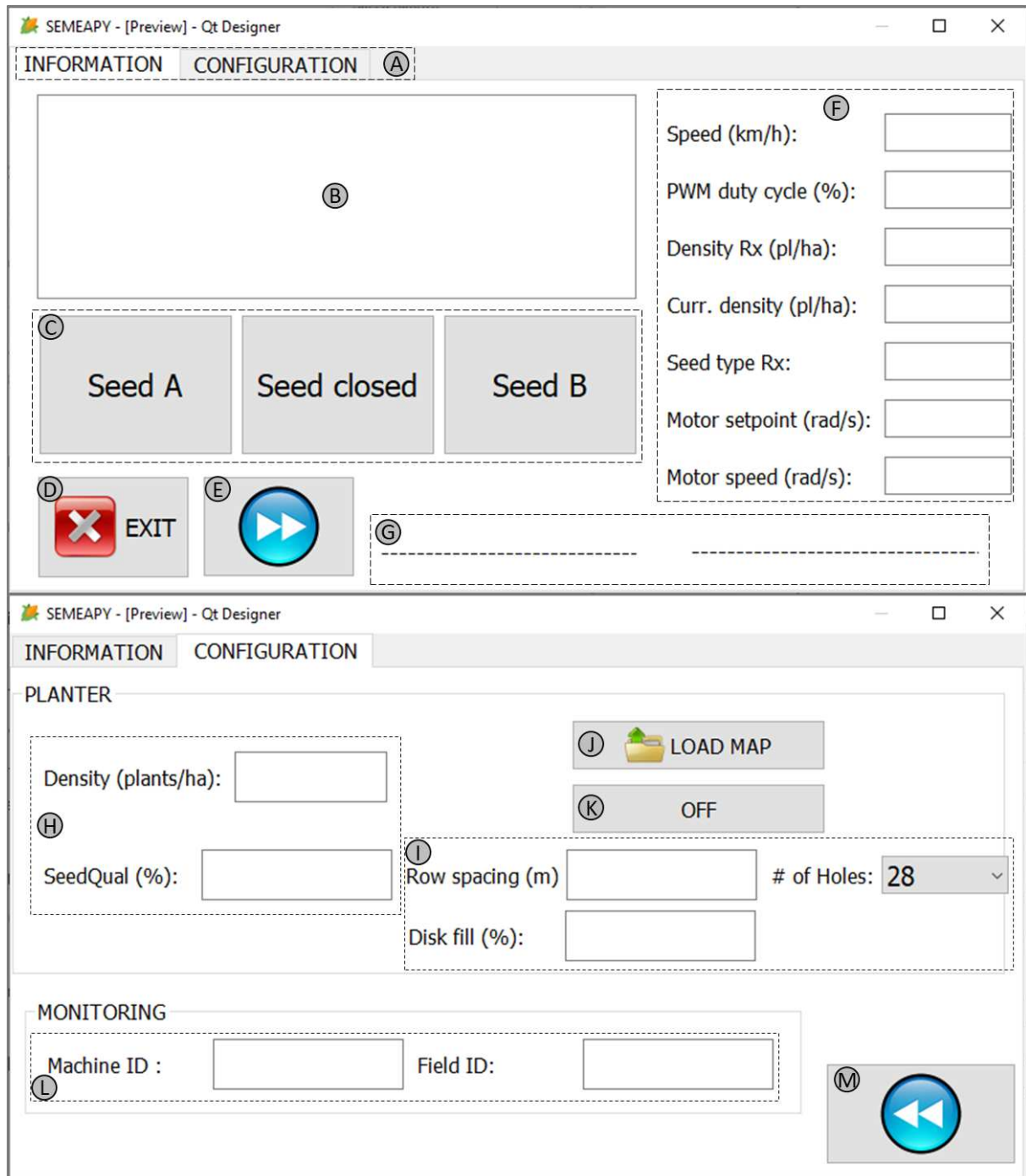
$$\omega_{target} = \frac{2 \cdot \pi \cdot pop \cdot row_s \cdot v_{machine}}{10000 \cdot n_{holes} \cdot s_{quality} \cdot d_{fill}} \quad (1)$$

where  $\omega_{target}$  is the target seed meter's angular speed in  $rad \cdot s^{-1}$ ,  $pop$  is the plant population in  $plants \cdot ha^{-1}$ ,  $row_s$  is the row spacing in  $m$ ,  $v_{machine}$  is the machine speed in  $m \cdot s^{-1}$ ,  $n_{holes}$  is the horizontal disk's number of holes,  $s_{quality}$  is the combined seed quality score (germination, physical purity, and vigor) in decimal, and  $d_{fill}$  is the horizontal disk's fill efficiency in decimal.

The seed type read by the controller's software defined the position of the servomotor. The position was controlled by the PWM signal's duty cycle, which corresponded to a certain angular position of the servomotor. A proportional-integral-derivative (PID) controller was implemented to control the angular speed of the electric motor driving the horizontal disk seed meter. The PID gains were obtained by the Ziegler-Nichols tuning method and finetuned by trial-and-error. The resulting controller gains were  $K_p = 12$ ,  $K_i = 60$ , and  $K_d = 1.2$ . The PID controller's inputs were the target seed meter angular speed, calculated by Equation 1, and the current horizontal disk seed meter's angular speed read by an optical encoder. The PID controller then outputted a PWM duty cycle that was sent to the motor driver every tenth of a second. All operation parameters were logged to a text file.

A Graphical User Interface (GUI) was developed with Qt Designer (The Qt Company, Espoo, Finland) and processed with PyQt5 (Riverbank Computing, Dorchester, UK). The GUI contained two tabs: a main screen showing real-time operation parameters, and a configuration tab holding fields for the operator's data input. Both tabs are shown in Figure 9.

Figure 9 – Controller’s graphical user interface: (a) tabs, (b) map view, (c) seed type selection, (d) exit and (e) next tab buttons, (f) operation parameters, (g) UTM coordinates, (h) and (i) planter parameters, (j) prescription map input, (k) seed metering halt, (l) machine and field identification, and (m) previous tab button



