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Development and Evaluation of a Variable-Rate Fertilizer Distribution System for Coffee Plants

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Abstract: Currently, Brazilian coffee farming seeks the rational use of resources through sustainable practices. As a result, the development of machinery with more efficient input application systems and the adoption of precision agriculture techniques have been yielding excellent results. This study was divided into two stages, with the first involving the adaptation of a solid fertilizer application machine with fixed doses, allowing dose variation using an electronic controller. The second stage consisted of conducting trials and their applications under operational conditions. The results confirmed that the developed system remained stable in terms of variable-rate fertilizer distribution for coffee cultivation. The machine's lateral fertilizer distribution range met the demands of coffee farming satisfactorily. In field conditions, the developed system exhibited an average error of −2.9%, compared to the programmed doses, validating the accuracy of the machine and its suitability for use in coffee plantations.

Keywords: precision agriculture; coffee farming; machine design; machine testing

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1. Introduction

Coffee is one of the main crops produced in Brazil and currently accounts for 39% of the global production of Arabica coffee, making it a commodity of great importance to the Brazilian economy [1]. These results are directly related to various factors, ranging from the mechanization and automation of planting and harvesting, improvements in management techniques, and the use of pesticides with suitable and more technologically advanced machinery to the development of disease-resistant varieties through genetic improvement [2].

Currently, agricultural properties have been facing significant challenges, and to meet the demands for resource optimization, greater control in the production process is needed to increase productivity and the sustainability of production [3]. Specifically in recent years, due to the rising input costs, the agricultural sector, especially machinery and equipment, has been urgently seeking more sustainable solutions for resource utilization in the agricultural production process [4].

In this scenario, precision agriculture is a tool that allows for the optimization of input use and cost reduction, benefiting both the environment and agricultural production [5]. The characterization of spatial variability in soil chemical and physical attributes through sampling is indispensable, as precision agriculture (PA) utilizes variable input rates in this management system to meet the specific needs of each location, thereby optimizing the production process in that area [6].

However, according to [7], a large number of coffee growers still maintain conventional management practices on their properties. In light of this, ref. [8] mentions that a practice increasingly common among farmers is the monitoring of the nutritional status of coffee crops, aiming for balanced and economical recommendations, thus allowing for more productive crops.

In recent years, several studies on precision agriculture (PA) in coffee cultivation have been showing significant variability in soil and production attributes. In this context, the spatial variability of soil chemical attributes in coffee cultivation shows a structure of spatial dependence and a wide variation in soil chemical attributes [9,10].

Through comparative studies between grid sampling and conventional sampling, ref. [11] concluded that grid sampling for coffee farming revealed interpretation classes for soil attributes that were not identified by conventional sampling. These observations by various authors further emphasize the need for differentiated and localized applications of fertilizers in coffee plantations.

In general, variable-rate technology is a tool that allows for the application of inputs at variable rates within a field, according to the spatial variability of the crop and soil, resulting in more rational input use and less environmental impact. It has become a crucial component in the implementation of precision agriculture systems [12–14].

Current projects focusing on variable-rate fertilizer application technology primarily involve data collection and communication, machine design, and control system implementation [15]. Within this context, various research efforts are aiming to improve the controllers' interface and the machine's distribution system to increase distribution precision [16–18].

With the current emphasis on more sustainable processes, there is still a significant challenge regarding the development of equipment and the determination of specific evaluation parameters for coffee cultivation [19]. Basically, the machines available on the market for the fertilization process are equipment capable of distributing the input in the field from a reservoir, with variable capacity depending on the model, by transporting it via a conveyor belt at the base to the rotating discs [20].

It is worth noting that most precision agriculture technologies are applied to annual crops, with few variable-rate application machine projects aimed at perennial crops. In one of the most recent projects, ref. [21] developed a machine capable of spreading three different mineral fertilizers at the same time, aimed at application in olive orchards.

Evaluating the performance and accuracy of the main components of a modified variable-rate granular fertilizer spreader (MVRG) for blueberry cultivation, ref. [22] observed that the controller used performed reliably and efficiently in controlling the fertilizer application rate. Additionally, the results indicated efficient and fast operation during fieldwork, thus allowing for productivity gains in the operation.

Despite precision agriculture already being a reality in coffee cultivation, there are still significant challenges, due to the size of most tractors used, as their hydraulic systems provide low oil flow, which is insufficient for use in variable-rate application machines. Furthermore, another aspect to be developed is the independent application of fertilizers and soil amendments in each coffee planting row, as due to spatial variability, adjacent coffee rows may have different nutritional or soil correction needs.

Due to the rising production costs of coffee and fertilizers used, there is a need for each side of the machine's distribution to be independent. Considering the above, the present study aimed to develop and evaluate a variable-rate fertilizer and soil amendment distribution machine with an independent hydraulic system to make it compatible with any type of tractor and the characteristics of coffee cultivation

2. Materials and Methods

The present work was carried out at the university campus of the Federal University of Lavras in the state of Minas Gerais, Brazil, at the geographical coordinates of 21°14′ S and

45°00′ W, with an average altitude of 918 m. Thus, all stages of the project development, machine adaptations, and field system tests were conducted on-site.

