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Spatial and temporal variability of coffee fruit detachment force in relation to maturity aiming at smart harvesting

João de Deus Godinho Filho [1], Jarlyson Brunno Costa Souza [1,*], Samira Luns Hatum de Almeida, Luis Alberto Rocha Rodrigues Junior, Igor Cristian de Oliveira Vieira, Tiago de Oliveira Tavares, Rouverson Pereira da Silva

Department of Engineering and Mathematical Sciences, São Paulo State University, Jaboticabal, São Paulo, Brazil

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ABSTRACT

The implementation of smart harvesting, guided by variability in fruit detachment force, has the potential to facilitate and expand selective coffee harvesting, thereby strengthening the specialty coffee market. This study aimed to evaluate the variation in coffee fruit detachment force throughout the day, considering ripening stage and solar exposure. Evaluations were conducted over two harvest seasons (2018/2019 and 2019/2020) in an East-West-oriented Catuaí Vermelho IAC 144 coffee plantation located in Presidente Olegário, MG, Brazil. Following the principles of Statistical Quality Control (SQC), we analyzed the detachment force of fruits at different ripening stages across various times of the day and on the North- and South-facing sides of the plants, which receive higher and lower solar exposure, respectively. A portable digital dynamometer was used for measurements. The results indicate that both the time of day and solar exposure influence the coffee fruit detachment force, with increased solar exposure reducing the force required for fruit detachment. Fruits at the cherry stage exhibited the lowest detachment force and least variation in the afternoon, suggesting that this period is optimal for selective mechanized harvesting from a process quality standpoint.

1. Introduction

Understanding the factors that influence the force required to detach coffee fruits is essential to improve the efficiency of selective mechanized harvesting. This operation aims to harvest the maximum number of ripe fruits while keeping green fruits on the plants for future harvests. This method adds value to the product, as fruits at the cherry stage are responsible for producing higher-quality coffees [1,2].

The removal of green fruits requires mechanized harvesters to apply greater force, which contributes to more efficient execution of selective harvesting [3]. In this context, the difference in detachment force (DF) between green and ripe fruits is intrinsically linked to the performance of selective mechanized harvesting [4]. However, several factors directly influence the DF of fruits, including the cultivated variety [4–6], soil moisture and fertility [7], the geographical location of the crop [8], the specific harvest time [9], and the solar orientation of the plants [10]. These factors contribute to variations in the force required to detach fruits, directly impacting the efficiency and uniformity of the harvesting process under different conditions.

Given this, studies have been conducted to determine and evaluate detachment force to promote more efficient and smarter harvesting. Interpolated maps of coffee fruit detachment force have been created to identify the best locations and times for harvesting (Araújo and Silva [11]). Additionally, artificial intelligence techniques have been employed to classify detachment force in irrigated and rainfed areas, demonstrating potential to optimize harvest management [2]. Barros et al. [9] explored the use of artificial neural networks to distinguish between green and cherry fruits based on DF, concluding that the first half of the analyzed period would be ideal for harvesting. Finally, Godinho et al. [12] identified that factors such as the time of day and the

Abbreviations: SQC, Statistical Quality Control; σ, Standard deviation; CV, Coefficient of variation; Ck, Kurtosis coefficient; Cs, Skewness coefficient; T*, Anderson-Darling normality test; FD, Detachment force; UCL, Upper control limit; LCL, Lower control limit; RPAs, Remotely Piloted Aircrafts.

* Corresponding author.
E-mail address: jarlyson.brunno@unesp.br (J.B.C. Souza).

[1] These authors have contributed equally to this work and share first authorship.

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solar exposure of plants influence the force required to detach fruits, with cherry-stage fruits showing less resistance at different times of the day.

Understanding the dynamics of detachment force is crucial for the success of coffee harvesting. However, no studies to date have analyzed the variability of DF throughout the day as a function of the solar exposure of the plant's face, aiming to identify the best times for selective harvesting. Recognizing that the time of day influences the force required for fruit detachment, Statistical Quality Control (SQC) emerges as a powerful tool to monitor and evaluate this process's behavior throughout the day. This approach enables the identification of significant patterns and variations, aiding in the development of optimized strategies for selective harvesting based on more precise data.

Statistical Quality Control is based on a temporal analysis of data, which makes it possible to monitor the behavior of mechanized coffee harvesting [13,14]. In this way, the analysis can be carried out through the use of control charts, trend charts, and other tools that allow for inferring process quality, which may in turn be linked to common or special causes. These causes are commonly associated with factors considered "unnatural patterns". Through this monitoring, it is possible to enhance quality indicators, reduce variability, and improve operational management. It is important to emphasize that this approach, unlike classical statistics, which employs tools such as ANOVA and mean comparison tests, relies on continuous analysis.

Thus, the following hypotheses were proposed: the behavior of the coffee fruit detachment process varies throughout the day and between the solar-exposed faces of the coffee plant, with lower force required during periods of higher solar intensity; the variability in detachment force over the day can be effectively monitored using SQC. Therefore, this study aimed to: (1) evaluate the variability and stability in the force required to detach coffee fruits throughout the day, considering the maturity stage and the plant's exposure face; and (2) quantify the differences in detachment force across maturity stages.

2. Material and methods

The experiment was conducted during the harvest periods of the 2018/2019 season on May 29, 2019, and the 2019/2020 season on May 31 and June 1, 2020, in a commercial *Coffea arabica* plantation of the Catuaí Vermelho IAC 144 cultivar, irrigated by a central pivot system and located in Presidente Olegário, Minas Gerais, Brazil (Fig. 1), at an average altitude of 883 m. The region's climate is classified as tropical, with precipitation concentrated in the summer months and a drier winter, according to the Köppen-Geiger classification Aw [15]. The plantation was established in December 2013, with row spacing of 4.0 m, plant spacing of 0.5 m, and an east-west orientation.

The apparent trajectory of the sun in the celestial sphere throughout the year at the latitude of the evaluated plantation shows that the north-facing side of the plants receives greater solar exposure compared to the south-facing side. Thus, the study analyzed different times of the day, the plant's solar exposure faces (north and south), and the maturity stages of the fruits during the harvest period. Adapted from Meneses et al. [2] (Fig. 2).

The evaluations were conducted over time in a pre-selected plot, following the guidelines of Statistical Quality Control [16]. During the first year (2018/2019), the analyzed periods of the day included: early morning (7:30–8:30), mid-morning (9:30–10:30), early afternoon (12:30–13:30), mid-afternoon (14:30–15:30), and late afternoon (16:30–17:30). The analyses considered the plant's north and south-facing sides, as well as the maturity stages: green, green cane, cherry, and dry.

In the 2019/2020 season, the evaluated periods were morning (9:00–10:00), afternoon (15:00–16:00), night (21:00–22:00), and early morning (4:00–5:00), covering both exposure sides and maturity stages: green, cherry, and dry. In the 2019/2020 harvest, the green and green cane maturation classes did not show a statistical difference, so they were grouped and represented by the green class.

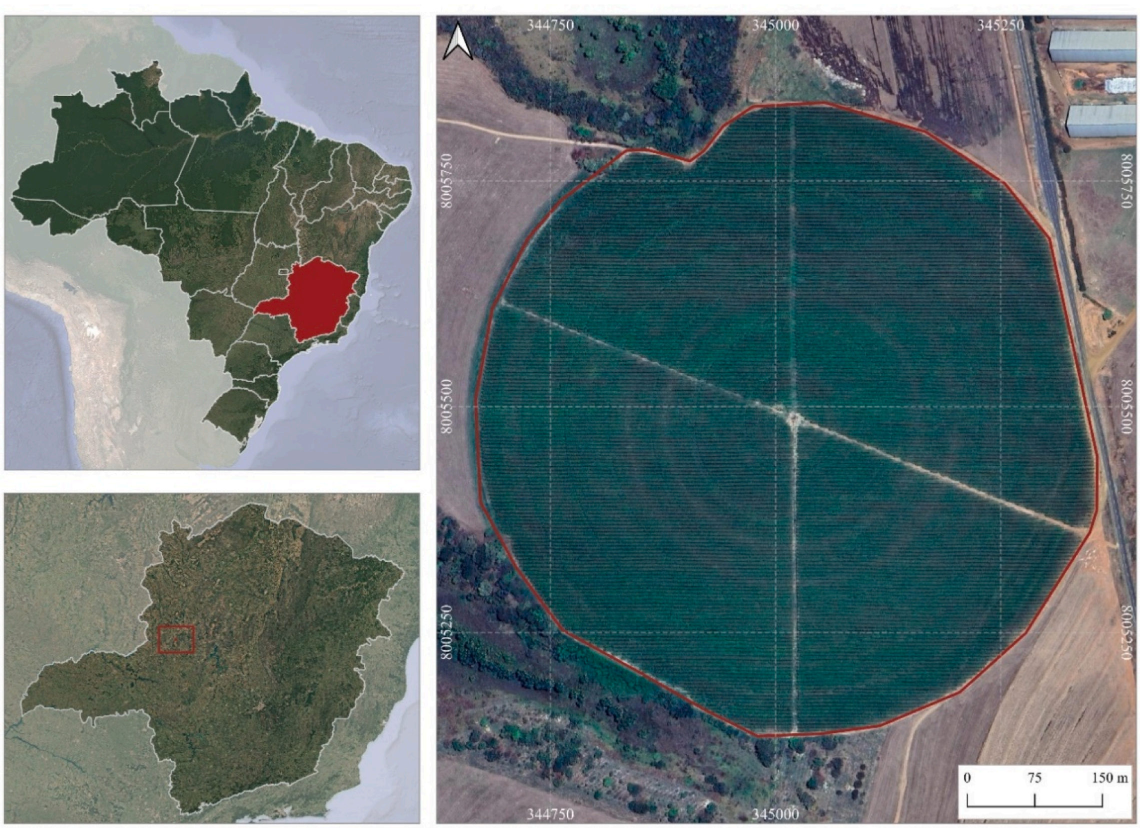

Fig. 1. Experimental area in presidente Olegário, Minas Gerais State, Brazil.