Source: Author’s own

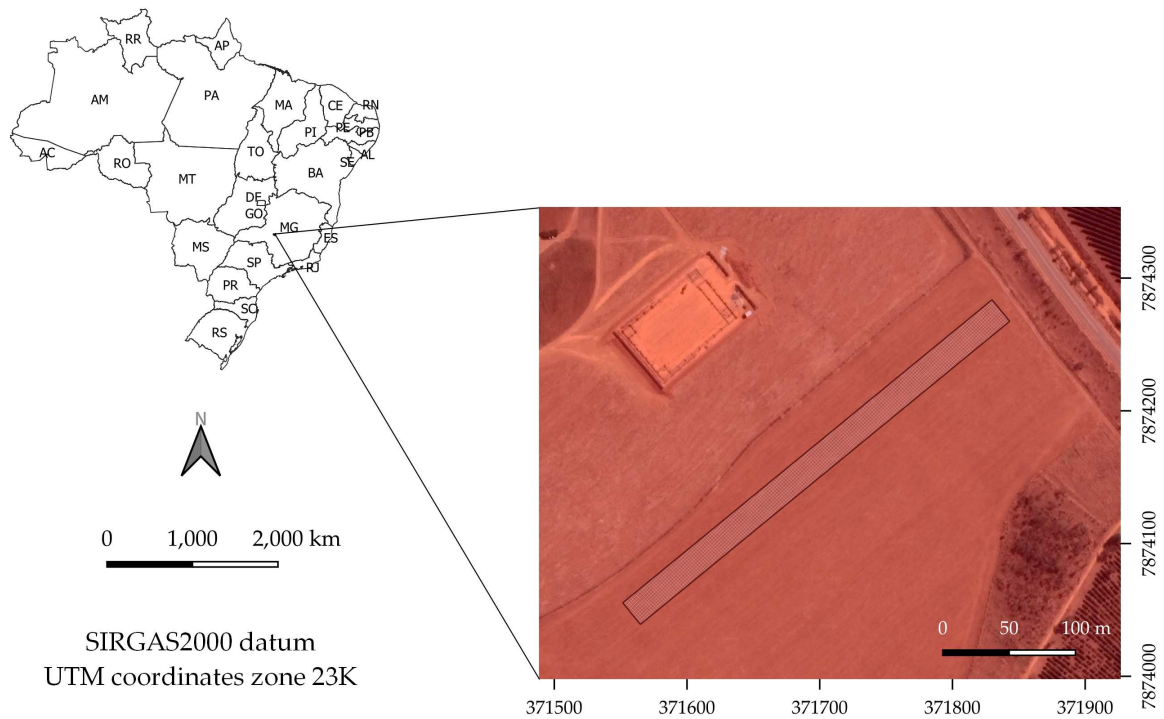
The controller could switch between tabs (Figure 9a, 9e, and 9m) easily. The operator typed current planter row spacing and selected the number of holes of the horizontal disk via a drop-down menu (Figure 9i). The operator could also enter a machine and field ID (Figure 9l) to be saved in the log file. When operating under a

fixed rate, the operator typed target plant density, as well as seed germination (Figure 9h). Manual seed type selection could be made from the main screen (Figure 9c) for ease of use. If a prescription map was available, the operator could load a shapefile to the software (Figure 9j). After configuration, the main tab showed the machine position as well as the prescription map's management zones, when available, in the white screen (Figure 9b). During operation, relevant parameters were shown in the right panel (Figure 9f). If a GNSS signal was available, the machine's Universal Transverse Mercator (UTM) coordinates were also logged and displayed in a specific field (Figure 9g). The seed metering could be halted by pressing a button (Figure 9k) at any time, and the planting operation could be finished by pressing the exit button (Figure 9d).

### **2.3 Experimental design**

The validation of the electric-driven multi-hybrid variable rate seed meter (MVSM) was carried out in the municipality of Rio Paranaíba, Minas Gerais state, Brazil, and occurred in four experiments. Hybrid corn seed KWS 9005 PRO (KWS Sementes Ltda., Patos de Minas, Brazil) was used in all experiments. For that, a 21-meter-wide, 360-meter-long tilled field was delimited. The experimental area was divided into six 3.5-meter-wide strips (plots). Each strip was further divided into four 90-meter-long strips (subplots). The location of the experimental area is shown in Figure 10.

Figure 10 – Location of the experimental area



Source: Author's own

Three of the four experiments comprehended evaluating corn seed spacing distribution. For that, six variables were estimated: multiple (MUI), miss (MII) and quality of feed (QFI) indices, precision - which is here referred to as dispersion of acceptable seed spacings (DAS) - (KACHMAN; SMITH, 1995), mean spacing (MSP), and coefficient of variation of seed spacing (CVS). The equations for each variable are described in Table 2. Each experiment is then further detailed.

Table 2 – Planting performance variables

Variable	Equation
Multiple index	$MUI = 100 \frac{n_{mult}}{N}$
Miss index	$MII = 100 \frac{n_{miss}}{N}$
Quality of feed index	$QFI = 100 \frac{n_{accep}}{N}$
Dispersion of acceptable seed spacings	$DAS = 100 \frac{s_{accep}}{x_{ref}}$
Mean spacing	$MSP = \sum_{i=1}^N \frac{x_i}{N}$
Coefficient of variation of seed spacing	$CVS = 100 \frac{s_N}{MSP}$

$n_{mult}$ : number of spacings less than or equal to half of the theoretical spacing;  $n_{miss}$ : number of spacings greater than 1.5 times the theoretical spacing;  $n_{accep}$ : number of spacings greater than half and less than or equal to 1.5 times the theoretical spacing;  $N$ : number of sampled spacings;  $s_{accep}$ : sample standard deviation of the  $n_{accep}$  spacings;  $x_{ref}$ : theoretical spacing;  $x_i$ :  $i$ -th spacing of the sample;  $s_{MSP}$ : standard deviation of the  $N$  spacings

The first experiment of the MVSM's validation used a 3x2 factorial randomized complete block design (RCBD) with eight replications. Three corn seeding rates (3, 3.5, and 4.1 seeds per meter) were tested on two system setups: MVSM and the planter's factory-built, ground-wheel-driven seed meter (GWSM). As suggested by Kachman & Smith (1995), a sample size of 250 spacings was adopted for estimating the variables in Table 2. For the MVSM plots specifically, 250 spacings were collected in four 90-meter-long subplots each. These subplots represented four working positions of the multi-hybrid system used in the second experiment (open and closed for the first seed type, and open and closed for the second seed type). Indices were calculated for each subplot and then averaged. For the GWSM plots specifically, 250 spacings were collected in the first 90 meters of each plot. Analyses of variance and Tukey's tests at 5% significance level were performed in RStudio 4.2 (ExpDes package).

The second experiment of the MVSM's validation evaluated seed spacing distribution through variables in Table 2 for the multi-hybrid system's working positions. In this case, four positions were considered: open and closed positions for the first seed type, and open and closed positions for the second seed type. For this evaluation, a split-plot RCBD was installed within the MVSM's plots from the first experiment. The three seeding rates (3, 3.5, and 4.1 seeds per meter) were assigned to the plots, and the multi-hybrid system's working positions were assigned to the subplots. The order of seed types was randomly assigned to each subplot, following an open-closed-open-closed sequence according to the system's logic. The planter ran through the full

360-meter-long strip, and at each 90-meter checkpoint, the GUI's seed type selection buttons (Figure 9c) were used to change the MVSM's working position. During the switch, the tractor kept constant speed. Seed spacings were then collected in each subplot. Analyses of variance and Tukey's tests at 5% significance level were performed in RStudio 4.2 (ExpDes package).

The third experiment of the MVSM's validation comprehended an estimation of the multi-hybrid system's transition distance. In order to estimate the transition distance, the two corn seed types needed to be visually different. Polymer coating was applied to the corn seed, half of the seeds receiving red and the other half receiving blue coating. The coated corn seeds loaded in the seed hopper are shown in Figure 11. The red seeds were loaded in the left side of the seed hopper, as seen from the rear of the planter. The left side was designated as seed type A. Accordingly, blue seeds were loaded in the right side of the hopper and designated as seed type B.

