

Effects of displacement speed and rod vibration frequency on the efficiency of mechanized coffee harvesting

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Editor: Samuel Pereira de Carvalho

Received in October 29, 2024 and approved in January 23, 2025

ABSTRACT

Mechanized harvesting of coffee plantations in Minas Gerais has grown rapidly due to its benefits, including increased productivity and reduced labor costs. However, these benefits can only be realized if the harvesting process is properly adjusted to align with the capabilities of the harvesting machine and the specific conditions of the crop field. This study aimed to evaluate the effects of harvester displacement speed and rod vibration frequency on harvesting efficiency and coffee fruit yield. A 3 × 3 factorial design was employed, testing three displacement speeds (600, 800, and 1000 m·h⁻¹) and three vibration frequencies (15, 16.7, and 18.3 Hz). Parameters of the crop were assessed prior to the mechanized harvesting process, including the load of hanging fruits, fruit ripeness, and fallen fruits on the ground. Immediately after the harvest, the following parameters were evaluated: (i) harvesting efficiency, (ii) volume of harvested coffee fruits, and (iii) volume of fallen coffee fruits during mechanized harvesting process. Each treatment combination was tested on 12 plots, and data were analyzed using ANOVA followed by Tukey's test for pairwise comparisons. Results showed that vibration frequency significantly affected both harvested volume and fruit loss, with notable differences between frequencies. The highest harvesting efficiency was achieved at a displacement speed of 1000 m·h⁻¹, while 600 m·h⁻¹ provided greater consistency across frequencies. These findings highlight the critical role of optimizing speed and vibration parameters to enhance mechanized harvesting efficiency and minimize fruit losses, offering valuable insights for improving coffee production practices globally.

Key words: Mechanized harvesting; coffee harvester; operational performance.

1 INTRODUCTION

According to the International Coffee Organization (International Coffee Organization - ICO, 2023), Brazil is expected to produce 59.1 million 60-kg bags during the 2023/24 season, reaffirming its position as the largest coffee producer in the world. In Brazil, coffee crops cover more than 2.25 million hectares of land, with Arabica coffee accounting for 1.82 million hectares and the state of Minas Gerais leading the country in coffee production (Companhia Nacional de Abastecimento - CONAB, 2024). Given the economic significance of coffee, exploring approaches to enhance the efficiency of mechanized coffee operations and reduce production costs is essential. Notably, mechanized coffee harvesting can account for up to 40% of the total production cost (Silva, F. C. et al., 2013) and directly influences product quality (Silva et al., 2016). Harvester machines can substantially lower farming expenses and improve the economic viability of coffee production (Lanna; Reis, 2012).

During mechanical coffee harvesting, coffee fruit detachment occurs through the transfer of vibrational energy and impact (Gomes et al., 2020). Silva et al. (2015) highlighted that adjustments to vibration settings, travel speed, and the distribution of vibration rods can enhance the harvesting process. Among these, the configuration of vibration rods

is particularly useful for selective harvesting and specific field conditions. Generally, three key adjustments are made to coffee harvesters: rod vibration, travel speed, and torque exerted by the brake belt springs (Kazama et al., 2020). These adjustments are usually made empirically and with a lack of precise technical information.

Although several studies have examined dynamic frequency interaction ranges to enhance selective harvesting using test benches and controlled conditions (Coelho et al., 2016; Gomes et al., 2020; Villibor et al., 2016), examining parameters such as vibration frequency and displacement speed under actual field conditions is essential (Kazama et al., 2020). Furthermore, harvesters with varying designs and mechanisms offer unique advantages and disadvantages in mechanized harvesting, requiring thorough evaluations for optimal outcomes.

Santinato et al. (2014) evaluated the quality of mechanized harvesting across two crop seasons and observed that increased vibration did not necessarily increase the volume of harvested coffee fruits, with a particularly low harvesting efficiency in low-yield seasons. In a subsequent study, Santinato et al. (2015) concluded that for high-yield crops (121.54 bags of processed coffee per hectare), two to three passes of the harvester were sufficient to eliminate the need for manual handling. Meanwhile, for intermediate-yield crops (50.78 bags of processed coffee per

hectare), two passes of the harvester were deemed adequate. These findings highlight the importance of understanding the specific characteristics of harvesters to ensure their suitability under diverse crop conditions.

To optimize the mechanical harvesting process, producers often rely on empirical trials to determine the best settings for vibration frequency and displacement speed (Silva, F. C. et al., 2013). However, systematic testing is necessary to refine machinery recommendations and identify new approaches for improving the efficiency of mechanized operations (Ferreira Júnior et al., 2016, Kazama et al., 2020). The findings from these tests can help producers enhance the efficiency of the harvesting process. Hence, the objective of this study was to assess the harvesting efficiency of a coffee harvester by recording the volume of harvested coffee beans and the volume of fallen coffee fruits as functions of different harvester displacement speeds and rod vibration frequencies.