2.1. Machine Adaptation

As the first step of this study, the adaptation of a conventional fertilizer spreader from the Marispan brand (Batatais, Brazil), model FERTINOX 1200, was performed. It had a loading volume of 1.10 m^3, a total width of 1.50 m, a length of 3.36 m, a height of 1.40 m, and a gauge of 1.25 m. The attachment to the tractor was performed through the lower bars of the tractor's hydraulic system. The fertilizer spreader was equipped with two conveyors for distributing fertilizer, volumetric dosing mechanisms with variable openings, and centrifugal distributors with horizontal discs, with targeted application to the planting line. The double feeder conveyor was driven by a system of gears and chains with cylindrical rollers, powered by the machine's own motion. The distributor discs were powered by a hydraulic motor equipped with a flow control valve through the tractor's hydraulic control system.

The machine operated based on the movement of conveyor belts that transported fertilizer. After the conveyor belts, the fertilizer fell onto centrifugal distributors with horizontal discs, which distributed the fertilizer to the projection area beneath the coffee tree canopy through their rotational motion and a directional guide.

The adaptation aimed to enable the distribution of fertilizers at variable rates, achieved by varying the speed of the fertilizer spreader's conveyors. To achieve this variation, the transmission system was removed, and a hydraulic system was designed to vary the speed and provide the necessary torque for independent operation on each conveyor. Another modification to the fertilizer spreader was the division of its reservoir to allow the separation of fertilizers for each side of application, as shown in Figure 1.

Figure 1. Fertilizer spreader variable-rate application system and machine reservoir adaptation.

Regarding the hydraulic system for variable-rate operation and adaptation to the machine's reservoir, it consisted of an oil reservoir, a filter, a hydraulic pump, a pressure relief valve, two electro-hydraulic flow control valves, and two hydraulic motors.

An agricultural tractor of the Agrale brand (Rio Grande do Sul, Brazil), model BX6110, 4 × 2 TDA, with a maximum power of 78.3 kW, was used as the power source for driving the system and towing the fertilizer spreader. The hydraulic pump was attached to the power take-off (PTO) of the tractor, generating a constant flow of oil for the system (Figure 2).

Figure 2. Mechanized tractor and fertilizer spreader set used in the test.

The entire system's operation was coordinated by the controller, which required information about the doses to be applied, provided through maps, as well as the location and speed of movement, obtained via GNSS signal reception (Figure 3). The controller then sent electrical signals to the electro-hydraulic flow control valves, which received these signals and regulated the oil flow to the hydraulic motors. The amount of oil reaching the motors determined their rotation and, consequently, the speed of the conveyors. If necessary, the oil flow was adjusted to change the conveyor speed, resulting in a variable application rate for fertilizers and soil conditioners. Additionally, pulse counters were installed, each positioned to read the gear attached to the hydraulic motors. These pulse counters sent electrical signals back to the controller, providing real-time information about the system's rotation.

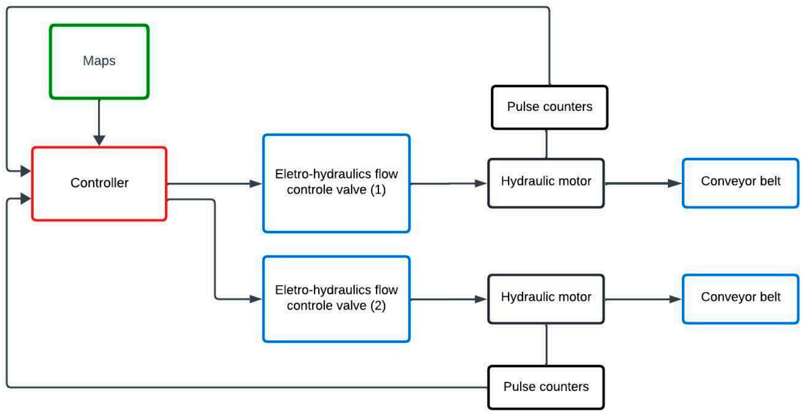

Figure 3. Diagram of the operation of the variable-rate system and reception of GNSS signals.

Finally, the Raven Envizio Pro controller was installed on the tractor, with the purpose of coordinating the application of manually programmed doses (fixed rates with possible conveyor speed variation) or based on application recommendation maps (variable rates). After all the described steps, the adapted system allowed for independence from the tractor's auxiliary hydraulic system and the variation of doses on each side of the fertilizer spreader during the application process.

2.2. Composition of the Developed Hydraulic System

The first components sized were the hydraulic motors, as the entire operation of the distribution system was controlled by them. The hydraulic motors used were from the Sauer Danfoss® brand (Nordborg, Denmark), DS 50 model.

To supply oil flow to the system, a gear pump from the Rexroth® brand (Lohr a. Main, Germany), G2 model, was used. The pump was connected to the system through the power take-off (PTO) of the tractor, along with a rotation multiplier in a 1:3 ratio. Since the standard rotation of the tractor's PTO was 540 rpm, the pump operated at three times this rotation, which was 1620 rpm. With these characteristics, the pump was able to provide an oil flow of approximately 32 L/min. With this result of hydraulic pump oil flow, it was possible to obtain the torque and rotation characteristics of the hydraulic motors by analyzing their characteristic curve. The maximum working rotation of the hydraulic motors was around 520 rpm. Due to this factor, the motor was considered suitable for the application.