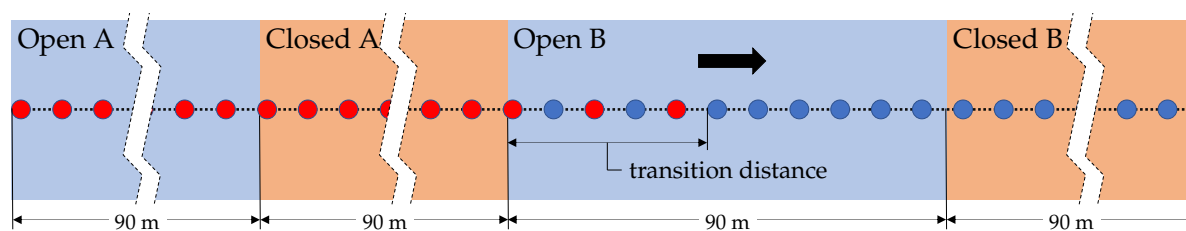
Figure 11 – Corn seed with red and blue polymer coatings loaded in the seed hopper



Source: Author's own

The transition distance was measured in the third of four 90-meter-long strips, where the multi-hybrid system kept an open position for the second seed type after running 90 meters at a closed position for the first seed type (Figure 12). The position after which no seeds from the previous type could be found was defined as the transition distance. For each seeding rate, mean transition distance and mean absolute deviation of the transition distance were calculated from eight replications.

Figure 12 – Measurement of the transition distance for a switch between seed types A and B. The arrow indicates the planter's direction of travel



Source: Author's own

Finally, the fourth experiment evaluated the corn seed spacing distribution of the electric-driven variable rate seed meter without the multi-hybrid system (VSM) for the same three seeding rates of 3, 3.5, and 4.1 seeds per meter. For this evaluation, an RCBD with eight replications was installed. This experiment was carried out on 90-meter-long plots. A sampling of 250 seed spacings was done in each plot, and the variables in Table 2 were estimated. An analysis of variance was performed, and Tukey's test at 5% significance level was used to compare variable means of seeding rates. Independent samples t-tests were used to compare means of variables between the VSM and MVSM for the same seeding rates. All statistical procedures were performed with RStudio 4.2 (ExpDes package).

The experiments were conducted with a New Holland TL85e tractor (CNH Industrial Brasil Ltda., Curitiba, Brazil) running at  $4 \text{ km}\cdot\text{h}^{-1}$ , and a JM 2570 POP mounted, 4-row planter. The speed was selected based on the electric motor's angular speed limit, and was under the manufacturer's working speed limit recommendation of  $6 \text{ km}\cdot\text{h}^{-1}$ . The horizontal disk's fill efficiency and combined seed quality score were both considered 1.0. The planter's leftmost row was used to test the MVSM and VSM, whereas the planter's rightmost row was kept with the factory-built GWSM. Both middle rows were disabled. Trash coulters were kept, whereas fertilizer shanks were removed from the planter. The double disc furrow openers were also removed. The planter's tilt was adjusted by the top link length in order to keep the seed tube's ending close to the ground. Closing wheels were raised so that seeds were left uncovered. At the end of each run, the experimental area was tilled with an off-set disc harrow equipped with plain edge discs in order to bury the seeds. Figure 13 shows the planter mounted on the tractor with the MVSM installed on the leftmost row and the GWSM on the rightmost row.

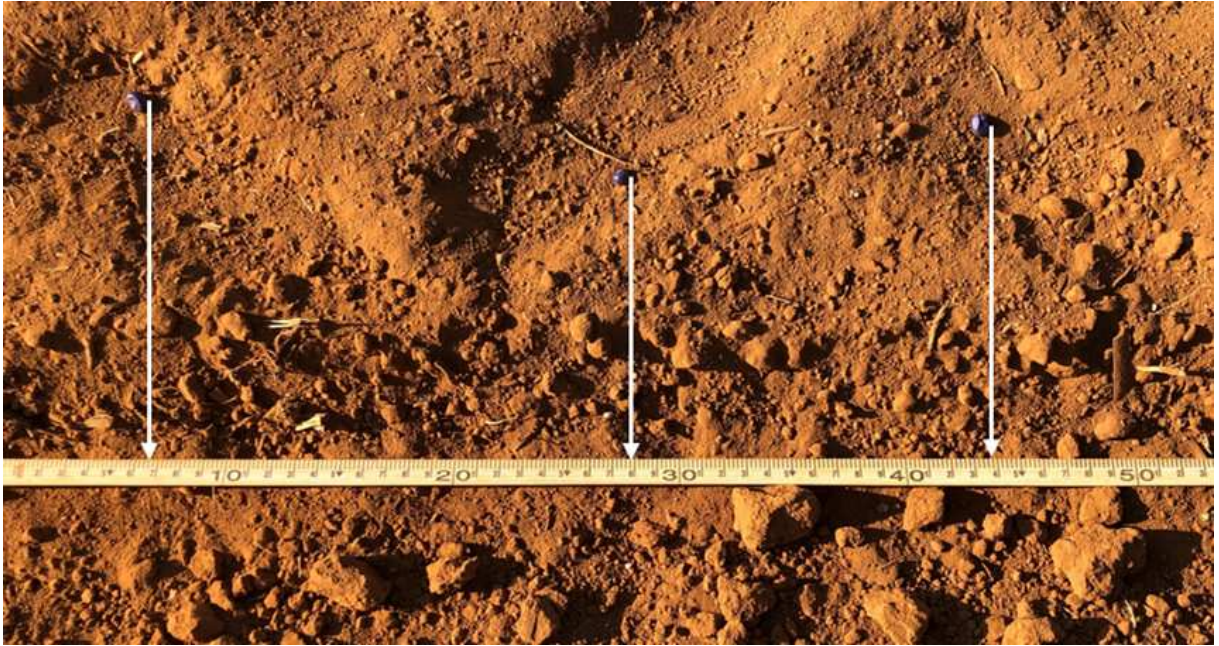
Figure 13 – MVSM and GWSM installed on the planter's outer rows



Source: Author's own

Each hopper was kept at a quarter full capacity during the experiments. A 28-hole horizontal disk with 11-millimeter diameter holes recommended by the seed company was used in all experiments. Measurements of seed spacing in centimeters were taken with a 100-meter fiberglass measuring tape. The tape was stretched alongside the row, and the longitudinal position of each seed was recorded in a worksheet (Figure 14). Distances between seeds were then calculated using a spreadsheet, and the variables in Table 2 were estimated through a Python script.

Figure 14 – Measurements of seed position



Source: Author's own

### 3 RESULTS AND DISCUSSION

The first experiment comprehended a comparison between the planting performance of the GWSM and the MVSM. The second experiment evaluated how the MVSM's working positions affected planting performance. The third experiment estimated the transition distance when a switch between two seed types is performed. Finally, the fourth experiment evaluated the planting performance of the electric-driven variable seed meter when the multi-hybrid system was not present (VSM). Since the first and fourth experiments provided planting performance data for all three systems tested – GWSM, VSM, and MVSM - data from these experiments was used to provide an overview of planting performance (Table 3) and seed spacing distribution (Figure 15) for each system. Afterward, the individual results of each experiment are presented sequentially.