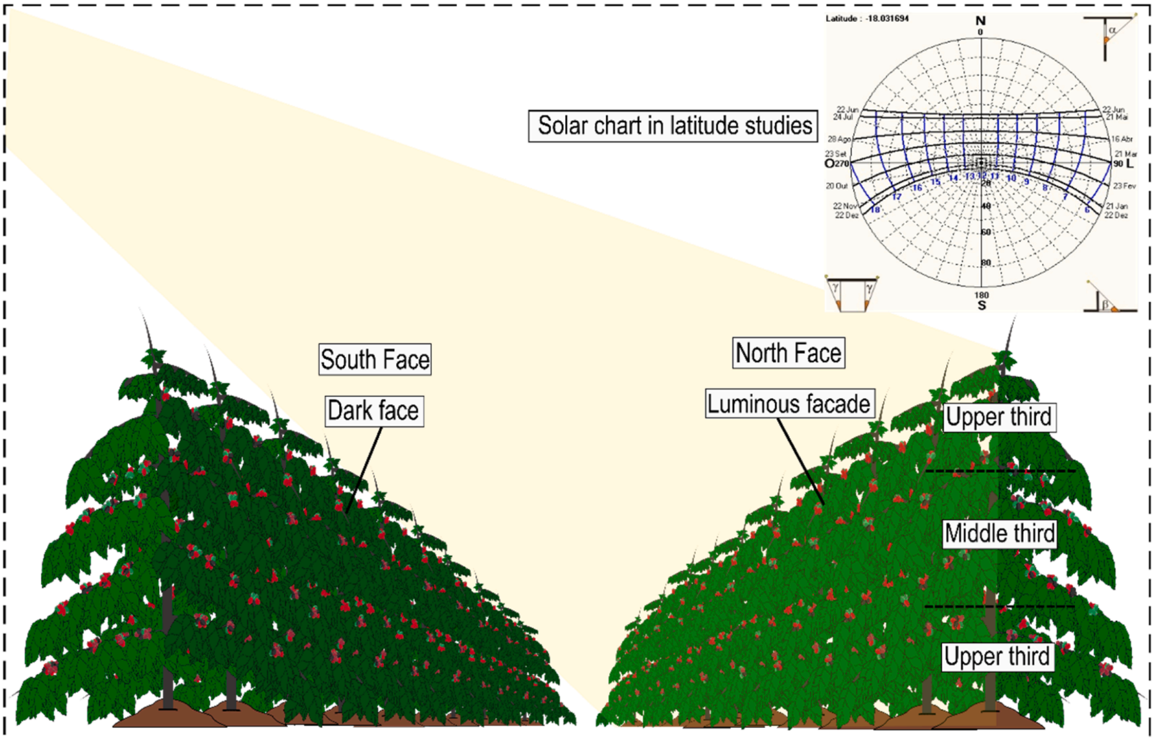

Fig. 2. Projection of the sun's position throughout the year for the plantation's latitude (Source: Sol-Ar Software) and schematic representation of the plant sections evaluated and their solar exposure faces.

For each period, 36 sampling points were defined, each consisting of six plants. On each plant face, two fruits were evaluated for each maturity stage across three parts of the plant: upper, middle, and lower sections. The detachment force was measured using a portable digital dynamometer (Instrutherm, model DD-500) with a measurement capacity of 0 to 49 N and a resolution of 0.01 N. A detailed flowchart of the analyzed factors is presented in Fig. 3. Adapted from Meneses et al. [2].

The climatic conditions were monitored using a digital thermo-hygrometer (model HT-350) with an accuracy of ±1.0 °C (ambient temperature) and ±5 % (relative humidity) and a resolution of 0.1 °C (temperature) and 0.01 % (humidity). During sample collection, the average ambient temperature and relative humidity were measured, as shown in Fig. 4.

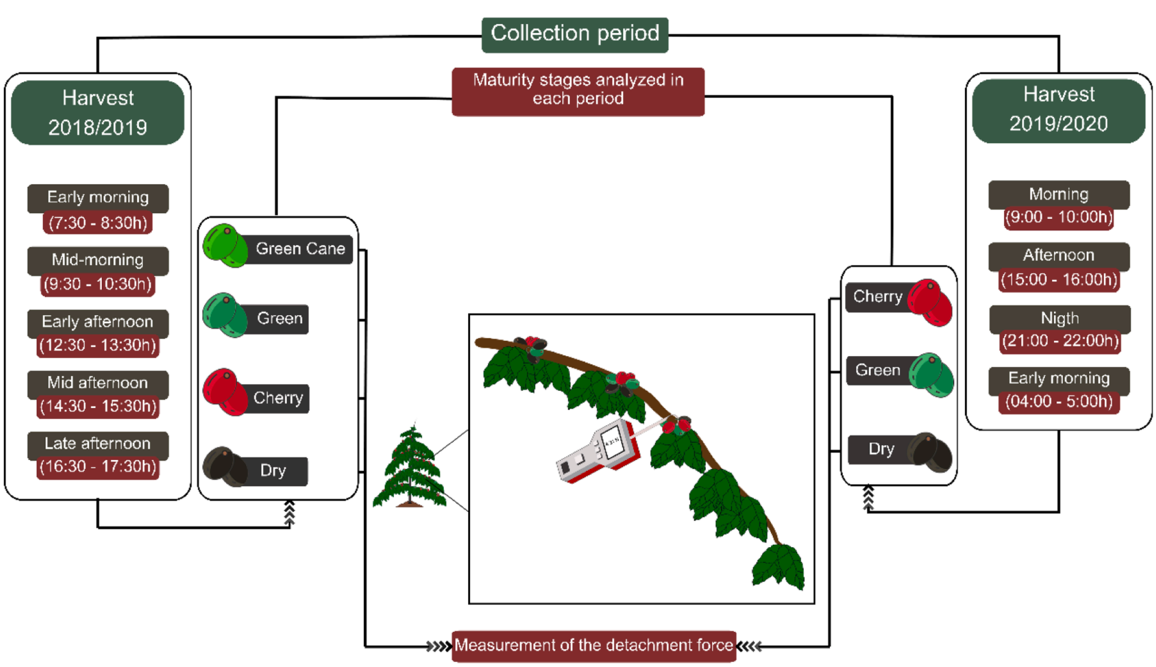

Fig. 3. Methodological scheme of collection periods and maturity stages.

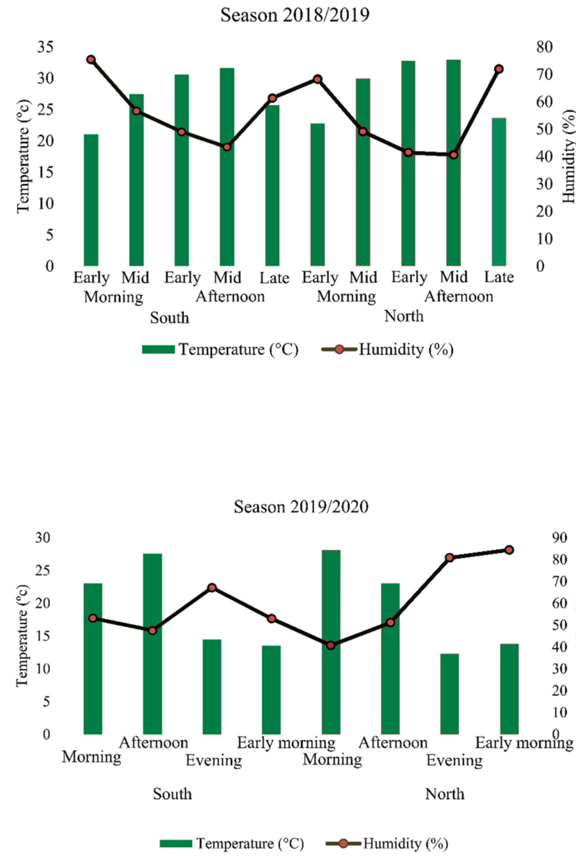

Fig. 4. Environmental parameters were measured during the evaluations of coffee fruit detachment force in the 2018/2019 (A) and 2019/2020 (B) harvest seasons, on May 29, 2019, and May 31 and June 1, 2020, respectively.

2.1. Descriptive statistics

The obtained results were initially analyzed using descriptive statistics, including arithmetic mean, median, standard deviation, and coefficients of kurtosis, skewness, and variation. The coefficient of variation was interpreted using the following classification: low (0–10 %), medium (11–20 %), high (21–30 %), and very high (>30 %) [17]. Data normality was assessed based on the parameters of descriptive statistics and the Anderson-Darling test.