2 MATERIAL AND METHODS

This study was conducted at Sabaré Farm, located in Boa Esperança, Minas Gerais, from June 2 to June 22, 2018. This region has an average altitude of 930 m and a terrain slope of 5%. The regional climate is classified as subtropical with dry winters (Cwb), according to the Köppen classification system (Alvares et al., 2013). The experimental area comprises 525 Topázio cultivar plants, with a phenological age of 15 years. The plants are spaced 3.5 m between rows and 0.70 m between plants, resulting in a planting density of 4,082 plants per hectare.

Our experiment followed a 3×3 factorial design, with three displacement speeds and three rod vibration frequencies. The chosen settings were employed, as the objective was to harvest as many as possible the fruits ripe, leaving the unripe fruits on the plant. For the experiment, three rows of coffee plants were randomly selected, and each row was tested under a different harvester speed (T1): $V1 = 600 \text{ m} \cdot \text{h}^{-1}$, $V2 = 800 \text{ m} \cdot \text{h}^{-1}$, and $V3 = 1000 \text{ m} \cdot \text{h}^{-1}$. For each harvester speed, harvesting was performed at three rod vibration frequencies (T2): $F1 = 15 \text{ Hz}$, $F2 = 16.7 \text{ Hz}$, and $F3 = 18.3 \text{ Hz}$. For each frequency, harvesting was repeated four times, resulting in 12 plots for each speed setting. Each plot was 10 m long, with a 5 m border between adjacent plots. The harvesting process was conducted using an OXBO 9220 harvester with 48-cm-long vibrating rods. The harvester maneuvered on raffia cloths measuring $12 \text{ m} \times 3 \text{ m}$, placed beneath the canopy of the coffee plants in each experimental plot. The raffia cloths were placed beneath the coffee plant canopy to catch fallen fruits during the harvesting process. This ensures that all fruits dislodged by the harvester are collected for further analysis.

The crop considered in this study followed a “zero harvest” management system, which involves a year without production owing to planned pruning, followed by a year with substantial fruit yields (Japiassú et al., 2010). The initial hanging load on the coffee plants was determined by randomly sampling five plants for each plot one day before the start of mechanized harvesting. Then the average pending load per plant ($\text{L} \cdot \text{plant}^{-1}$) was calculated using the arithmetic mean. The maturation stage of the plants was determined as follows: manually harvesting all coffee fruits from two plants, followed by homogenizing the collected fruits. A 5-liter sample was then extracted, further homogenized, and reduced to a 1-liter sample. The coffee fruits in this final sample were manually counted and classified into three categories according to their ripeness stage: unripe, ripe, and overripe. Pre-harvest losses were quantified by accounting for the volume of coffee fruits that had fallen to the ground prior to the harvesting with the coffee harvester. The area under the projection of the canopies coffee plants was swept and winnowed in each experimental plot to collect the fallen fruits, thus determining the volume ($\text{L} \cdot \text{plant}^{-1}$) of coffee fruits on the ground due to natural drop.

The mean hanging load ($\text{L} \cdot \text{plant}^{-1}$), ripeness stage of the fruits (%), and fruit losses during the harvesting process ($\text{L} \cdot \text{plant}^{-1}$) were evaluated in each experimental plot. Then it was determined the following harvester parameters: (i) harvesting efficiency, (ii) volume of harvested coffee fruits, and (iii) volume of fallen coffee fruits during mechanized harvesting. The harvesting efficiency was determined by the ratio between the volume of coffee contained in the machine’s reservoir ($\text{L} \cdot \text{ha}^{-1}$) and the initial load of coffee cherries present on the plants ($\text{L} \cdot \text{ha}^{-1}$) at the time of detachment (Oliveira et al., 2007). The volume of harvested coffee fruits ($\text{L} \cdot \text{plant}^{-1}$) was measure by collected in the machine’s reservoir the coffee harvested using a container with graduated volume capacity, and the volume of fruits lost to the ground ($\text{L} \cdot \text{plant}^{-1}$) were measured by collecting the coffee fruits in the ground and in the raffia cloths measuring placed beneath the canopy of the coffee plants in each experimental plot. Both parameters were recorded immediately after harvesting. Here, losses represent the volume of coffee fruits lost during transport and cleaning within the harvester. All variables were analyzed using analysis of variance (ANOVA) with the SISVAR 5.6 statistical software (Ferreira, 2019). Averages were compared using Tukey’s test at a 5% significance level.

3 RESULTS

The average handing load was $10 \text{ L} \cdot \text{plant}^{-1}$, with a natural pre-harvest loss of $1.48 \text{ L} \cdot \text{plant}^{-1}$. On average, the crop consisted of 7.39% unripe fruits, 59.80% ripe fruits, and 29.74% overripe fruits. This categorization is important because the vibration intensity and maturity index of the

coffee fruits directly affect both the volume of harvested fruits and the efficiency of the mechanical harvesting process (Silva et al., 2015).

The mechanical harvesting efficiency for each tested vibration frequency is illustrated in Figure 1.

The lowest displacement speed of the harvester resulted in greater uniformity in harvesting efficiency across the tested vibration frequencies, with values ranging from 96.47% to 96.62%. Notably, the variations in these values could be attributed to the working conditions of the crop field. The volume of harvested coffee fruits as a function of the displacement speed and vibration frequency is resented in Figure 2.