Table 3 shows planting performance variables for the three systems tested (GWSM, VSM, and MVSM). The data gives an overview of the seed spacing distribution produced by each system tested in this study. There is a tendency of increase in MUI, MII, DAS, and CVS as the seeding rate is increased across all systems. Moreover, DAS and CVS's higher values indicate higher variability of seed spacings. The difference between these two variables is that, while the CVS considers all seed spacing observations per sample, the DAS only considers the seed spacings classified as acceptable, that is, greater than half and less than or equal to 1.5 times the target spacing. For this reason, DAS tends to be lower than CVS. Kachman & Smith (1995) propose a practical upper limit of DAS of 29%. From Table 3, all three systems were within this limit. The MVSM appears to have been consistently outperformed by the GWSM and VSM. While the GWSM shows minor decrease in QFI and increase in MII, DAS, MSP, and CVS as the seeding rate is increased, the VSM and MVSM show major decrease in QFI and increase in MII, DAS, MSP, and CVS, especially when the seeding rate increased from 3.5 to 4.1 seeds per meter. That could have been caused by the electric motor operating close to its limit. Therefore, the developed VSM and MVSM should be limited to an angular speed up to  $0.87 \text{ rad}\cdot\text{s}^{-1}$ , in order to keep seed spacing distribution acceptable.

Table 3 – Values of planting performance (mean  $\pm$  standard deviation) of the three systems (GWSM, VSM, and MVSM) at three seeding rates (3, 3.5, and 4.1 seeds per meter) and 4  $km \cdot h^{-1}$

Seeding rate (seed·m <sup>-1</sup> )	3 <sup>a</sup>			3.5 <sup>b</sup>			4.1 <sup>c</sup>		
	GWSM	VSM	MVSM	GWSM	VSM	MVSM	GWSM	VSM	MVSM
MUI (%)	1.7±0.9	1.6±0.8	3.3±1.0	1.6±1.6	1.5±0.8	3.3±1.1	2.5±1.7	3.9±1.4	4.7±1.2
MII (%)	2.7±2.0	2.1±1.2	7.0±2.4	3.8±2.5	2.6±1.6	9.0±1.9	4.0±3.8	5.9±4.1	11.1±3.7
QFI (%)	95.7±2.3	96.4±1.5	89.7±2.6	94.7±3.3	95.9±2.0	87.6±1.5	93.6±5.3	90.30±5.0	84.3±2.9
DAS (%)	17.9±1.8	19.3±0.9	21.0±1.3	19.2±1.4	20.6±1.3	22.2±1.7	21.1±2.1	21.4±0.8	23.4±0.7
MSP (cm)	34.7±1.4	34.6±0.6	35.8±1.7	30.2±1.6	29.8±0.6	32.0±1.3	25.6±1.0	26.0±1.7	27.8±2.0
CVS (%)	25.7±9.2	23.4±4.0	35.7±5.9	27.0±6.5	25.1±3.9	42.7±6.2	29.2±11.0	34.7±16.9	48.0±12.1

GWSM: ground-wheel-driven seed meter; VSM: electric-driven variable rate seed meter; MVSM: electric-driven multi-hybrid variable rate seed meter; MUI: multiple index; MII: miss index; QFI: quality of feed index; DAS: dispersion of acceptable seed spacings; MSP: mean spacing; CVS: coefficient of variation of seed spacing.

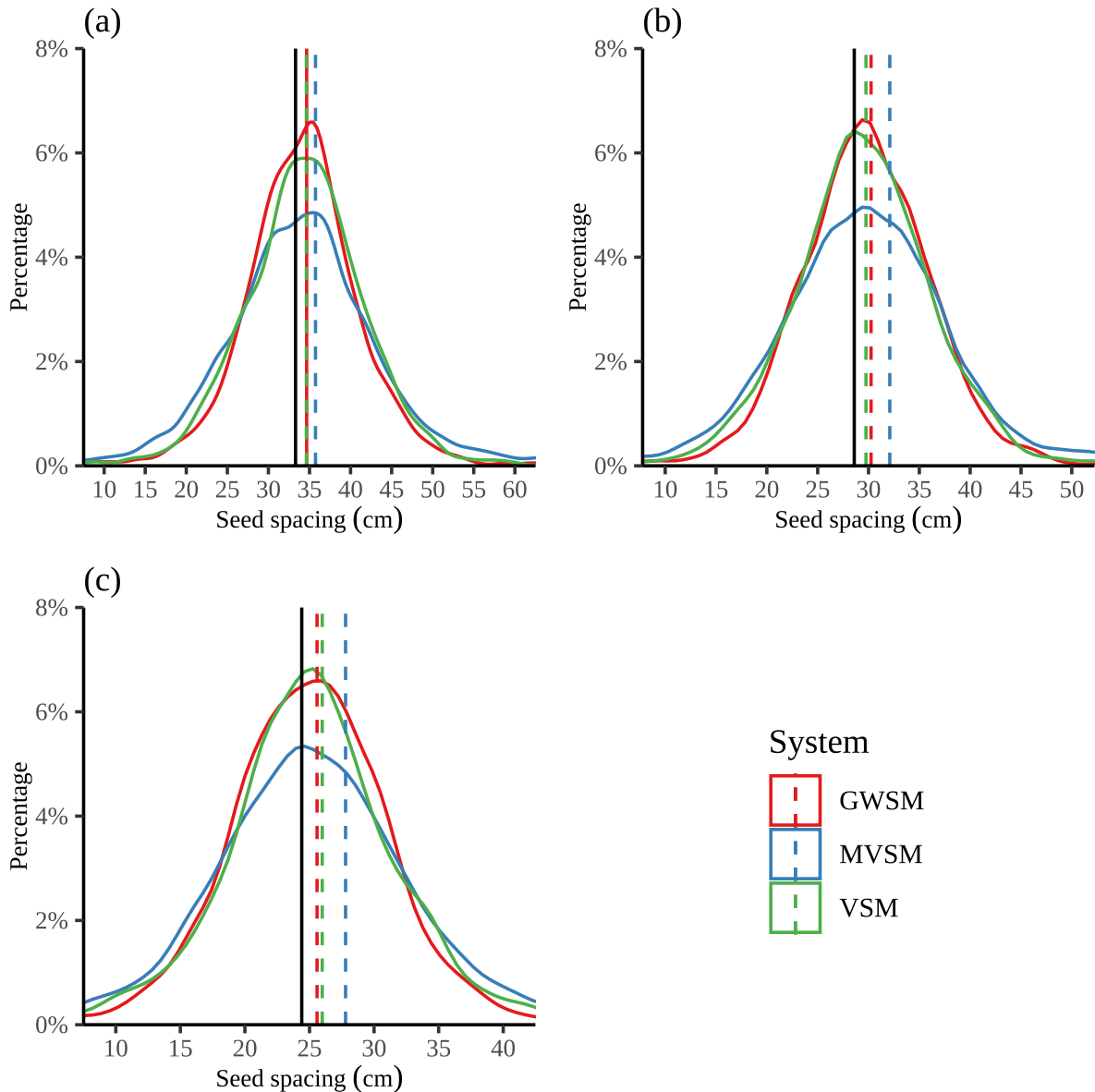
<sup>a</sup> Seed meter's angular speed of 0.75  $rad \cdot s^{-1}$ .

<sup>b</sup> Seed meter's angular speed of 0.87  $rad \cdot s^{-1}$ .

<sup>c</sup> Seed meter's angular speed of 1.02  $rad \cdot s^{-1}$ .