Regarding torque, the system could support up to 110 Nm, after which the relief valve controlled the pressure and indirectly controlled the torque as well. The developed system had a good torque reserve because the calculated requirement was 68.67 Nm. The torque reserve was justified because the working conditions of the variable-rate fertilizer and corrective distribution system in the field were variable. A simple depression that the distributor passed over in the field could generate overloads, increasing the load applied to the conveyor belt or even in relation to the heterogeneity of the material to be applied, causing variations in the load applied to the conveyor belt at certain times.

The system came into operation when the pump generated negative pressure in the direction from the reservoir to itself, passing through a filter, characterizing it as a suction line filter. This negative pressure allowed the oil in the reservoir to be displaced to the pump, providing flow to the entire hydraulic system, through the activation by the tractor's PTO.

As shown in Figure 4, the relief valve can be observed, which had the function of controlling the system's pressure. If the pressure increased excessively, it would open, directing the oil back to the reservoir. After this component, the oil continued its flow and encountered the first of the flow control valves, which controlled the amount of oil that reached the motors or returned to the system.

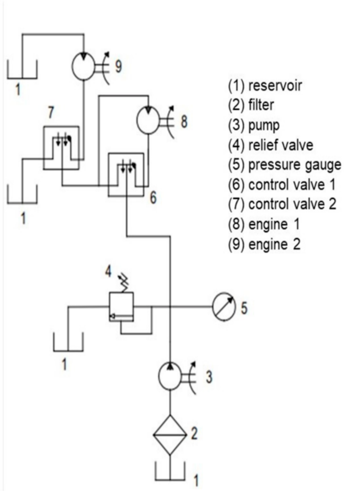

Figure 4. Schematic diagram of the hydraulic system adapted in the variable-rate fertilizer and corrective distributor.

The operation of the valves was based on variations in electrical pulses, which were sent by the controller. Consequently, depending on the signal sent to the valves, there was a variation in the oil flow to the motors. Specifically, the second valve was supplied by the return flow from the first valve and the first motor.

The motors, responsible for providing torque and rotation to the conveyors, allowed for a variation in dosages in the variable-rate fertilizer and corrective distribution system. Therefore, as the oil flow increased, the valves allowed the motors to operate at higher rotations, resulting in an increase in the applied dosages. After the oil passed through the second motor, it returned to the reservoir, creating a closed-loop oil flow system. Based on the above, the developed system allowed applications to vary independently on each side of the variable-rate distribution machine.

2.3. Characteristics of Applied Products

To conduct the tests, the climatic conditions of temperature, wind speed, and relative humidity and the physical characteristics of the fertilizer were characterized, including granulometry and angle of repose, in accordance with the ISO 5690/1 standard [23]. The density and moisture content of the fertilizers were also analyzed. The moisture calculation followed the standard method, in which the fertilizer was kept in an oven at 105 ± 3 °C until it reached a constant mass.

In light of the above, fertilizer A, in its chemical composition, had 20% nitrogen (N) and 20% potassium oxide (K2O), a density of 1.09 g/cm^3, 2.1% moisture, an angle of repose of 25.2 degrees, and a granulometry greater than or equal to 2.8 mm. Fertilizer B, in its chemical composition, contained 60% calcium oxide (CaO) and 30% magnesium oxide (MgO), with a density of 0.86 g/cm^3, 1.8% moisture, an angle of repose of 26.8 degrees, and granulometry greater than or equal to 4.0 mm. Specifically, the products used exhibited good flowability through the distribution system due to their angle of repose, which fell below 40 degrees [24].

2.4. Lateral Deposition Test with Trays

To validate the developed variable rate application system, a lateral deposition test with trays was conducted. The objective of this test was to characterize the maximum transverse distribution reach on both sides of the fertilizer distribution system.

Therefore, it should be noted that all tests were conducted under conditions considered suitable for application, i.e., RH < 80% and wind speed < 0.6 m s^{-1}. These conditions helped minimize application problems related to moisture absorption by the products used and material drift, directly impacting the efficiency of the operation.

Specifically, mechanized coffee plantations have row spacings of up to 4.0 m, so this variable needed to be considered to ensure that the equipment could operate under real field conditions. For the analysis of the data obtained in the test, a completely randomized design (CRD) in a factorial scheme with three repetitions was used. This allowed us to assess the effects of dosage variations (400, 700, and 1000 kg/ha) and product types (A and B) on the maximum reach. Significant data were subjected to the Scott–Knott mean comparison test at a 5% significance level using the Sisvar® computer program (Version: 5.6).

The trays used in this test followed the ISO 5690/1 standard [23], with dimensions of 0.5 m × 0.5 m and a depth of 0.30 m. The trays were arranged to cover the entire transverse deposition width applied by the equipment, spaced at 2.20 m in the same row, forming two groups: the left side, composed of five trays named E1, E2, E3, E4, and E5, and the right side, composed of five trays named D1, D2, D3, D4, and D5, as shown in Figure 5.

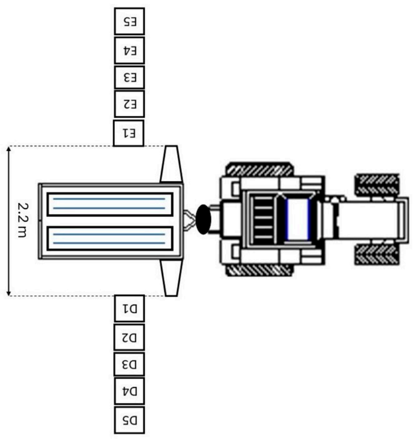

Figure 5. Transverse distribution of trays in the lateral deposition test.