2.2. Statistical quality control

The variability analysis of detachment force over time was conducted using Statistical Quality Control tools. The first tool applied was run charts, which allow the identification of non-random patterns. These patterns enable process monitoring by identifying and classifying data variations over time [18]. This classification categorizes the data into four types of patterns: mixture, clustering, oscillation, and trend.

The mixture pattern occurs when no points are close to the central line (median), with successive mixtures indicating data associated with two distinct populations. Clustering arises when groups of points appear in specific areas of the chart, indicating variations related to special causes, such as measurement errors. Oscillation is observed when data alternates between the upper and lower parts of the median, indicating that the process is non-uniform.

The trend pattern occurs when data shows non-uniformity, either above or below the central line, indicating that points outside the control limits are likely to appear soon. Data sets with $p \langle 0.05$ indicate significant non-random patterns, whereas values with $p \rangle 0.05$ are not significant and suggest random behavior, indicating normal process variation.

Another SQC tool used was the I-MR control charts (individual – moving range), which allow monitoring the process mean and variation when data is observed continuously. These charts consist of two plots: the upper plot displays individual data points for each sample, while the lower plot represents the moving range calculated between two successive points. The moving range represents the variation between consecutive observations, calculated by the absolute difference between two adjacent values, and is used in X-MR charts to monitor the dispersion in processes with unit samples.

To identify uncontrolled causes in the process (special causes), control limits were defined based on the standard deviation of the variables. The upper control limit (UCL) was calculated as the mean plus three times the standard deviation, and the lower control limit (LCL) as the mean minus three times the standard deviation, with values below zero excluded from the LCL.

When interpreting control charts, attention should be paid to points outside the control limits. When these occur, the process is said to be out of control, indicating instability caused by special causes. The explanation for these causes is explained by the "unnatural pattern" factors: labor, materials, method, measurement, machinery, and environment [19].

3. Results

3.1. Descriptive statistics

In the descriptive analysis, it was observed that, for cherry-ripened fruits, the mean and median values of detachment force decreased consistently in the afternoon compared to the other periods, regardless of the harvest time analyzed (Figs. 5 and 6). This reduction suggests a possible change in detachment processes throughout the day, indicating greater ease of harvesting during this period.

In the 2018/2019 harvest (Fig. 5), green fruits showed normality in most of the variables analyzed (70 %), while the other ripening stages (green cane, cherry, and dry) showed lower normality percentages: 50 %, 40 %, and 30 %, respectively. In contrast, in the 2019/2020 harvest (Fig. 6), the normality percentages were higher: 75 % for green fruits, 63 % for cherries, and 38 % for dry fruits. The non-normality observed in 55 % of the variables in 2018/2019 was confirmed by the difference between the mean and median values, as well as by the coefficients of asymmetry, kurtosis, and variability, which highlighted the amplitude of the data in both harvests evaluated.

The kurtosis coefficient analysis revealed significant dispersion compared to the reference curve for a normal distribution. A kurtosis value of zero indicates a mesokurtic distribution (normal curve), while values less than or greater than zero represent platykurtic (flattened curve) and leptokurtic (peaked curve) distributions, respectively. In the evaluated seasons, a leptokurtic distribution predominated in 2018/2019, while a platykurtic distribution prevailed in 2019/2020, reflecting the high intrinsic variability of the detachment process. Thus, positive or negative kurtosis coefficients result in a lower probability of data being normally distributed around the mean.

In the 2018/2019 season, the difference in mean detachment force between green and cherry fruits was more pronounced in the afternoon (early, mid, and late), with an increase of approximately 40 % compared to the morning period. In the 2019/2020 season, this increment was 18 % between morning and afternoon, and an even greater difference (28 %) was observed between the morning and early morning periods.

3.2. Run charts

In the 2018/2019 season, the analysis of run charts (Table 1) identified patterns of special causes for different maturity stages. For green fruits, a clustering pattern was observed during the two morning evaluations, both on the north-facing side. In green cane fruits, in addition to

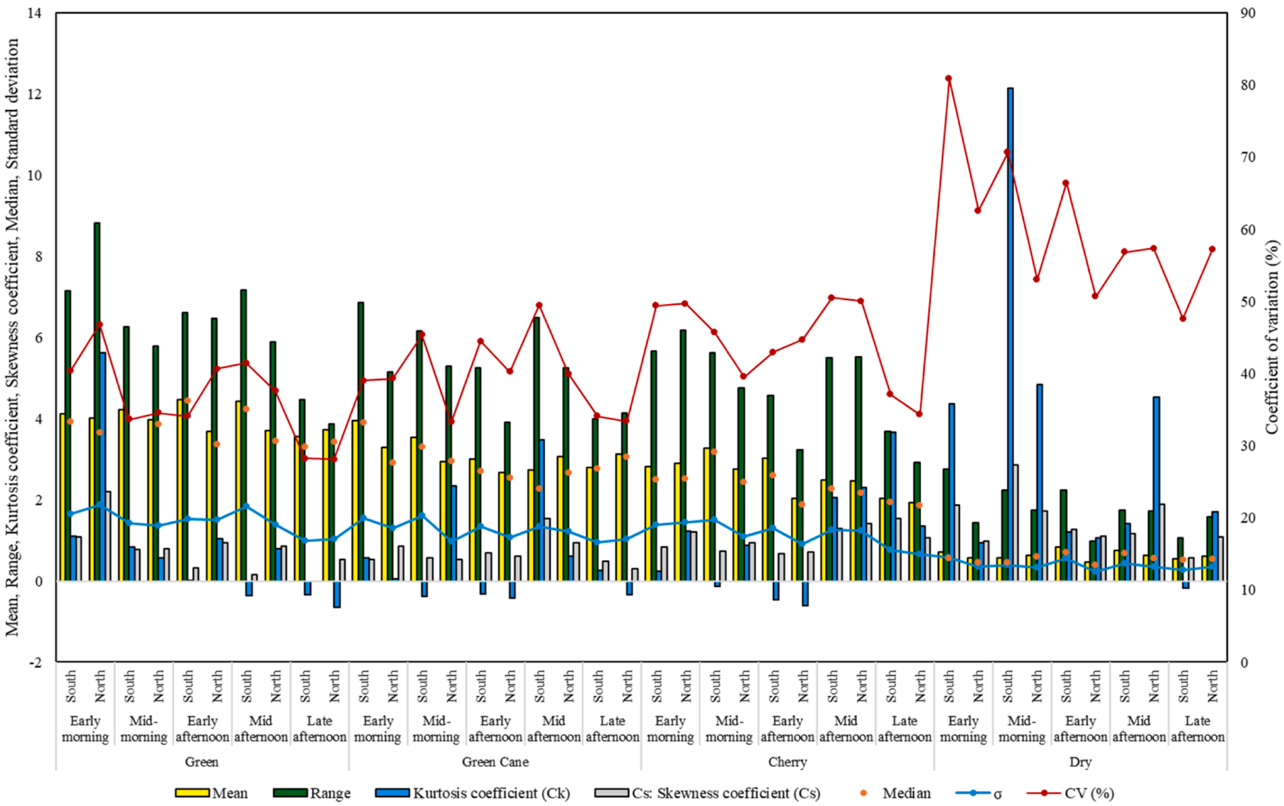

Fig. 5. Descriptive statistics of parameters related to the detachment force (N) of *C. arabica* fruits during the 2018/2019 harvest season. σ: standard deviation; CV: coefficient of variation; Ck: kurtosis coefficient; Cs: skewness coefficient.