The seed spacing distribution for the three systems is shown in Figure 15. For the three seeding rates of 3, 3.5, and 4.1 seeds per meter, the MVSM's mean seed spacing sits farthest from the target seed spacings. It can be observed that both VSM and GWSM have similar mean seed spacings. On all cases, the GWSM's distributions appear to be narrower, indicating smaller standard deviation and, therefore, smaller dispersion of seed spacings. The data indicates that spacings produced by the MVSM were less precise than the ones produced by the VSM and GWSM under all seeding rates. A possible cause of this effect is the presence of the dead volume limiter, which interferes with the flow of seeds from the hopper to the seed meter's horizontal disk. The internal surfaces of the multi-hybrid system could also be responsible for negatively influencing the seed flow. An experiment conducted by Cay, Kocabiyik & May (2018b) found that plant spacing distribution for an electro-mechanic drive system was more uniform and closer to the desired plant spacing when compared to a classical, mechanical drive system. The electro-mechanic drive system developed by Cay, Kocabiyik & May (2018b) is similar to the VSM, and promoted a lower fuel consumption when compared to the mechanical drive system.

Figure 15 – Seed spacing distribution of the three systems (GWSM, MVSM, and VSM) at seeding rates of (a) 3, (b) 3.5, and (c) 4.1 seeds per meter. Solid black vertical lines indicate target spacings of each seeding rate

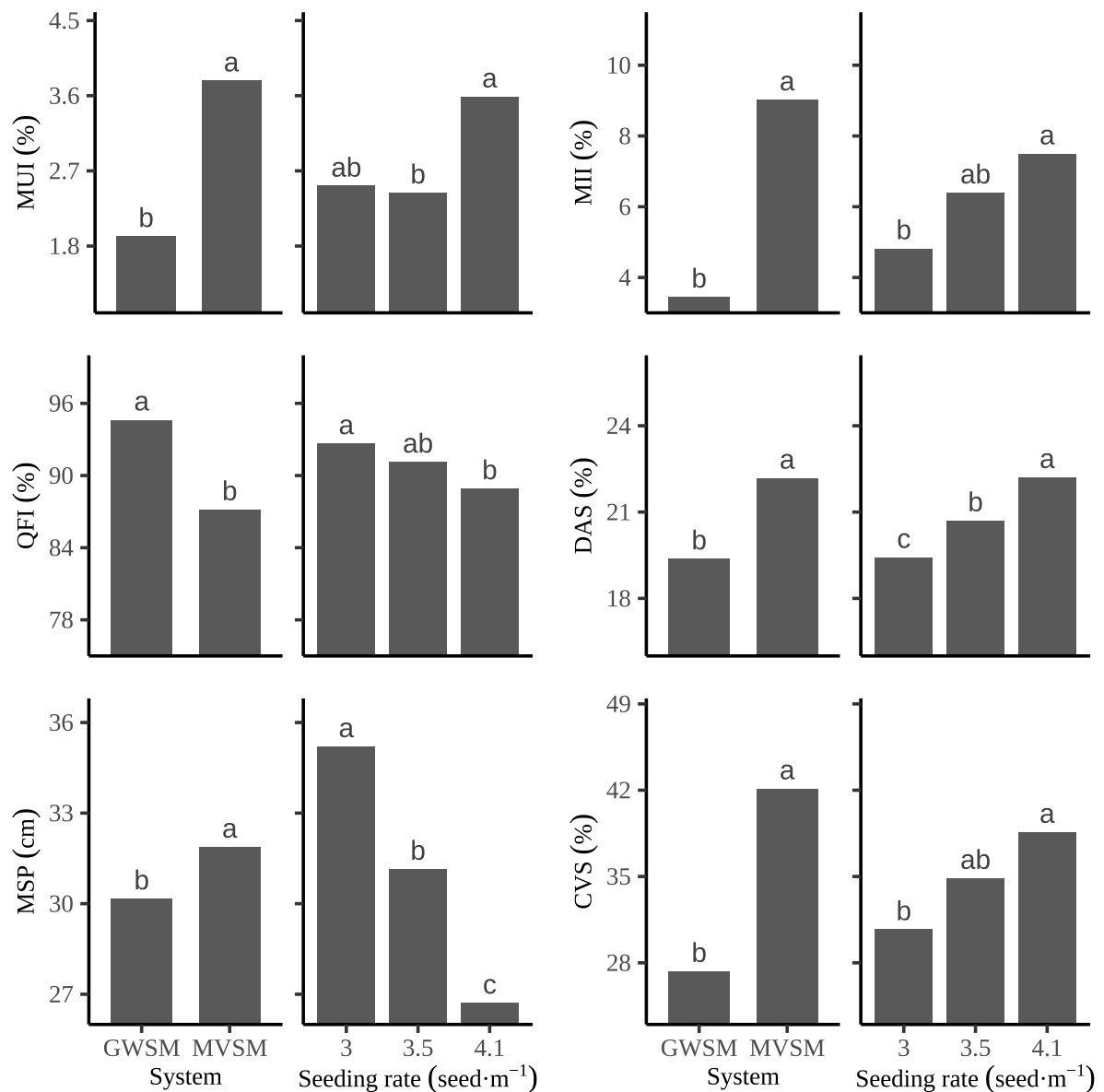


Source: Author's own

Although the aim of this study was not to develop a system with better planting performance than that of the GWSM, a comparison was made in order to identify possible flaws in the MVSM. For the first experiment, the ANOVA did not find significant interaction between the two factors analyzed (system and seeding rate). However, the ANOVA showed significant main effects. Figure 16 illustrates a comparison of the variables estimated for the first experiment. The GWSM showed significantly lower MUI, MII, DAS, MSP, and CVS than the MVSM on average, regardless of seeding rate. It can be concluded that the MVSM significantly disturbed the seed metering process. Nonetheless, the MVSM consisted of a seed meter that was different from the

planter's factory-built seed meter, which could have benefited the DAS. Additionally, the MVSM produced a much larger MII than the GWSM. This could be explained by the limited exposure of the horizontal disk due to the dead volume limiter in the MVSM. Consequently, a significantly higher MII would decrease the QFI and increase the DAS, MSP, and CVS. Regarding the QFI, the GWSM significantly outperformed the MVSM. The MVSM's average MSP was significantly higher than the GWSM's, which could be explained by the higher MII. Cay, Kocabiyik & May (2018b), on the other hand, found no significant difference of MUI, MII, QFI, and DAS between an electro-mechanical and a mechanical drive seed metering system. Li et al. (2015) also compared a mechatronic driving system with a mechanical driving system at three planting speeds – 9, 11, and 12  $km \cdot h^{-1}$  – and found that the mechatronic driving system significantly outperformed the mechanical driving system in terms of QFI, MII, and DAS. The results presented in both publications indicate that the electric-driven seed meters have the potential to increase planting performance at different scenarios. Regarding the MVSM's lower performance in this study, potential reasons are further discussed. Firstly, the electric motor was operating close to its angular speed limit at a seeding rate of 4.1 seeds per meter. A more powerful motor could improve the seed meter's overall performance, since angular speed oscillations are less likely. Secondly, the adopted method of measurement of the planter's speed - counting pulses from the teeth of a gear mounted on the ground wheel shaft - is susceptible to error, mostly due to low resolution, ground wheel slip, and signal jitter. Thus, using a GNSS receiver to obtain planter speed is a potential solution (AKKAMIS; KESKIN; SEKERLI, 2021; WANG et al., 2022a).