This test was conducted in a stationary manner because the tractor's width was greater than the minimum product distribution distance. Therefore, the simulated speed was entered into the controller, and the application of the system was collected for 15 s in each of the three repetitions.

The maximum reach obtained was characterized through regression analysis, using the values from each repetition for each condition, i.e., the interaction of dosage and product. Regression models were created because, since each collection tray had a width of 0.50 m, this unit would be too large for evaluation, allowing for the analysis of only five reach values: 3.2, 4.2, 5.2, 6.2, and 7.2 m. These values represent the distances at which the trays were arranged, and the use of equations estimated the maximum application distances of the system.

The values for creating linear regression equations were obtained from the material collected in the trays in descending order, from the fifth tray to the first. The value of each position was added to the value of the previous position, and in positions E1 and D1, the sample contained all the materials deposited in all trays. This configuration was used because it was considered that, when analyzing a distance anterior to another position, the material deposited at a posterior distance would be intercepted by the coffee plant itself.

Thus, the averages of repetitions were obtained, generating equations that were performed between different dosages and products. We considered that the estimated dosage value should have a variation of up to 15%, compared to the required dosage to be accepted. In this way, the values representing the accepted dosage were calculated and inserted into the equations, resulting in the maximum reach values, and an average was calculated to obtain the average maximum reach value of the system.

2.5. Work Regime Test

The work regime test was conducted to verify the behavior of the fertilizer distribution system developed in real field conditions. Seven pairs of tarps were spread across the field in parallel, with a distance of 4.0 m between them and a length of 2.0 m, covering both sides of the machine distribution. The working speed used for this test was 5 km/h, and considering maximum operational efficiency (nf = 1), the field capacity of this system would be 2 ha/h under the tested conditions, as described in the methodology by [25].

The doses applied in the test varied according to pre-defined application maps in the test planning, which were inserted into the controller, as shown in Figure 6. For these tests, doses ranging from 0 to 1000 kg/ha were applied, with variations at each collection point (tarp) during two passes of the machine in the experimental field. In this test, only one product was used, but each side of the machine applied different doses.

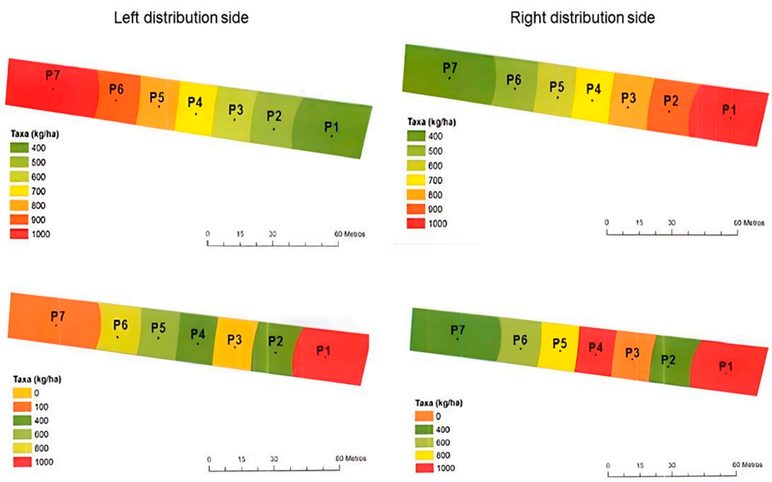

Figure 6. Maps of distribution for the programmed doses on the left and right sides of the distributor in the field test.

After the passage of the mechanized assembly at the marked points, all the materials were collected, weighed, and extrapolated into kilograms of fertilizer applied per hectare, allowing for a comparison with the programmed dose inserted into the controller. With the differences obtained between the programmed and obtained values, the application errors were determined, making it possible to visualize the overall behavior of the data.

In this way, the errors in fertilizer application by the machine were subjected to a descriptive data analysis, calculating the arithmetic mean, median, maximum and minimum values, standard deviation, coefficients of variation (CV), skewness (Cs), and kurtosis (Ck). The normality of the data was verified using the Shapiro–Wilk test and statistical methods, including control charts for individual values. The control charts and range charts displayed the overall mean as the centerline, the average range, and the upper control limits (UCL) and lower control limits (LCL), calculated based on the standard deviation of the variables (LCL = -3σ and UCL = 3σ when greater than zero).

3. Results and Discussion

3.1. Analysis of the Cross-Deposition Assay with Trays

The analysis of variance of the data related to the evaluations of the transversal distribution of the applied product is shown in Table 1. It was observed that the interaction of the factors Side × Doses × Products was significant ($p < 0.05$), where it was possible to confirm that all evaluated factors interfered with the reach of the variable-rate distribution system.

Table 1. Summary of the analysis of variance of the range of the two tested products at three different doses, considering both sides of the variable-rate distribution system.

Sources of Variation	GL	Mean Square and F Test Significance
		Range
Product (P)	1	1.291360 *
Dosage (D)	2	0.014322 *
P × D	2	0.031274 *
Side (S)	1	0.034062 *
S × P	1	0.019049 *
S × D	2	0.028950 *
S × D × P	2	0.038582 *
Error	24	0.000479
cv (%)		5.6
Overall Average		3.9196

*: Significant in the F test at 5% probability. cv: Coefficient of variation

In Table 2, the results of the Scott–Knott test at a 5% probability level for the response variable 'Range' in the various treatments studied are presented. Based on the results, it is possible to observe that the distribution sides of the machine only differed under the same condition for the dose of 400 kg/ha using Product B.