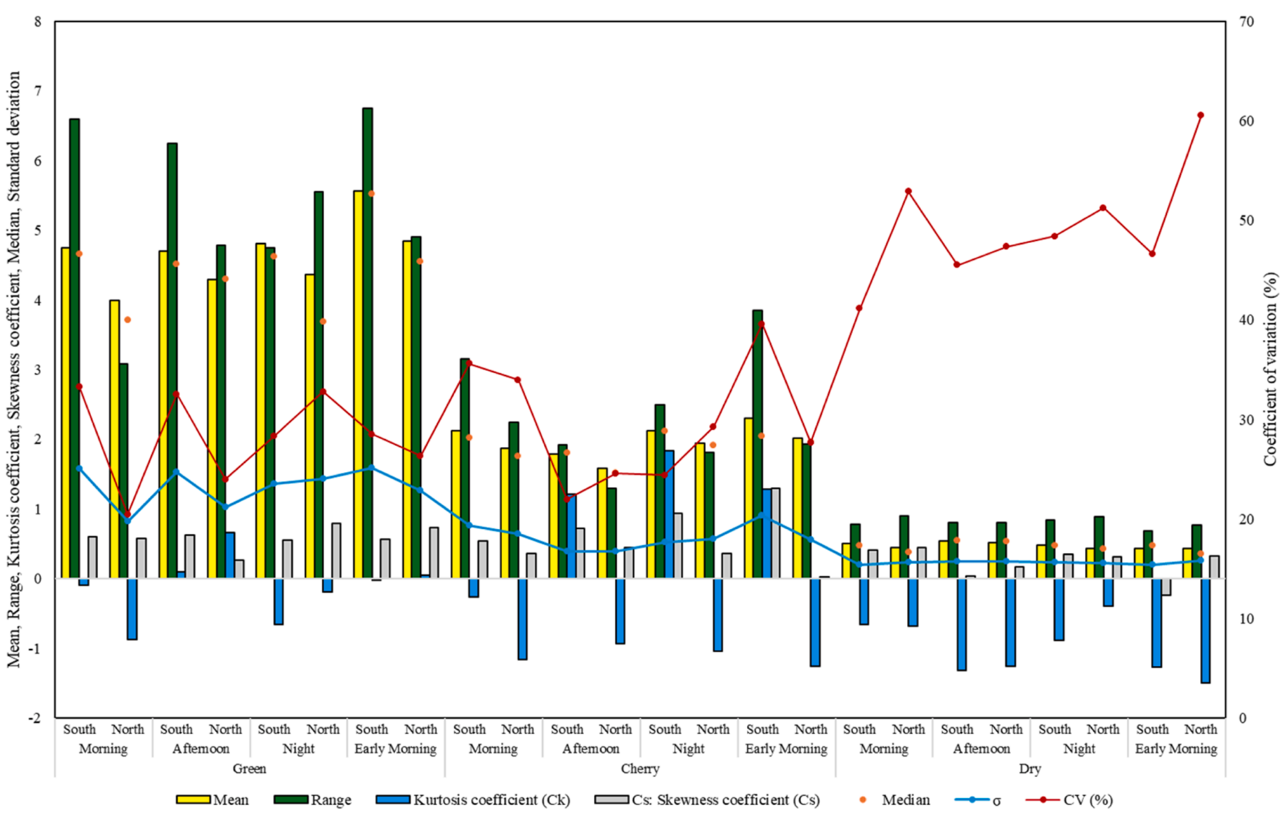

Fig. 6. Descriptive statistics of parameters related to the detachment force (N) of *C. arabica* fruits during the 2019/2020 harvest season. σ: standard deviation; CV: coefficient of variation; Ck: kurtosis coefficient; Cs: skewness coefficient.

Table 1
Probability values for verifying the occurrence of patterns related to the detachment force of *C. arabica* fruits during the 2018/2019 harvest season.

Maturity Stage	Time of Day	Face	Patterns			
			Clustering	Mixture	Trend	Oscillation
Green	Early morning	South	0,37ns	0,63ns	0,71ns	0,29ns
		North	0,00*	0,10ns	0,71ns	0,29ns
	Mid-morning	South	0,09ns	0,91ns	0,39ns	0,61ns
		North	0,05*	0,96ns	0,71ns	0,29ns
	Early afternoon	South	0,85ns	0,16ns	0,39ns	0,61ns
		North	0,50ns	0,50ns	0,39ns	0,61ns
	Mid afternoon	South	0,25ns	0,75ns	0,07ns	0,93ns
		North	0,37ns	0,63ns	0,25ns	0,75ns
	Late afternoon	South	0,37ns	0,63ns	0,71ns	0,29ns
		North	0,50ns	0,50ns	0,39ns	0,61ns
Green Cane	Early morning	South	0,05*	0,96ns	0,39ns	0,61ns
		North	0,37ns	0,63ns	0,55ns	0,45ns
	Mid-morning	South	0,09ns	0,91ns	0,25ns	0,75ns
		North	0,05*	0,96ns	0,39ns	0,61ns
	Early afternoon	South	0,09ns	0,91ns	0,39ns	0,61ns
		North	0,16ns	0,85ns	0,14ns	0,86ns
	Mid afternoon	South	0,37ns	0,63ns	0,55ns	0,45ns
		North	0,05*	0,96ns	0,03*	0,97ns
	Late afternoon	South	0,50ns	0,50ns	0,55ns	0,45ns
		North	0,85ns	0,16ns	0,71ns	0,29ns
Cherry	Early morning	South	0,05*	0,96ns	0,39ns	0,61ns
		North	0,01*	0,99ns	0,71ns	0,29ns
	Mid-morning	South	0,50ns	0,50ns	0,39ns	0,61ns
		North	0,63ns	0,37ns	0,91ns	0,09ns
	Early afternoon	South	0,16ns	0,85ns	0,55ns	0,45ns
		North	0,37ns	0,63ns	0,39ns	0,61ns
	Mid afternoon	South	0,37ns	0,63ns	0,03*	0,97ns
		North	0,05*	0,96ns	0,00*	1,00ns
	Late afternoon	South	0,16ns	0,85ns	0,25ns	0,75ns
		North	0,09ns	0,91ns	0,99ns	0,02*
Dry	Early morning	South	0,05*	0,95ns	0,71ns	0,29ns
		North	0,16ns	0,85ns	0,14ns	0,86ns
	Mid-morning	South	0,16ns	0,85ns	0,00*	1,00ns
		North	0,05*	0,96ns	0,14ns	0,86ns
	Early afternoon	South	0,37ns	0,63ns	0,83ns	0,17ns
		North	0,96ns	0,04*	0,71ns	0,29ns
	Mid afternoon	South	0,51ns	0,49ns	0,25ns	0,75ns
		North	0,50ns	0,50ns	0,25ns	0,75ns
	Late afternoon	South	0,96ns	0,05*	0,83ns	0,17ns
		North	0,37ns	0,63ns	0,03*	0,97ns

* : Standard non-random values detected by the probability test at $p < 0.05$; ns: Standard random values detected by the probability test at $p > 0.05$.

clustering in the early morning on the south-facing side and the mid-morning and afternoon on the north-facing side, a rising trend was also noted in the mid-afternoon on the same side. This upward pattern in the force required for fruit detachment from mid-afternoon to the end of the day was confirmed by higher mean and median values in the late afternoon compared to mid-afternoon.

For cherry fruits, a clustering pattern was detected in the early morning on both solar exposure faces, while in the mid-afternoon, it occurred only on the north-facing side. Decreasing trends were observed in the mid-afternoon on both faces, and an oscillation pattern appeared in the late afternoon on the north-facing side. For dry fruits, clustering occurred in the early morning on the south-facing side and in the mid-morning on the north-facing side. Heterogeneous behavior was observed in the early afternoon on the north-facing side and in the late afternoon on the south-facing side, while trends were identified in the mid-morning on the south-facing side and in the late afternoon on the north-facing side.

In the 2019/2020 season, the run charts identified a clustering pattern for green fruits in the morning on the north-facing side and at dawn on the south-facing side, as well as an increasing trend in detachment force on the north-facing side in the afternoon (Table 2). This pattern suggests a rise in the force required to detach green fruits from late afternoon to early evening.

For cherry fruits, a trend pattern was also detected in the afternoon on the north-facing side, with an initial reduction in detachment force between the morning and afternoon periods, followed by an increase in subsequent evaluations (evening and early morning). In the morning, the north-facing side exhibited an oscillation pattern, while the south-facing side showed a clustering pattern, which was repeated in the afternoon on the north-facing side and at dawn on the south-facing side.

For dry fruits, detachment force showed lower variability compared to the other maturity stages. In both seasons, most evaluations did not indicate special causes. Common cause variations accounted for 57.5 % in the 2018/2019 season and 66.7 % in the 2019/2020 season, reflecting random behavior in the detachment process.

3.3. Control charts

Analyzing the results from the 2018/2019 and 2019/2020 seasons, it was observed that the quality indicator, detachment force, exhibited an unstable process throughout the day, regardless of the maturity stage (Figs. 7 and 8).

In the 2018/2019 season, for fruits in the green and cherry maturity stages, there was, in general, a decrease in the variability of detachment force evaluated throughout the day. However, the process remained unstable during most periods, except for mid-morning evaluations on the north-facing side for green fruits and on the south-facing side for cherries. Additional exceptions were observed in the early afternoon on the north-facing side for cherries and on both faces for green fruits, as well as in the mid-afternoon on the south-facing side and late afternoon

Table 2
Probability values for verifying the occurrence of patterns related to the detachment force of *C. arabica* fruits during the 2019/2020 harvest season.

Maturity Stage	Time of Day	Face	Patterns			
			Clustering	Mixture	Trend	Oscillation
Green	Morning	South	0,09ns	0,91ns	0,07ns	0,93ns
		North	0,05*	0,96ns	0,14ns	0,86ns
	Afternoon	South	0,25ns	0,75ns	0,39ns	0,61ns
		North	0,16ns	0,85ns	0,01*	0,99ns
	Night	South	0,25ns	0,75ns	0,83ns	0,17ns
		North	0,16ns	0,85ns	0,07ns	0,93ns
	Early Morning	South	0,02*	0,98ns	0,55ns	0,45ns
		North	0,16ns	0,85ns	0,25ns	0,75ns
Cherry	Morning	South	0,05*	0,96ns	0,25ns	0,75ns
		North	0,25ns	0,75ns	1,00ns	0,01*
	Afternoon	South	0,76ns	0,24ns	0,39ns	0,61ns
		North	0,05*	0,96ns	0,01*	0,99ns
	Night	South	0,16ns	0,85ns	0,39ns	0,61ns
		North	0,91ns	0,09ns	0,39ns	0,61ns
	Early Morning	South	0,02*	0,98ns	0,25ns	0,75ns
		North	0,63ns	0,37ns	0,39ns	0,61ns
Dry	Morning	South	0,26ns	0,75ns	0,83ns	0,17ns
		North	0,25ns	0,75ns	0,14ns	0,86ns
	Afternoon	South	0,75ns	0,25ns	0,91ns	0,09ns
		North	0,16ns	0,85ns	0,03*	0,97ns
	Night	South	0,26ns	0,75ns	0,25ns	0,75ns
		North	0,64ns	0,36ns	0,25ns	0,75ns
	Early Morning	South	0,25ns	0,75ns	0,07ns	0,93ns
		North	0,63ns	0,37ns	0,71ns	0,29ns

* : Standard non-randomness values detected by the probability test at $p < 0.05$; ns: Standard randomness values detected by the probability test at $p > 0.05$.

when instability was reduced for green fruits on both faces of the plant.