Figure 16 – Performance of the GWSM against the MVSM at three seeding rates (3, 3.5, and 4.1 seeds per meter). Columns labeled with different letters are significantly different by Tukey’s test ( $P \leq 0.05$ ). MUI: multiple index; MII: miss index; QFI: quality of feed index; DAS: dispersion of acceptable seed spacings; MSP: mean seed spacing; CVS: coefficient of variation of seed spacing



Source: Author’s own

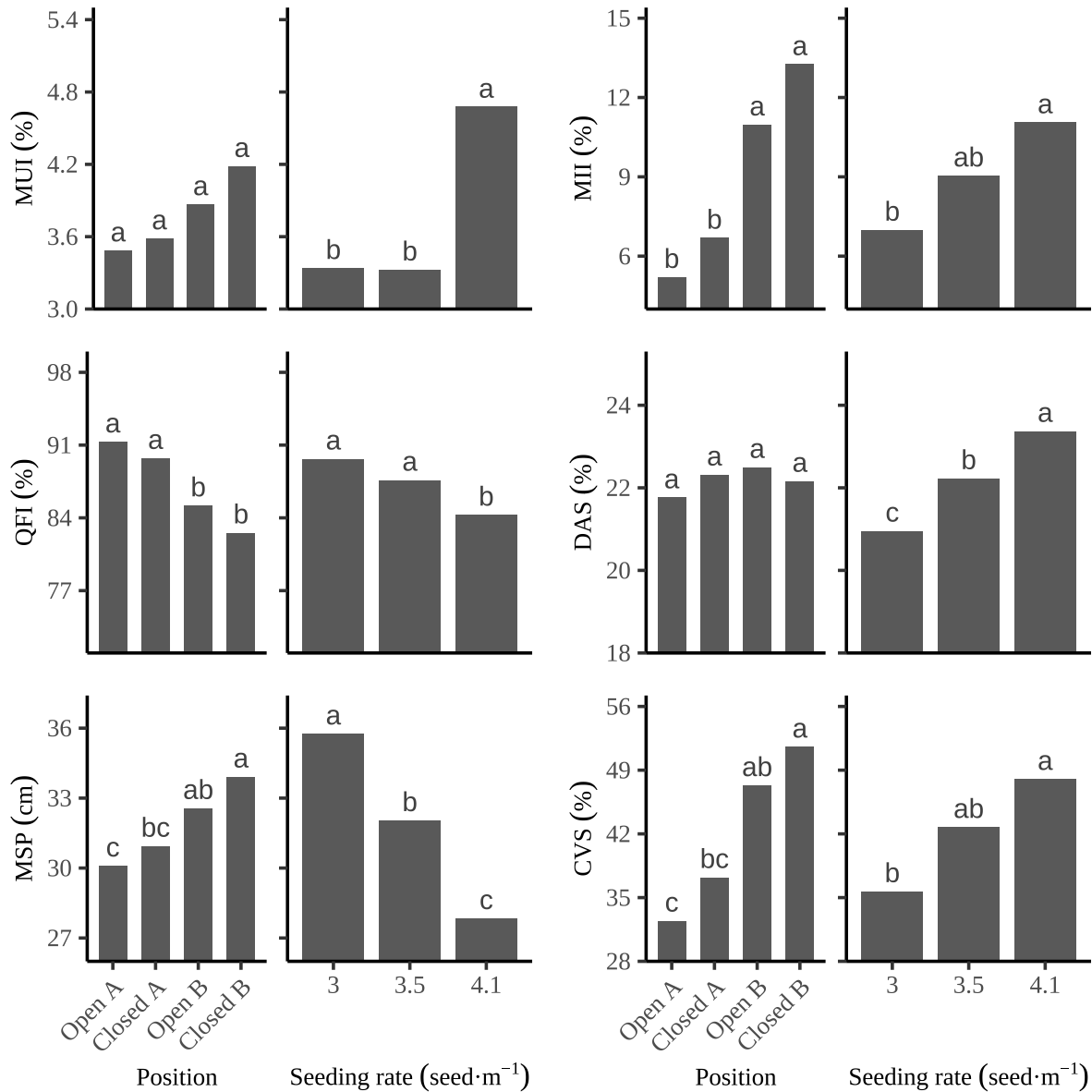
All variables showed significant differences across the three seeding rates, regardless of the system. The MUI showed significant difference between the seeding rates of 3.5 and 4.1 seeds per meter. However, the MUI at a seeding rate of 3 seeds per meter was not different than at the other two seeding rates. The MII was significantly higher at a seeding rate of 4.1 seeds per meter than at 3 seeds per meter. The same was observed by Chen et al. (2022), Ding et al. (2021), He et al. (2017), and Yang et al. (2022). That might be due to the reduced amount of time that the seeds have in order to accommodate in the horizontal disk’s holes. The QFI, accordingly, was sig-

nificantly higher at a seeding rate of 3 seeds per meter, and decreased slightly as the seeding rate increased. The DAS and CVS increased significantly as the seeding rate increased. An increase in DAS was also observed by Ding et al. (2021) when planting speed increased. As expected, the MSP at each seeding rate differed significantly. Overall, if either planting speed or seeding rate increased, the planting performance could drastically worsen.

A limiting factor for both GWSM and MVSM systems appears to be the seed meter's angular speed. This fact was highlighted by Van Loon et al. (2020) on the evaluation of gravity-fed seed meters. Although the average DAS for both systems didn't surpass the practical upper limit of 29% suggested by Kachman & Smith (1995), there is a tendency of increase in DAS as the seeding rate, or in this case, the seed meter's angular speed, increases. Thus, at higher seeding rates, it would be recommended to proportionally decrease planting speed in order to maintain acceptable planting performance.

In Figure 17, the variables estimated for the second experiment are presented. Due to the non-significant interaction between the two factors (MVSM's working position and seeding rate), only the main effects were analyzed. No effect of the MVSM's working position was noticed in the MUI and DAS. The MII reached its significantly highest values at Open B and Closed B positions, regardless of the seeding rate. The same was observed with the QFI, except that values under these circumstances were the lowest. MSP and CVS presented significant increase when positions switched from the Open A – Closed A – Open B – Closed B sequence. That could have been caused by the higher MII achieved at the Open B and Closed B positions. In general, the Open B and Closed B positions showed the lowest planting performance regardless of the seeding rate. That effect could be attributed to the seed placement in relation to the seed meter's ejector. The seed type A was positioned further from the seed ejector compared to the seed type B. As a result, seed A had a longer period of time to accommodate in the horizontal disk's holes.

Figure 17 – Performance of the MVSM’s working positions at three seeding rates (3, 3.5, and 4.1 seeds per meter). Columns labeled with different letters are significantly different by Tukey’s test ( $P \leq 0.05$ ). MUI: multiple index; MII: miss index; QFI: quality of feed index; DAS: dispersion of acceptable seed spacings; MSP: mean seed spacing; CVS: coefficient of variation of seed spacing



Source: Author's own

There was significant increase in the MUI only when the seeding rate increased from 3.5 to 4.1 seeds per meter, regardless of the MVSM’s working position. Other studies on electric-driven seed meters have shown no influence of seeding rate or planting speed on the MUI (COELHO et al., 2020; YANG et al., 2022). A slight increase in both MII and CVS can also be observed when seeding rate increases. QFI showed a significant decrease when seeding rate decreased from 4.1 to 3.5 seeds per meter, in agreement with the MUI’s behavior. The MSP presented significant decrease as seeding rate increased, which confirms that the MVSM correctly adjusted seeding

rates. Regarding the DAS, there was significant increase when seeding rate increased. Thus, an increase in seeding rate contributed to a decrease in overall planting performance. Still, in every scenario, the DAS was kept below the 29% limit.