Table 2. Means of reach as a function of applied doses, products used, and machine application side.

		Dosage (kg ha^{-1})		
Product	**Side**	**400**	**700**	**1000**
A	Left	3.72 aB	3.71 aB	3.74 aB
	Rigt	3.72 aB	3.73 aB	3.76 aB
B	Left	4.02 bA	4.11 aA	4.04 aA
	Rigt	4.37 aA	4.11 aA	4.01 aA

Values followed by the same lowercase letter do not differ at 5% statistical probability using the Scott–Knott test for "side" splitting, and values followed by the same capital letter do not differ at 5% statistical probability using the Scott–Knott test for splitting "product".

The observed phenomena can be explained by a possible variation in the horizontal alignment of one of the centrifugal distribution discs, which can cause differences in depositions, as described by [26]. During the tests, no apparent variation in the mechanism was noticed, and the distribution discs were under the same rotational condition. However, the variation was only detected when working with the lowest application dose.

Another observed factor was the difference in distribution reach for the Product variable. Product A reached a maximum average distance of 3.76 m, while Product B reached 4.11 m, both under the same condition of distribution disc speed. This variation was due to the different physical properties of the products used, as noted by [27] in their study on nutrient segregation. They observed changes in the distribution when applied with centrifugal distribution machines, with products of greater density or size being thrown at greater distances.

Regarding the application distance for both products, it was satisfactory, as in areas where mechanized coffee cultivation was employed, row spacing varied from 3.5 to 4.0 m. Therefore, each side of the application system should cover half the distance between rows in the crop. In other words, the distribution system should have a distribution reach of at least two meters to be suitable for the application of fertilizers and soil amendments in coffee cultivation.

For Product A, the higher the dose, the greater the reach, whereas for Product B, the lower the dose, the greater the reach. This variation may be due to differences in the physical properties of the products used. The authors of ref. [28] observed in their work that the application from their equipment varied cyclically and concluded that this variation was due to the product's particle size, which affected its flowability in the machine. The authors in ref. [29] noted that fertilizers with larger particle sizes had less error in application due to requiring higher rates and, consequently, a higher number of dosing shaft rotations per meter of travel.

3.2. Analysis of the Work Regime Trial

A descriptive analysis of the data obtained indicated a significant variation in application error based on the machine sides. According to Table 3, it was observed that the coefficient of variation (CV) of the data was above 35%. The authors in ref. [20] concluded in their studies that the CV of the distribution profile increased rapidly with an increase in the effective application width, reaching 65% for a width of 14 m. The authors in ref. [30] found a CV exceeding 40% for application with an effective width of 30 m. These findings demonstrate the complexity of the operation, which can be affected by various factors that compromise distribution uniformity [31].

Table 3. Descriptive statistical analysis of data related to error as a function of machine sides.

Side	Average	Median	Min	Max	Sd	Coefficient			Test
						CV	Ck	Cs	
Left	−2.77	−2.97	0.0	−4.94	1.39	50.31	−0.31	0.5	N
Right	−2.80	−3.06	0.0	−3.98	1.01	36.07	4.0	1.73	A

Sd: standard deviation; CV: coefficient of variation; Ck: Kurtosis coefficient; Cs: skewness coefficient; N: normal frequency distribution by the Shapiro–Wilk test ($p < 0.05$); A: asymmetric distribution.

Evaluating variable rate fertilizer distribution using rotary discs, ref. [32] observed variations between 23% and 35% between the rates requested and those applied by the system. The authors emphasized that a broader understanding of the necessary setup for specific fertilizers will ensure better distribution and management of the inputs used.

The behavior of the application error for both sides showed a positive skewness coefficient (Cs > 0), with moderate and high values for the left and right sides, respectively. In the same table, it can be observed that the negative kurtosis coefficient explains the greater amplitude of the error relative to the mean of the obtained data. In the case of the kurtosis coefficient, the left side showed a negative coefficient (Ck < 0), while the opposite behavior was observed for the right side. These behaviors explain a greater data spread relative to the mean for the left side, compared to the right side.

Based on the results obtained at a 5% significance level, the data on the left side showed a normal distribution, while the data on the right side exhibited an asymmetric distribution. Similarly, ref. [33] mentioned that hypothesis tests, such as the Shapiro–Wilk test, rigorously assess the normality of variables, and most of the time, these tests reject the hypothesis of normality.

In Figure 7, process control charts for the product application error and data range are presented. It can be seen that the left side exhibited a greater variability in error compared to the right side. Nevertheless, it can be concluded that the error remained within the upper control limit (UCL) and lower control limit (LCL), indicating that the process was under control. The same behavior was observed when analyzing the control chart for data range.