The moving range charts indicated that the lowest variability in detachment force occurred in the late afternoon on both solar exposure faces. During this same period, the lowest mean detachment force was recorded for green and cherry fruits, suggesting greater ease of detachment. Conversely, the highest detachment force was recorded on the south-facing side in the early afternoon for green fruits and mid-morning for cherry fruits.

In the following year, during the 2019/2020 season, the variability in detachment force for green fruits was more consistent, with lower values on the north-facing side during the morning and afternoon periods. For cherry fruits, as in the previous season, the detachment process showed less variability in the afternoon.

In the 2019/2020 season, a lower percentage of out-of-control points was observed, indicating a more homogeneous process compared to the previous season. However, instabilities were detected in the detachment of green fruits on the south-facing side during the morning and early morning, while on the north-facing side, the process was unstable only in the afternoon. For cherry fruits, instability was recorded in the afternoon, evening, and early morning, being restricted to the south-facing side of the coffee plant.

The green cane fruits, evaluated only in the 2018/2019 season, showed the highest detachment force values and greater variation during mid-morning on the south-facing side and early morning on both sides of the plant. On the other hand, process stability was identified in the early morning on the north-facing side, on both sides in the afternoon, and the north-facing side during early morning hours.

For dry fruits, in the 2018/2019 season, there was less variation in detachment force throughout the day, with the lowest force and variation values recorded on the north-facing side in the early afternoon. Process stability was observed during the same period and in the early morning for the north-facing side, as well as on both sides in the late afternoon. In the 2019/2020 season, the process was entirely stable. The lowest force and variation values for dry fruits were recorded on the south-facing side during the early morning.

Finally, the analysis of special causes confirmed the results of the run charts, indicating that the detachment process of coffee fruits was unstable regardless of the maturity stage or season, except for dry fruits in the 2019/2020 season.

4. Discussion

The results of this study demonstrate that, despite the observed variability, the percentage of out-of-control points in the detachment process was relatively small, indicating a greater influence of common causes. In the 2018/2019 season, the percentages were 1.67 % for green fruits, 1.25 % for green cane fruits, 1.67 % for cherry fruits, and 2.09 % for dry fruits. In the 2019/2020 season, the percentages were even lower: 1.22 % for green fruits, 0.87 % for cherry fruits, and 0.17 % for dry fruits. These values highlight that, although special causes of variability exist, they represent a limited portion, with most oscillations being associated with the inherent characteristics of the agricultural process.

The high variability in the fruit detachment process was confirmed by the divergence between mean and median values, as well as the elevated coefficients of skewness, kurtosis, and variation in both seasons (Figs. 5 and 6). For variables with normal distribution, the coefficients of variation were classified as high (21–30 %) or very high (>30 %) according to Pimentel-Gomes and Garcia [17]. This variability reflects the complexity of selective mechanized harvesting, where the difference in detachment force between green and ripe fruits is crucial for the process's success. This difference allows ripe fruits to be detached while green fruits remain on the plant, ensuring greater selectivity and efficiency [7].

The observed clusters (Tables 1 and 2), regardless of fruit maturity stage or harvest year, can be attributed to the three sections of the plant evaluated. Coffee fruit ripening is notoriously uneven and is influenced by these sections [20]. Additionally, the non-random patterns observed in all evaluations reflect the non-random behavior of the data, indicating the presence of special causes in the detachment process. The occurrence of these special causes can be explained by the "unnatural pattern" factors: labor, materials, method, measurement, machinery, and environment [19].

The coffee variety and the maturity stages of the fruits constitute the material factor, while the time of day, plant section, and solar exposure face represent the environmental factor. As seen in the results, environmental conditions have a direct impact on the fruit detachment force. In general, the south-facing side was the one where the fruits required greater force for detachment. Compared to the north-facing side, the

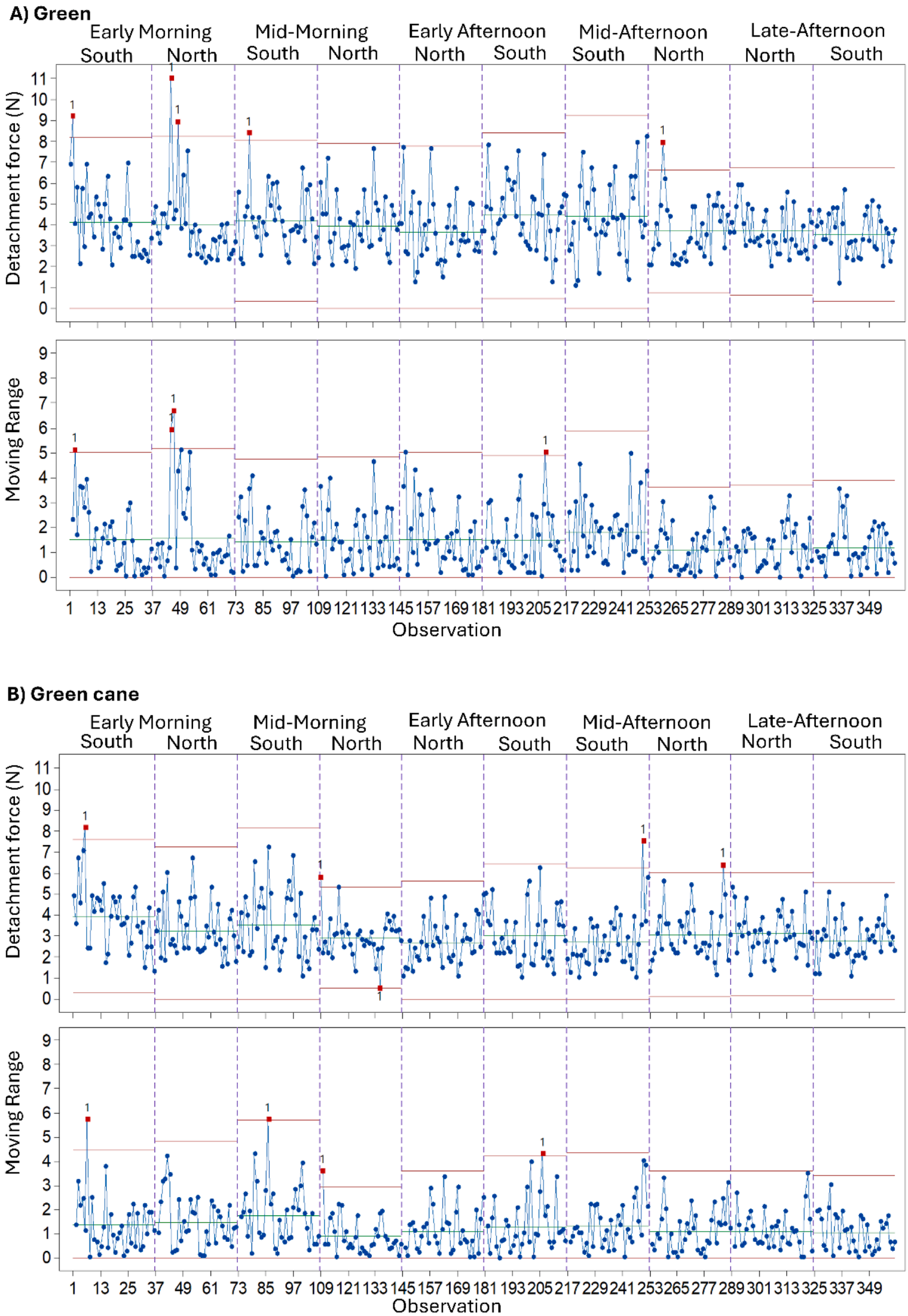

Fig. 7. Individual and moving range control charts for the detachment force of *C. arabica* fruits during the 2018/2019 harvest season, categorized by time of day, solar exposure face, and maturity stage. Upper control limit (UCL), mean ($\bar{x}$), and mean moving range ($\overline{AM}$).