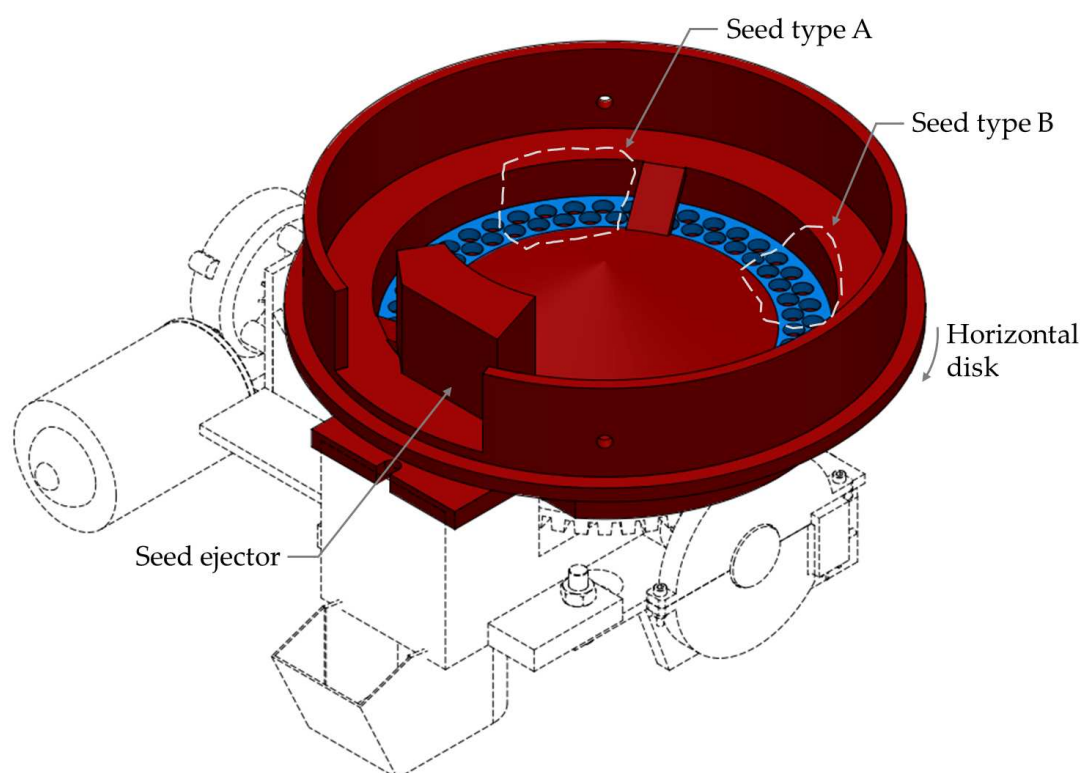
The results of the third experiment are presented in Table 4. For the seeding rate of three seeds per meter, the transition from seed type A to B could not be determined along the plot length of 90 meters. That could have been caused by an excessive amount of type A seeds accommodated in the dead volume limiter. In that case, the system's seed type switch performance was unsatisfactory. For the two other seeding rates switching from seed type A to B, transition distances were close to half the plot length of 90 meters. Variability among the transition distance of each of the eight replications is represented by the mean absolute deviation. There is tendency of decrease in both mean distance as well as mean absolute deviation when seeding rate increased from 3.5 to 4.1 seeds per meter.

Table 4 – Performance of the multi-hybrid system's switch between seed types (A to B and B to A) at three seeding rates (3, 3.5, and 4.1 seeds per meter)

Transition	A to B			B to A		
	3	3.5	4.1	3	3.5	4.1
Seeding rate (seed·m <sup>-1</sup> )	3	3.5	4.1	3	3.5	4.1
Mean distance (m)	≥ 90 m	49.14	42.56	6.30	5.17	4.89
Mean absolute deviation (m)	-	28.31	14.93	0.23	0.47	0.48

The transition from B to A could be determined for all seeding rates. There is on average a tendency of decrease in transition distance as the seeding rate increases. The seeding rate of 3 seeds per meter presented the lowest mean absolute deviation of transition distance. The transition from B to A achieved much lower mean distances and mean absolute deviations than those from A to B. That could be explained by the seed placement in relation to the seed ejector. Figure 18 shows the regions where seed type A and seed type B are fed to the horizontal disk, as well as its direction of rotation.

Figure 18 – Placement of seed types A and B, position of the seed ejector, and direction of rotation of the seed meter's horizontal disk



Source: Author's own

As shown in Figure 18, seed type A meets the horizontal disk earlier than seed type B in regard to the seed ejector. Thus, when a transition from seed type A to B is taking place, all remaining seed type A must be ejected before seed type B can be accommodated in the horizontal disk's holes. As a result, the planter must travel a longer path until the transition fully occurs. Alternatively, when there is a transition from seed type B to A, the horizontal disk reaches the seed type A empty. As seed type A is accommodated in the horizontal disk's holes, seed type B finds the horizontal disk's holes already filled. In practice, this means that transition from seed type B to A will occur regardless of the shutoff distance traveled by the planter. A decrease in transition distance when seeding rate increases could be explained by the angular speed of the horizontal disk. If the seed type A is accommodated in the horizontal disk's holes immediately, the last portion of seed type B to be metered is restricted to the horizontal disk's holes between the seed type B's placement region and the seed ejector. When the seeding rate increases, the horizontal disk's angular speed also increases. Thus, seed type B is ejected at a proportionally smaller distance.