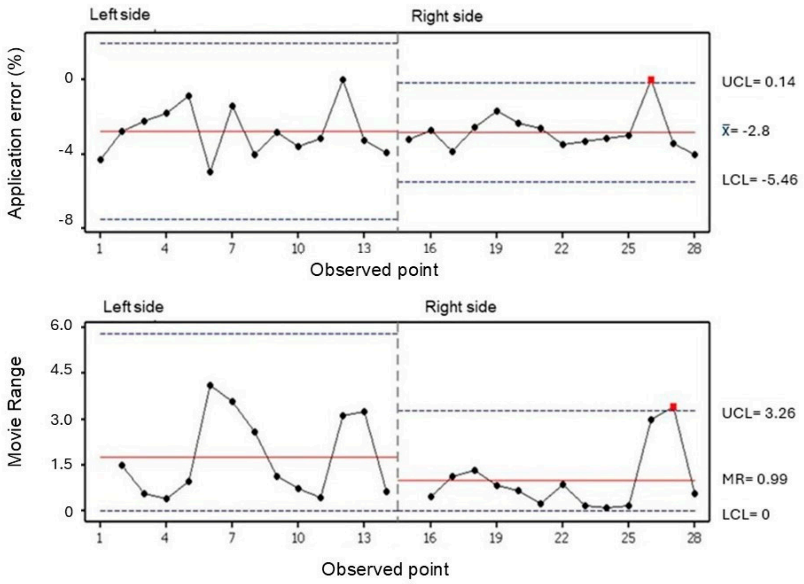

Figure 7. Control chart and amplitude for application error, depending on the distribution side of the machine.

Regarding the right side of application, the observation of a point above the upper control limit (UCL) indicated process instability. However, this process was not considered unmanageable because the values were within an acceptable range for the process, despite exhibiting a non-normal distribution.

According to [34], possible variations between the sides of the spreader occurred due to imbalances in the machine when distributing fertilizer, resulting in a consistently higher application rate on one side, compared to the other. Additionally, ref. [35] mentioned that differences in application between the sides of the machine may occur due to latency in the transfer of information from the controller to the distribution mechanisms.

The trial presented average application errors of −2.77% and −2.8% for the left and right sides, respectively. This result is consistent with those obtained by [19], who, in a similar study, obtained an application error of −3.31%. Aimed at improving the variable-rate application system in orchards, ref. [36] achieved errors of 1.16% and 1.07% under conditions of varying the target amount of fertilization and machine speed. These data demonstrated that, overall, the system yielded acceptable results in the variable-rate application of fertilizers and amendments.

While evaluating a variable-rate fertilizer spreader for surface fertilization in rice paddies, ref. [37] found significant effects on feed flow, machine rotation speed, and ground speed. The average error in the application rate was 9.25%, which was considered satisfactory for uniformity and application accuracy.

When evaluating different types of actuators for variable-rate application in rice, ref. [38] found that the average application error was 9.67% for different work regimes. In another study, ref. [29] assessed a variable-rate application system with different fertilizers and obtained field distribution errors ranging from 20% to 29% when considering a 1 m resolution and an error range of 12% to 14% for a 5 m resolution.

Regarding the quality of the application process, ref. [39] mentioned that variable-rate systems must meet dosage requirements with high precision, resulting in potential operational gains and cost reduction. Therefore, with the adoption of these systems, it is possible to carry out sustainable operations that meet the necessary nutritional demands [40,41]. Thus, it is emphasized that the results obtained in this experiment show the great potential of the developed system for use in coffee crop fertilization.

4. Conclusions

The present study was conducted to develop a variable-rate granular fertilizer application system adapted to coffee cultivation. Based on the results obtained, it is possible to affirm that the adapted system allowed for the extensive application of fertilizers according to the needs of the coffee crops.

In general, the tractors used in coffee farming must be small because the spaces between the coffee rows are narrow. However, many of these tractors do not have the capacity to provide sufficient oil flow through the auxiliary hydraulic system, making it necessary to supply the oil flow required by the distribution systems through an independent system, as developed in this study.

Notably, the variations in the system experienced in terms of dosage parameters, product type, and distribution speeds did not affect the accuracy of the developed system, thus validating the use of the controller under different field conditions. Under real field conditions, the system presented an average error of −2.9%, compared to the programmed doses, confirming the accuracy of the machine and its suitability for use in coffee plantations.

In the future, other aspects of the developed system should be evaluated, such as the independent application of fertilizers and soil amendments to each planting row, considering spatial variability and allowing the farmer to choose fertilizers formulated according to price variations, as the machine has two distribution systems, enabling product separation. Another important point is that the machine applies fertilizer directly under the canopy of the plants, making it possible to apply the full dose in a single pass without the need to apply it on both sides of the plant, resulting in potential gains in operational capacity.