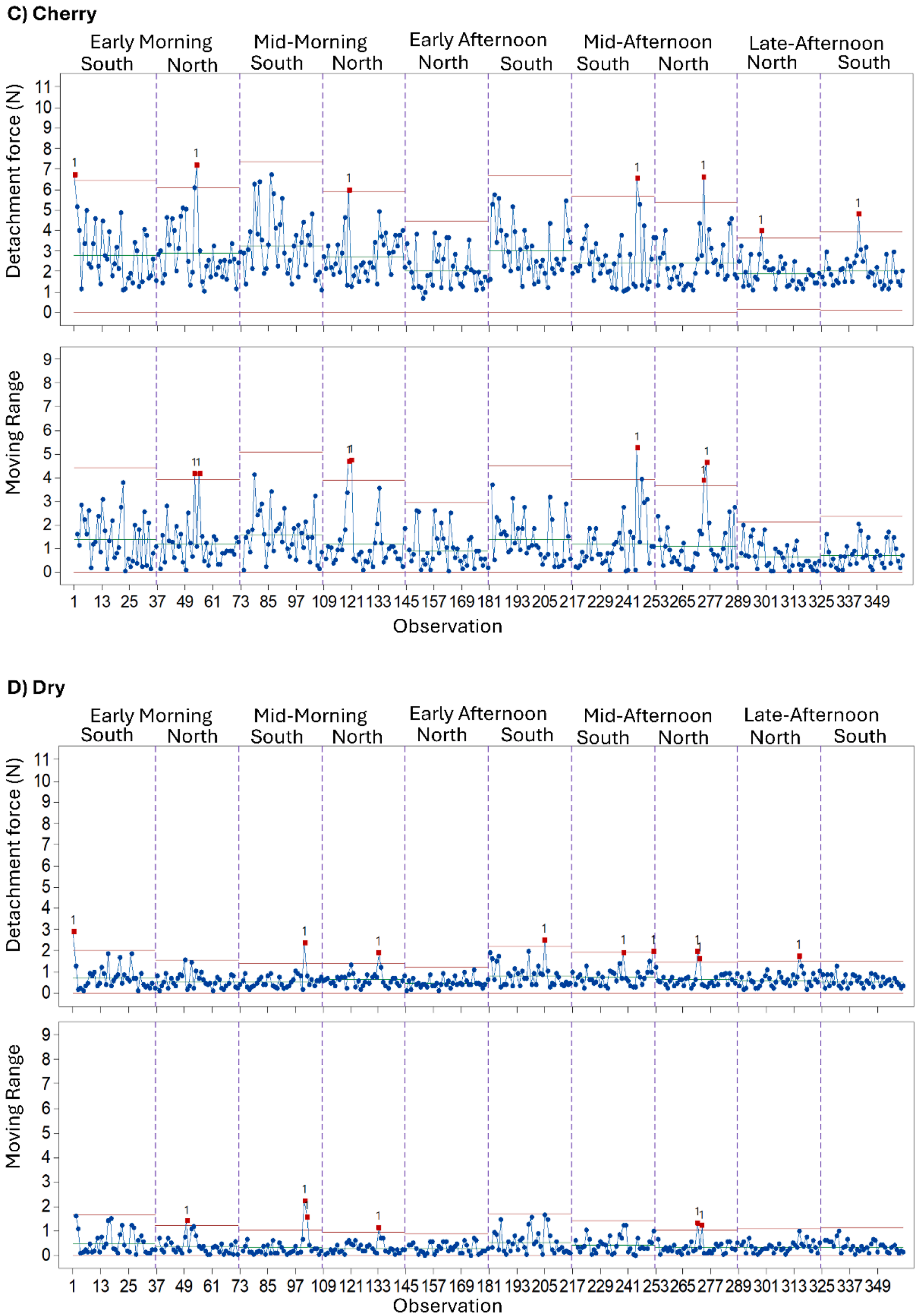

Fig. 7. (*continued*).

south receives less radiation, consequently lower temperature and higher humidity. Under these conditions, the pedicel remains moister, acquiring greater resistance to detachment. Higher temperatures, as also found by Silva et al. [21], reduce the elasticity of the pedicel and the fruit detachment force.

Regarding maturation, studies with the banana crop indicated the

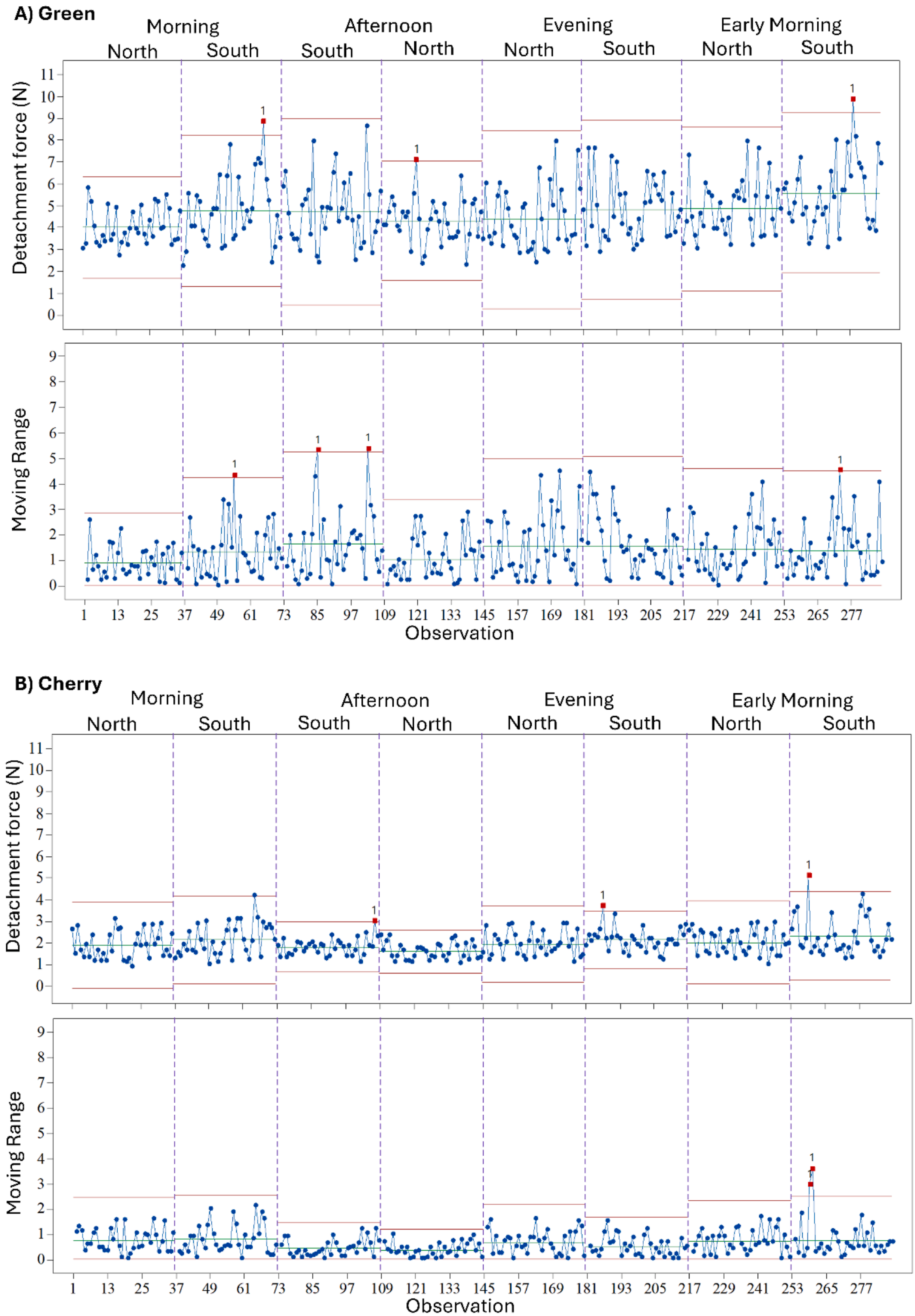

Fig. 8. Individual and moving range control charts for the detachment force of *C. arabica* fruits during the 2019/2020 harvest season, categorized by time of day, solar exposure face, and maturity stage. Upper control limit (UCL), mean ($\overline{x}$), and mean moving range ($\overline{AM}$).