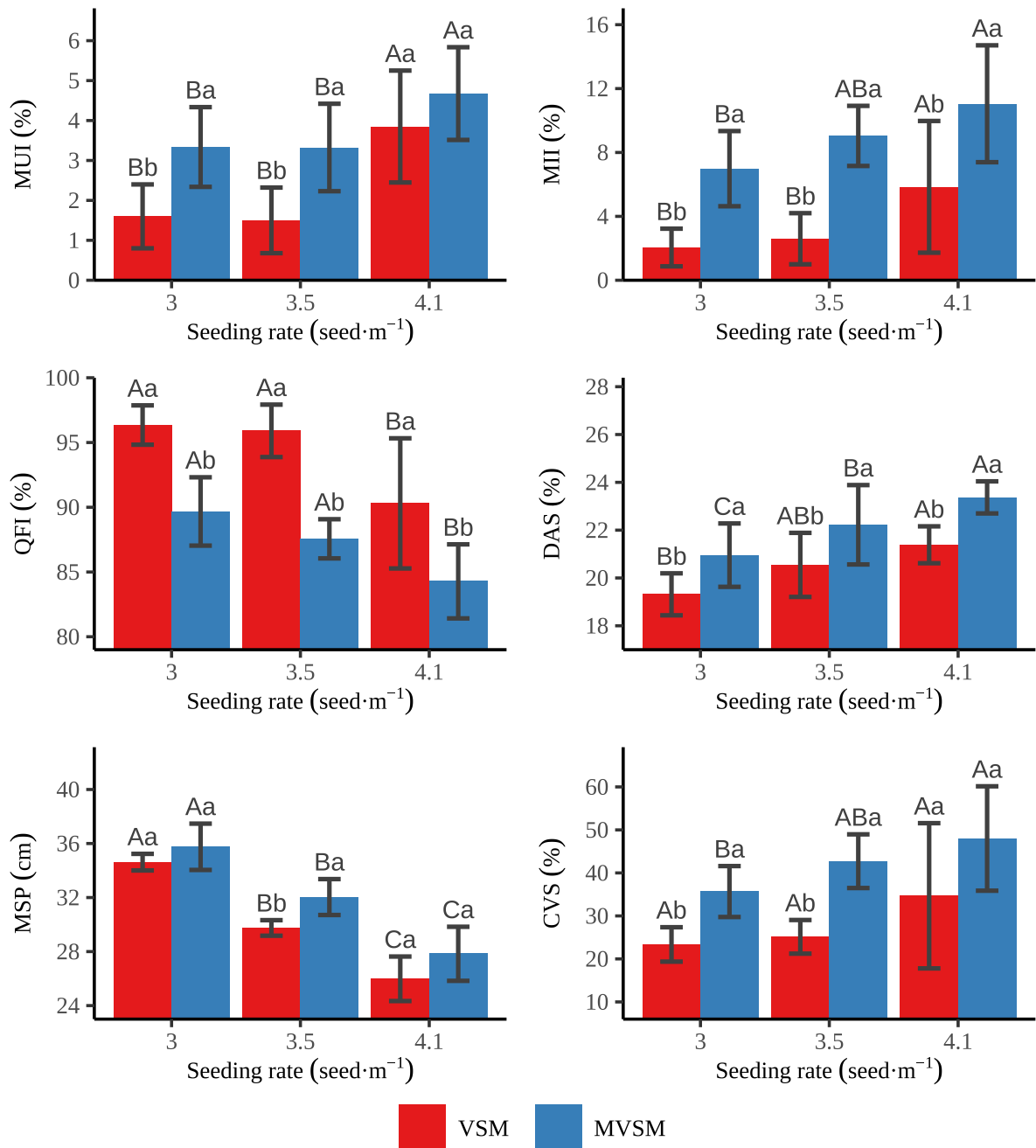
A redesign of the horizontal disk seed meter could improve the seed type switching performance. One possible approach is to add a second seed ejector opposite the first one, and design the seed ejectors so that they either eject seed down to the

seed tube or lift seed up from the horizontal disk back into the dead volume. In that scenario, each seed ejector would be dedicated to one of two seed types. A redesign of the dead volume limiter could also contribute to an improvement in the seed type switching performance, since it likely influences the interaction between seeds and the horizontal disk.

The results of the fourth experiment are presented in Figure 19. The VSM significantly outperformed the MVSM in terms of MUI and CVS at the seeding rates of 3 and 3.5 seeds per meter. The same result is observed for the MII, QFI, and DAS at all seeding rates. The MVSM presented a significantly higher MSP at a seeding rate of 3.5 seeds per meter. Thus, the MVSM's multi-hybrid system significantly affected the seed meter's performance in a negative way. That might be explained by the presence of the dead volume limiter (Figure 5), which restricts the horizontal disk's exposure to the seeds. The limited exposure of the horizontal disk, in turn, could increase the number of seed holes left unfilled, elevating the MII. Consequently, the enlarged MII also affects QFI, MSP, and CVS.

Regarding the effect of the seeding rate on the VSM's performance, the MUI and MII increased significantly only when seeding rate increased from 3.5 to 4.1 seeds per meter. QFI decreased in the same scenario. The DAS index increased as the seeding rate increased from 3 to 4.1 seeds per meter, whereas the CVS showed no significant difference across different seeding rates. The MSP presented significant difference for each seeding rate, which confirms the variable rate controller's ability to change seeding rates. Except for the DAS, all variables' standard deviations tended to enlarge as seeding rate increased. It can be concluded that an increase in seeding rate leads to a more erratic planting performance, due to the shorter amount of time that the seeds have in order to accommodate in the horizontal disk's holes. That effect is corroborated by Cay, Kocabiyik & May (2018a), Chen et al. (2022), Coelho et al. (2020), Ding et al. (2021), He et al. (2017), Li et al. (2015), and Yang et al. (2022). Additionally, the erratic planting performance might indicate a flaw in the PID control when the electric motor runs at high angular speed. A more sophisticated approach to the electric motor's closed-loop control, such as the self-tuning fuzzy PID control algorithm developed by Wang et al. (2022b), could improve planting performance.

Figure 19 – Performance of the VSM against the MVSM at three seeding rates (3, 3.5, and 4.1 seeds per meter). Means followed by the same lowercase letters do not differ by the t-tests ( $P \leq 0.05$ ) or by the same uppercase letters do not differ by Tukey's test ( $P \leq 0.05$ ). Lowercase letters compare means of different systems within each seeding rate while uppercase letters compare seeding rates within each system. MUI: multiple index; MII: miss index; QFI: quality of feed index; DAS: dispersion of acceptable seed spacings; MSP: mean seed spacing; CVS: coefficient of variation of seed spacing



Source: Author's own

## 4 CONCLUSIONS

An electric-driven multi-hybrid variable rate seed meter – MVSM - was developed and tested. Total cost of development was under USD400. The MVSM was evaluated regarding seed spacing distribution and seed type switching performance. Through the seed spacing distribution evaluation, the system was compared with a planter's factory ground-wheel-driven seed meter – GWSM - as well as with the system's own electric-driven variable rate seed meter without the multi-hybrid system - VSM. From these studies, the following conclusions can be drawn:

- The VSM and MVSM systems present mean dispersion of acceptable seed spacings below 29%, which confirms both systems' capability of replacing conventional, ground-wheel-driven seed meters with the advantage of on-the-go seeding rate adjustment.
- The variable rate controller developed successfully changes seeding rates of the VSM and MVSM.
- Seed spacing distribution produced by the MVSM is less uniform than that of both GWSM and VSM.
- The multi-hybrid system in the MVSM negatively affects the electric-driven seed meter's performance in terms of multiple index, miss index, quality of feed index, dispersion of acceptable seed spacings, and coefficient of variation of seed spacing.
- The MVSM's working positions also affect planting performance significantly. Working positions Open A and Closed A have the highest planting performance. That might have been influenced by the placement of the seed type A in regard to the seed type B and seed ejector.
- The MVSM achieves partial success in switching between two seed types.
- The performance of the MVSM's seed type switching is dependent upon the order of seed type transition. The switch from seed type B to A achieves the lowest mean transition distances and mean absolute deviations of the transition distance across the three tested seeding rates in comparison with the switch from seed type A to B.

These studies demonstrate the feasibility of designing a low-cost system which enables gravity-fed, horizontal disk seed meters to plant two seed types selectively. However, certain problems need to be addressed in order to turn the MVSM into a

ready-to-use product. Seed type switching performance needs improvement. A second seed ejector dedicated for one of two seed types could potentially enhance the MVSM's switching performance. Additionally, the MVSM should ideally outperform the GWSM in terms of planting performance. A study on the shape of the dead volume limiter could possibly lead to a more efficient design in terms of the interaction between seeds and horizontal disk. These problems shall be pursued in future work.

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