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References

1. Conab. 3° Acompanhamento da Safra Brasileira de Café. 2023. Available online: https://www.conab.gov.br/info-agro/safras/cafe/boletim-da-safra-de-cafe (accessed on 19 June 2024).
2. Moreira, P.C.; Moreira, G.C.; Castro, N.R.; Silva, R.P. Produtividade e economia de fatores de produção na cafeicultura brasileira. *Política Agrícola* **2019**, *2*, 6.
3. Bambi, G.; Iacobelli, S.; Rossi, G.; Pellegrini, P.; Barbari, M. Rural Tourism to Promote Territories along the Ancient Roads of Communication: Case Study of the Rediscovery of the St. Francis's Ways Between Florence and La Verna. *Eur. Countrys.* **2019**, *11*, 462–474. [CrossRef]
4. Mirzakhaninafchi, H.; Singh, M.; Bector, V.; Gupta, O.P.; Singh, R. Design and Development of a Variable Rate Applicator for Real-Time Application of Fertilizer. *Sustainability* **2021**, *13*, 8694. [CrossRef]
5. Barros, M.M.; Volpato, C.E.S.; Silva, F.C.; Palma, M.A.Z.; Spagnolo, R.T. Avaliação de um sistema de aplicação de fertilizantes a taxa variável adaptado à cultura cafeeira. *Coffee Sci.* **2015**, *10*, 223–232.
6. Bottega, E.L.; Queiroz, D.M.; Pinto, F.D.A.C.; Souza, C.M.A. Variabilidade espacial de atributos do solo em sistema de semeadura direta com rotação de culturas no cerrado brasileiro. *Ciência Agronômica* **2013**, *44*, 1–9. [CrossRef]
7. Carvalho, L.C.C.; Silva, F.M.; Ferraz, G.A.S.; Figueiredo, V.C.; Cunha, J.P.B. Comparação entre amostragem foliar convencional e de precisão para análise de micronutrientes na cafeicultura. *Coffee Sci.* **2017**, *12*, 272–281. [CrossRef]
8. Figueiredo, V.C.; Mantovani, J.R.; Leal, R.M.; Miranda, J.M. Levantamento da fertilidade do solo de lavouras cafeeiras em produção, no Sul de Minas Gerais. *Coffee Sci.* **2013**, *8*, 306–313.
9. Ferraz, G.A.S.; Avelar, R.C.; Bento, N.L.; Souza, F.R.; Ferraz, P.F.P.; Damasceno, F.A.; Barbari, M. Spatial variability of soil fertility attributes and yield in a coffee crop farm. *Agron. Res.* **2019**, *17*, 1630–1638. [CrossRef]
10. Silva, F.M.; Souza, Z.M.; Figueiredo, C.A.P.; Vieira, L.H.S.; Oliveira, E. Variabilidade espacial de atributos químicos e produtividade da cultura do café em duas safras. *Ciência Agrotecnologia* **2008**, *32*, 231–241. [CrossRef]
11. Ferraz, G.A.S.; Silva, F.M.; Oliveira, M.S.; Silva, F.C.; Carvalho, L.C.C. Comparativo entre os atributos químicos do solo amostrados de forma convencional e em malha. *Coffee Sci.* **2017**, *12*, 17–29. [CrossRef]
12. Colaço, A.F.; Molin, J.P. Variable rate fertilization in citrus: A long-term study. *Precis. Agric.* **2017**, *18*, 169–191. [CrossRef]
13. Wang, X.C.; Chen, M.; Sun, G.X.; Zhang, Y.; Zhang, Y.N. Design and test of control system on variable fertilizer applicator for winter wheat. *Trans. Chin. Soc. Agri. Eng* **2015**, *31*, 88–92. [CrossRef]
14. Zhang, Y.Z.; Chen, H.T.; Hou, S.Y.; Ji, W.Y.; Ouyang, B.L.; Dun, G.Q.; Zhang, J.C. Design and experiment of slave computer control system for applying variable-rate liquid fertilizer. *J. Northeast Agric. Univ.* **2015**, *22*, 73–79. [CrossRef]
15. Su, N.; Xu, T.S.; Song, L.T.; Wang, R.J.; Rujing, W.; Wei, Y.Y. Variable rate fertilization system with adjustable active feed-roll length. *Int. J. Agric. Biol. Eng* **2015**, *8*, 19–26. [CrossRef]
16. Nørremark, M.; Nielsen, M.; Persson, K. The improvement of centrifugal fertiliser spreaders for precision application control. In Proceedings of the International Fertiliser Society, Cambridge, UK, 7 December 2017; p. 816. Available online: http://fertiliser-society.org/proceedings/uk/Prc816.HTM (accessed on 19 June 2024).
17. Sharipov, G.M.; Heiß, A.; Eshkabilov, S.L.; Griepentrog, H.W.; Paraforos, D.S. Variable rate application accuracy of a centrifugal disc spreader using ISO 11783 communication data and granule motion modeling. *Comput. Electron. Agric.* **2021**, *182*, 106006. [CrossRef]
18. Zhang, J.; Liu, G. Effects of control sequence optimisation on the performance of bivariate fertiliser applicator. *Comput. Electron. Agric.* **2022**, *192*, 106594. [CrossRef]
19. Barros, M.M.; Volpato, C.E.S.; Silva, F.M.; Conceição, F.G.; Júnior, D.C.; Ribeiro, F.L. Performance of a variable-rate distribution system for simultaneous fertilizer application. *Rev. Bras. Eng. Agrícola Ambient.* **2016**, *20*, 188–192. [CrossRef]
20. Farret, I.S.; Schlosser, J.F.; Durigon, R.; Werner, V.; Knob, M. Variação da regulagem no perfil transversal de aplicação com distribuidores centrífugos. *Ciência Rural* **2008**, *38*, 1886–1892. [CrossRef]
21. Akdemir, B.; Saglam, C.; Atar, E.S.; Turen, N.; Özyürüyen, L.C. Development of a Multi-Fertilizer Spreader Machine and Variable Rate Controller for Olive Orchards. *Erwerbs-Obstbau* **2023**, *65*, 839–850. [CrossRef]
22. Chattha, H.S.; Zamana, Q.U.; Changa, Y.K.; Reada, S.; Schumannc, A.W.; Brewsterb, G.R.; Farooqued, A.A. Variable rate spreader for real-time spot-application of granular fertilizer in wild blueberry. *Comput. Electron. Agric.* **2014**, *100*, 70–78. [CrossRef]
23. ISO. Método de ensayos de distribuidores de abonado "a voleo". 5690/1. In *Maquinaria Para Siembra y Abonado: Métodos de Ensayo*; Focitec: Madrid, Spain, 1981; pp. 95–114.
24. Beakawi Al-Hashemi, H.M.; Baghabra Al-Amoudi, O.S. A review on the angle of repose of granular materials. *Powder Technol.* **2018**, *330*, 397–417. [CrossRef]
25. Srivastava, A.K.; Goering, C.E.; Rohrbach, R.P.; Buckmaster, D.R. Machinery Selection and Management. In *Chapter 15 Engineering Principles of Agricultural Machines*, 2nd ed.; ASABE: Saint Joseph, MI, USA, 2006; pp. 525–552.
26. Serrano, J.M.; Peça, M.J.O.; Silva, J.R.; Serrasina, H.; Mendes, J. Avaliação de um distribuidor centrífugo de adubo na perspectiva de utilização em agricultura de precisão. *Rev. Ciências Agrárias* **2007**, *30*, 79–86.
27. Molin, J.P.; Machado, T.M.; Magalhães, R.P.; Faulin, G.D.C. Segregação de fertilizantes aplicados a lanço. *Eng. Agrícola* **2009**, *29*, 614–622. [CrossRef]
28. Werner, V.; Schlosser, J.F.; Rozin, D.; Pinheiro, E.D.; Dornelles, M.E.C. Aplicação de fertilizantes a taxa variável em agricultura de precisão variando a velocidade de deslocamento. *Rev. Bras. Eng. Agrícola Ambient.* **2007**, *11*, 658–663. [CrossRef]