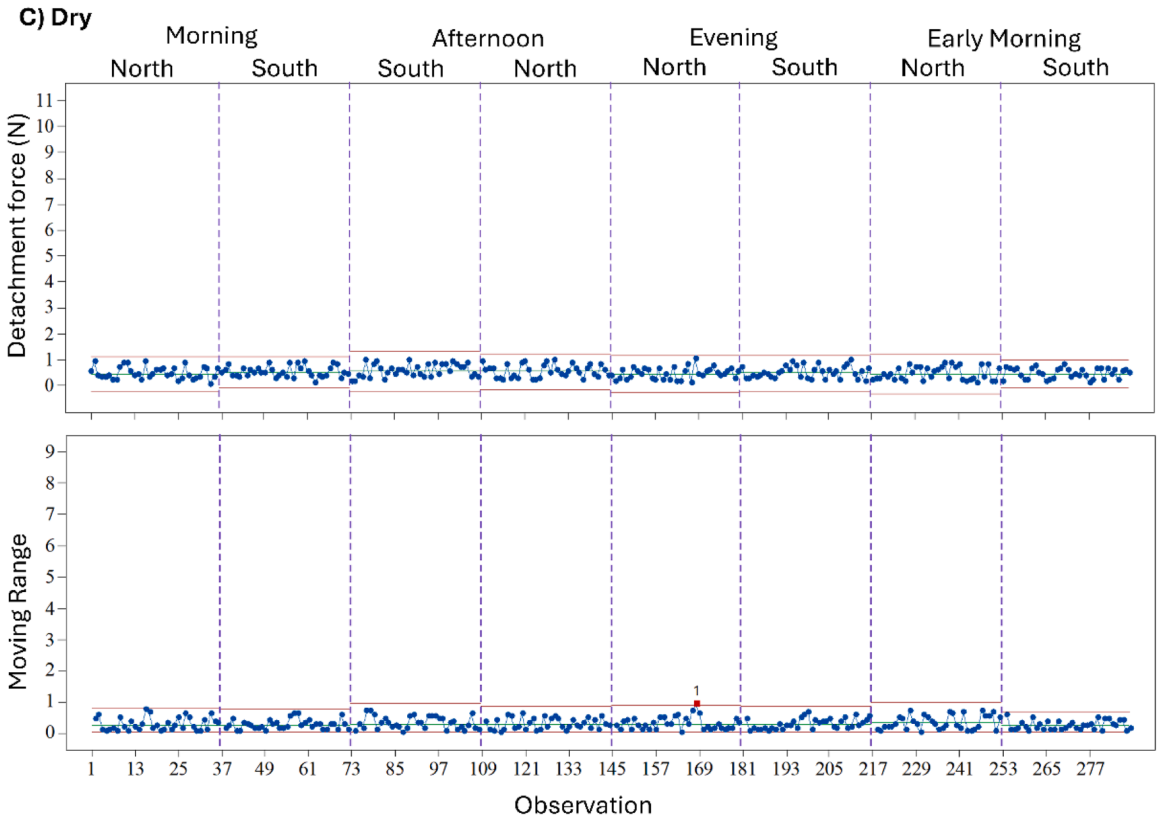

Fig. 8. (*continued*).

degradation of parenchyma cells in the pedicel of ripe fruits [22]. This is a possible explanation for the loss of pedicel resistance as ripening progresses. Coelho et al. [23] observed similar behavior, with higher detachment force in green fruits compared to cherry fruits. The authors attributed the greater fragility of the pedicel in ripe fruits to the degradation of the cell wall due to the action of the hormone ethylene.

Based on the p-values obtained from the run chart analysis, it is evident that non-random patterns are primarily related to solar exposure face, highlighting the influence of microenvironmental conditions on detachment force behavior. Greater solar radiation on one face of the coffee plant throughout the year can increase productivity compared to the less illuminated opposite face [24]. This production difference influences the force required for fruit detachment: Under more productive conditions, the plant has less energy to retain the fruits, as most of it is directed toward fruit development. In contrast, less productive plants have more available energy, causing the fruits to require greater detachment force [8,11,25].

The run charts (Tables 1 and 2) and control charts (Figs. 7 and 8) revealed significant changes in detachment force behavior throughout the day, characterized by increasing and decreasing trends directly influenced by environmental and physiological factors. In the 2018/2019 season, the lowest mean force and variation values were recorded in the late afternoon for green and cherry fruits, while the highest values were observed in the mid-afternoon for green fruits on the south-facing side and in the morning for cherry fruits. This trend suggests that late afternoon is the most favorable period for selective harvesting due to the greater difference in detachment force required for cherry and green fruits, as well as the lower variation observed for cherry fruits on both faces. This finding guides operational adjustments in harvesters, aiming to achieve smart harvesting.

In the 2019/2020 season, green fruits showed greater consistency in variability, with the lowest values observed on the north-facing side during the morning. For cherry fruits, as in the previous season, the afternoon period exhibited the lowest variability, confirming it as the most suitable time for selective mechanized harvesting. By considering variability as an indicator for selective harvesting, the aim is to ensure that the detachment force ranges for cherry and green fruits do not overlap or do so as minimally as possible. In the afternoon, all points within the lower and upper control limits for cherry fruits require a significantly lower detachment force than the average required for green fruits. With proper adjustments, this reduces the likelihood of undesired detachment of green fruits alongside cherries.

The use of SQC allowed for a more detailed analysis, providing a clearer understanding of the spatiotemporal variability of detachment force (DF) in coffee fruits. One of the most significant findings was the identification of the afternoon as the ideal period for selective harvesting, contrasting with previous approaches. These results are particularly relevant due to the in-depth analysis of DF variability as a quality indicator. Godinho et al. [12], in evaluating DF from another perspective, considering maturity levels and solar exposure face, concluded that all times of the day were suitable for selective harvesting. However, our study did not corroborate this generalization, emphasizing the importance of considering the temporal variability of DF throughout the day. This new perspective highlights the need for more precise approaches and techniques to determine the optimal harvesting time, contributing to advances in agricultural efficiency and quality management.

Nonetheless, relying exclusively on the late afternoon for selective harvesting is not operationally feasible, especially on larger farms. Technical adjustments are essential to optimize harvesting during less favorable times. Modifying the pressure of the beating cylinders, the vibration of the rods, and the harvesting machine's travel speed can mitigate the effects of higher detachment resistance in the morning and early afternoon. Onboard sensors capable of real-time monitoring of detachment force could provide precise data for automatic adjustments, enhancing efficiency under adverse conditions.

The instability observed in the detachment process, regardless of the harvest year, reflects the intrinsic characteristic of coffee plants to produce multiple flowering events within the same production cycle [26, 27]. This uneven flowering results in variations in ripening and, consequently, in the force required to detach the fruits. However, the low percentage of out-of-control points indicates that most of the variability is associated with common causes, typical of agricultural processes [28–30].

Considering that understanding the detachment force is crucial for planning selective harvesting, times of day with more unstable points are more prone to failures in selectivity. In the case of ripe (cherry) fruits, when applying stem vibration based on detachment force, periods with higher instability may favor the retention of cherry fruits on the plant. On the other hand, the instability observed in green fruits could lead to their detachment, even though this is not the intended outcome. Therefore, for selective harvesting, times of day that combine stability with lower variability in the detachment force of cherry fruits are more suitable.

For total harvesting, when adopting stem vibration based on the upper limit of detachment force of green fruits, green cane, cherry, and dry fruits would be harvested. At times when instability is due to points above the upper control limit, machine parameters should be adjusted to reduce the number of remaining fruits on the plant.

The identified patterns for green fruits include an increasing trend in detachment force in the afternoon on the north-facing side, which may be attributed to accumulated solar exposure increasing fruit resistance. For cherry fruits, the initial reduction in detachment force, followed by an increase in the late afternoon, reflects the interaction between environmental conditions and the ripening process. For dry fruits, the stability observed in the early afternoon on the north-facing side and in the late afternoon on the south-facing side highlights the importance of periods with lower thermal amplitude for more uniform harvesting.

Although the late afternoon proved to be the most favorable period for selective mechanized harvesting, the results underscore the need for robust strategies, more detailed studies, and the integration of advanced technologies to address challenges during less favorable periods. Integrating these findings with technological solutions could transform selective mechanized harvesting into an even more efficient and sustainable process.

Mapping and monitoring ripening stages have been widely investigated using digital agriculture techniques and tools. Recent studies highlight object detection methods for real-time coffee ripening classification [20]. Additionally, multispectral imagery acquired by remotely piloted aircraft systems (RPAS) has demonstrated good accuracy in ripening estimation [31]. Computer vision techniques have also shown satisfactory results in real-time identification of ripening and coffee yield [32].

That said, understanding the variability of detachment force is a promising indicator for the adoption of new technologies aimed at optimizing selective mechanized harvesting. This operation requires an integrated approach that considers environmental conditions, fruit physiology, and less favorable harvesting times. Beyond technical adjustments, prioritizing more stable areas and implementing staggered operational strategies can reduce losses and maximize operational efficiency. Practices aimed at synchronizing flowering, such as irrigation, represent a strategy that can contribute to making the process more homogeneous.

Based on the findings, this study provides significant advancements in understanding the variability of detachment force in *Coffea arabica* fruits at the field level. However, several aspects offer opportunities for further investigation. The analysis focused on two consecutive harvests in a specific region, providing a solid foundation but leaving room to explore how varying climatic conditions and management systems might influence the results. Moreover, while maturity stages and solar exposure faces were comprehensively addressed, incorporating additional factors, such as the specific characteristics of different cultivars, could further broaden the applicability of these findings.

Another area for deeper exploration is the integration of the results with different configurations of mechanized harvesters and operational parameters, enabling analyses even more tailored to agricultural practices. Although the study robustly characterized variability and identified significant patterns, these results should inspire future research aimed at mapping coffee ripening variability using remote sensing tools and artificial intelligence. The variability of detachment force and the significant influence of solar exposure on ripening throughout the day provide valuable insights that could guide these investigations more precisely, offering potential conditions for optimizing selective coffee harvesting.

Moreover, to analyze variability and ensure the quality of mechanized operations, Statistical Quality Control serves as a strategic tool, especially in the context of agriculture, which aims for operational excellence. Its use enhances decision-making through effective and rapid evaluations of process variability. The set of SQC tools include Statistical Process Control (SPC), Histogram, Pareto Diagram, Scatter or Correlation Graph, Flowchart, Check Sheet, and Cause and Effect Diagram, which are widely used in industrial processes, with SPC standing out by enabling distribution analyses through control charts [14]. However, despite its clear potential, the application of SQC in the agricultural sector is still in its early stages, even within the advanced context of modern agriculture [16]. One of the main challenges for its implementation is the need for a large volume of samples to support robust variability analysis, which can be a limiting factor in certain studies.