29. Reyes, J.F.; Esquivel, W.; Cifuentes, D.; Ortega, R. Field testing of an automatic control system for variable rate fertilizer application. *Comput. Electron. Agric.* **2015**, *113*, 260–265. [CrossRef]
30. Reynaldo, E.F.; Machado, T.M.; Taubinger, L.; Quadros, D. Distribuição de fertilizantes a lanço em função da qualidade do insumo. *Energ. Agric.* **2016**, *31*, 24–30. [CrossRef]
31. Andrade, A.D.; Ferraz, G.A.S.; Barros, M.M.; Faria, R.O.; Silva, F.M.; Vieri, M. Characterization of the Transverse Distribution of Fertilizer in Coffee Plantations. *Agronomy* **2020**, *10*, 601–614. [CrossRef]
32. Virk, S.S.; Mullenix, D.K.; Sharda, A.; Hall, J.B.; Wood, C.W.; Fasina, O.O.; McDonald, T.P.; Pate, G.L.; Fulton, J.P. Case study: Distribution uniformity of a blended fertilizer applied using a variable-rate spinner-disc spreader. *Appl. Eng. Agric.* **2013**, *29*, 627–636. [CrossRef]
33. Noronha, R.H.; Silva, R.P.; Chioderoli, C.A.; Santos, E.P.; Cassia, M.T. Controle estatístico aplicado ao processo de colheita mecanizada diurna e noturna de cana-de-açúcar. *Bragantia* **2011**, *70*, 931–938. [CrossRef]
34. Han, C.; Lee, S.; Hong, Y.; Kweon, G. Development of a variable rate applicator for uniform fertilizer spreading. *Int. J. Agric. Biol. Eng.* **2019**, *12*, 82–89. [CrossRef]
35. Heiß, A.; Dimitrios, S.; Paraforos, D.S.; Galibjon, M.; Sharipov, G.M.; Griepentrog, H.W. Real-time control for multi-parametric data fusion and dynamic offset optimization in sensor-based variable rate nitrogen application. *Comput. Electron. Agric.* **2022**, *196*, 106893. [CrossRef]
36. Wan, C.; Yang, J.; Zhou, L.; Wang, S.; Peng, J.; Tan, Y. Fertilization control system research in Orchard Based on the PSO-BP-PID control algorithm. *Machines* **2022**, *10*, 982. [CrossRef]
37. Yinyan, S.; Chen, M.; Wang, X.; Morice, O.O.; Li, C.; Ding, W. Design and Experiment of Variable-rate Fertilizer Spreader with Centrifugal Distribution Cover for Rice Paddy Surface Fertilization. *Trans. Chin. Soc. Agric. Mach.* **2018**, *49*, 86–93.
38. Yinyan, S.; Zhichao, H.; Xiaochana, W.; Odhiambo, M.O.; Weimina, D. Motion analysis and system response of fertilizer feed apparatus for paddy Variable-Rate fertilizer spreader. *Comput. Electron. Agric.* **2018**, *153*, 239–247. [CrossRef]
39. Akdemir, B.; Aydoğdu, B.; Üngör, M.G.; Atik, M.; Sağlam, N. Variable Rate Fertilizer Control System for Centrifugal Fertilizer Spreaders. *J. Agric. Fac. Gaziosmanpaşa Univ. (JAFAG)* **2018**, *35*, 319–329.
40. Yinyan, S.; Chen, M.; Wang, X.; Yang, H.; Yu, H.; Hao, X. Efficiency analysis and evaluation of centrifugal variable-rate fertilizer spreading based on real-time spectral information on rice. *Comput. Electron. Agric.* **2023**, *204*, 107505. [CrossRef]
41. Talha, Z.; Tola, E.; Al-Gaadi, K.A.; Kheiralla, A.F. Pneumatic System for Granular Fertilizer Flow Rate Control. *Middle-East J. Sci. Res.* **2011**, *8*, 688–693.