5. Conclusions

The detachment force of *Coffea arabica* fruits varies throughout the day and according to the solar exposure face, with lower resistance and variability observed in the afternoon, particularly for cherry-stage fruits. This period stands out as the most favorable for selective mechanized harvesting, as green fruits exhibited higher resistance and variability. These results demonstrate that maturity stage, time of day, and solar exposure face are crucial factors in planning strategies to enhance the efficiency and quality of the mechanized harvesting process and should be prioritized to guide smart harvesting.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

João de Deus Godinho Filho: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jarlyson Brunno Costa Souza:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Samira Luns Hatum de Almeida:** Writing – review & editing, Writing – original draft, Visualization. **Luis Alberto Rocha Rodrigues Junior:** Writing – review & editing, Visualization. **Igor Cristian de Oliveira Vieira:** Writing – review & editing, Visualization. **Tiago de Oliveira Tavares:** Writing – review & editing, Methodology, Conceptualization. **Rouverson Pereira da Silva:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

Jarlyson Brunno Costa Souza reports was provided by São Paulo State University Faculty of Agricultural and Veterinary Sciences. Jarlyson Brunno Costa Souza reports a relationship with São Paulo State University Faculty of Agricultural and Veterinary Sciences that includes:

funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] N.P. Arruda, A.M.C. Hovell, C.M. Rezende, S.P. Freitas, S. Couri, H.R. Bizzo, Discrimination between ripening stages and post-harvest processing types of arabica coffee by solid-phase microextraction and principal component analysis, Quím. Nova 34 (2011) 819–824.
[2] M.D. Meneses, V. dos Santos Carreira, B.R. de Almeida Moreira, W.G. do Vale, G. de Souza Rolim, R.P. da Silva, Machine learning models for classifying the detachment force of coffee fruits, Agron. J. 116 (2024) 2362–2369.
[3] G.S. Souza, J.A. Lani, M.B. Infantini, C.A. Krohling, J.F.B. Senra, Mechanized Harvesting of 'Conilon' Coffee Clones, Pesquisa Agropecuária Brasileira, 2020, p. 55.
[4] F.C. Silva, F.M. Silva, A.C. Silva, M.M. Barros, M.A.Z. Palma, Operacional performance of mechanically harvested coffee and selectivity in accordance to force detachment of fruit, Coffee Sci. 8 (2013) 53–60.
[5] F.L. Santos, D.M. Queiroz, F.D.A.C. Pinto, N.T. Santos, Analysis of the coffee harvesting process using an electromagnetic shaker, Acta Sci. Agron. 32 (2010) 373–378.
[6] F.C. Silva, F.M. Silva, M.C. Alves, M.M. Barros, R.S. Sales, Behavior of the detachment force of coffee fruits during the harvest period, Ciênc. Agrotecnologia 34 (2010) 468–474.
[7] F.C. Silva, F.M. Silva, M.S. Scalco, R.S. Sales, Correlation of the detachment force of coffee fruits under different nutritional conditions, Coffee Sci. 11 (2016) 169–179.
[8] V.C. Figueiredo, G.A.S. Ferraz, F.M. Silva, F.G. Conceição, L.C.C. Carvalho, Analysis of spatial variability of force detachment of coffee fruits in central pivot, Coffee Sci. 12 (2017) 84–92.
[9] M.M. Barros, F.M. Silva, A.G. Costa, G.A.S. Ferraz, F.C. Silva, Use of classifier to determine coffee harvest time by detachment force, Rev. Bras. Eng. Agríc. Ambient. 22 (2018) 366–370.
[10] M.T. Cassia, R.P. Silva, C.A. Chioderoli, R.H.F. Noronha, E.P. Santos, Quality of mechanized coffee harvesting in circular planting system, Ciênc. Rural 43 (2013) 28–34.
[11] G.A.S. Ferraz, F.M. Silva, M.C. Alves, R.L. Bueno, P.A.N. Costa, Geostatistical analysis of fruit yield and detachment force in coffee, Precis. Agric. 13 (2012) 76–89, https://doi.org/10.1007/s11119-011-9223-8.
[12] J.D. Godinho, J.B. Costa Souza, R.P. Silva, T.O. Tavares, W.C.A. da Costa, B.R. de Oliveira, S. Luns Hatum de Almeida, The best moment to carry out the selective harvest of coffee fruits, Agron. J. 114 (2022) 3297–3305, https://doi.org/10.1002/agj2.21175.
[13] L.S. Santana, G.A.S. Ferraz, J.P.B. Cunha, D.B. Marin, N.L. Bento, R.O. Faria, Quality of coffee planting techniques by aerial sensors and statistical process control, Rev. Ciênc. Agron. (2025) 56.
[14] R.P. Silva, A.F. Santos, B.R. Oliveira, J.B.C. Souza, D.T. Oliveira, F.M. Carneiro, Potential of using tatistical quality control in agriculture 4.0, Rev. Ciênc. Agron. (2020) 51.
[15] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644.
[16] R.P. Silva, M.A. Voltarelli, M.T. Cassia, Quality Control in Mechanized Agricultural Operations, 1st ed., Brazilian Association of Agricultural Engineering, Jaboticabal, 2015, p. 244.
[17] F. Pimentel-Gomes, C.H. Garcia, Applied Statistics For Agronomic and Forestry Experiments: Exposure With Examples and Guidance For Application Software, Fundação de Estudos Agrários "Luiz de Queiroz" (FEALQ), Piracicaba, 2002, p. 309.
[18] C. Werkema, Lean Six Sigma: Introduction to the Tools of Lean Manufacturing, 2nd ed., Elsevier, Rio de Janeiro, 2011, p. 94.
[19] R.H.F. Noronha, R.P. Silva, C.A. Chioderoli, E.P. Santos, M.T. Cassia, Statistical control applied in the process of mechanical sugar cane harvest in the diurnal and nocturnal periods, Bragantia 70 (2011) 931–938.
[20] E.H. Kazama, R.P. Silva, T.O. Tavares, L.N. Correa, F.N.L. Estevam, F.E.A. Nicolau, W. Maldonado Júnior, Methodology for selective coffee harvesting in management zones of yield and maturation, Precis. Agric. (2020), https://doi.org/10.1007/s11119-020-09751-1.
[21] F.C. Silva, F.M. Silva, R.S. Sales, G.A.S. Ferraz, M.M. Barros, Meteorological variables and soil moisture in the detachment force coffee fruit, Coffee Sci. 12 (4) (2017) 480–485.
[22] C.T.M. Pereira, Dissertação, in: Dissertação, 2020, (Mestrado em Agronomia) – Universidade Estadual de Londrina, Londrina, 2020.
[23] A.L.D.F. Coelho, F.L. Santos, F.A. Pinto, D.M. Queiroz, Determination of geometric, physical and mechanical properties of coffee fruit-stem-branch system, Rev. Bras. Eng. Agríc. Ambient. 19 (3) (2015) 286–293.
[24] E.A. Alves, Master's thesis, (Agricultural Engineering) – Universidade Federal de Viçosa, Viçosa, 2005, p. 64.
[25] J.A.T. Amaral, A.B. Rena, J.F.T. Amaral, Seasonal vegetative growth of coffee plants and its relation to photoperiod, fruiting, stomatal resistance, and photosynthesis, Pesqui. Agropecu. Bras. 41 (2006) 377–384.
[26] N. Majerowicz, M.R. Söndahl, Induction and differentiation of reproductive buds in *coffea arabica* L, Braz. J. Plant Physiol. 17 (2005) 247–254.
[27] Â.M. Nogueira, S.P. Carvalho, G.F. Bartholo, A.N.G. Mendes, Evaluation of coffee fruit maturation of Catuaí Amarelo and Catuaí Vermelho (Coffea arabica L.) lines planted individually and in combinations, Ciênc. Agrotecnologia 29 (2005) 18–26.
[28] A.F. Santos, L.N. Correa, L.A.S. Gírio, C.S.S. Paixão, R.P. Silva, Position errors in sowing in curved and rectilinear routes using autopilot, Eng. Agríc. 38 (2018) 568–576.
[29] A.F. Santos, R.P. Silva, C. Zerbato, P.C. Menezes, E.H. Kazama, C.S.S. Paixão, M. A. Voltarelli, Use of real-time extend GNSS for planting and inverting peanuts, Precis. Agric. 20 (2019) 840–856.
[30] R.P. Silva, F.G. Souza, J.W. Cortez, C.E.A. Furlani, G.P. Vigna, Spatial variability and statistical control of the losses process in cotton mechanized harvest, Eng. Agríc. 27 (2007) 742–752.
[31] R.N. Martins, F.A.C. Pinto, D.M. Queiroz, D.S.M. Valente, J.T.F. Rosas, M.F. Portes, E.S.A. Cerqueira, Digital mapping of coffee ripeness using UAV-based multispectral imagery, Comput. Electron. Agric. 204 (2023), https://doi.org/10.1016/j.compag.2022.107499.
[32] F. Eron, M. Noman, R.R. Oliveira, A. Chalfun-Junior, Computer vision-aided intelligent monitoring of coffee: Towards sustainable coffee production, Sci. Hortic. 327 (2024) 112847, https://doi.org/10.1016/j.scienta.2024.112847.