The volume of harvested coffee fruits ranged from 5.15 to 9.59 L·plant⁻¹, with harvesting efficiencies varying from 82.38% to 98.75%. The largest harvested volume was recorded at a displacement speed of 1000 m·h⁻¹ and a rod vibration frequency of 16.7 Hz (Figure 2). Figure 3 illustrates the volume of fallen coffee fruits as a function of the displacement speed and rod vibration frequency.

The average volume of coffee fruits falling to the ground during harvesting increased slightly with increasing rod vibration frequencies at an average harvester displacement of 600 m·h⁻¹. The fallen fruits accounted for approximately 8.98%, 7.54%, and 9% of the total harvested volume.

At a displacement speed of 800 m·h⁻¹, the volume of fallen coffee fruits exhibited a nearly linear increase with increasing rod vibration frequencies, representing 5.93%, 7.52%, and 11.12% of the total harvested volume.

At the highest displacement speed of 1000 m·h⁻¹, similar volumes of fallen fruits were observed at vibration

frequencies of 15 Hz and 16.7 Hz, accounting for 6.24% and 6.28% of the total harvested volume, respectively. However, a noticeable increase in the volume of fallen fruits occurred at a frequency of 18.3 Hz, accounting for 12.38% of the total harvested volume.

The effects of displacement speed and rod vibration frequency were examined using ANOVA, and the results were assessed using Tukey's test at a 5% significance level. The assumptions of ANOVA were verified prior to analysis. Normality of residuals was confirmed using the Shapiro-Wilk test ($p=0.766$), and homogeneity of variances was supported by the Breusch-Pagan test ($p=0.093$). No violations of independence were detected based on visual inspection of residual plots. The detailed results are presented in Table 1 and Table 2.

As presented in Table 1, the displacement speeds of the harvester did not significantly influence the volume of harvested coffee fruits. However, at vibration frequencies of 15 Hz and 18.3 Hz, the differences in the volume of harvested coffee fruits were considered statistically significant according to Tukey's test. Further analysis of the effect of vibration frequencies (Table 2) revealed that the frequency of 15 Hz resulted in the lowest volume of harvested coffee fruits.

While the vibration frequency of 16.7 Hz did not differ statistically from the other frequencies, it achieved the highest harvesting efficiency and the largest volume of harvested coffee fruits at a harvester speed of 1000 m·h⁻¹. Under these settings, the volume of fruits that fell to the ground was 6.28% of the total volume, a lower value compared to those observed in other scenarios with the same frequency and different displacement speeds.

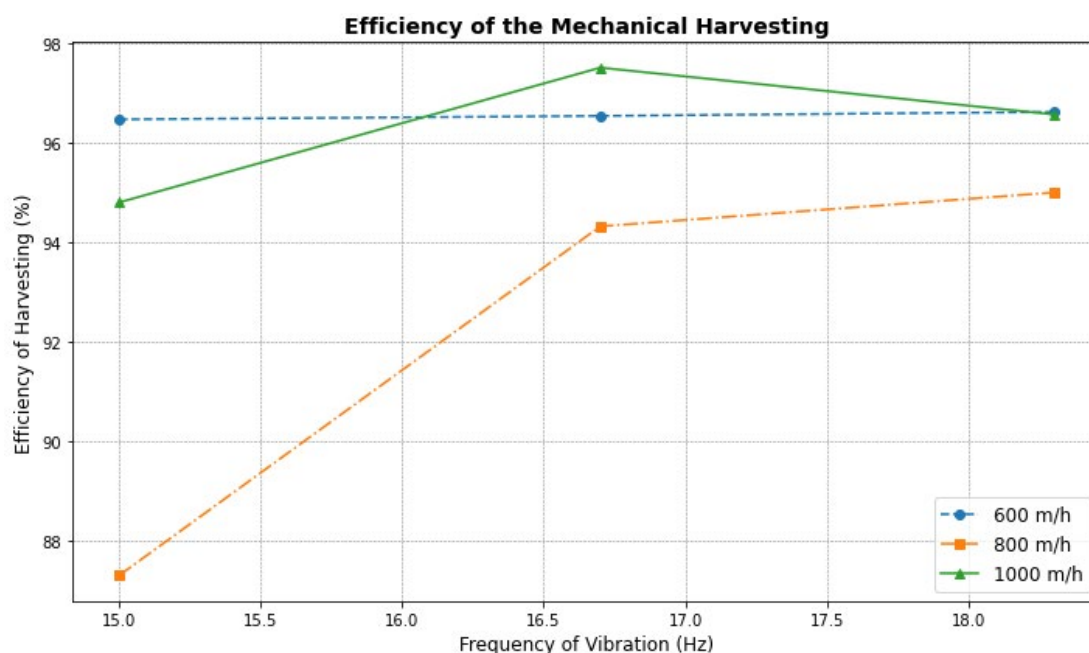


Figure 1: Mechanical harvesting efficiency as a function of the rod vibration frequency and harvester speed.

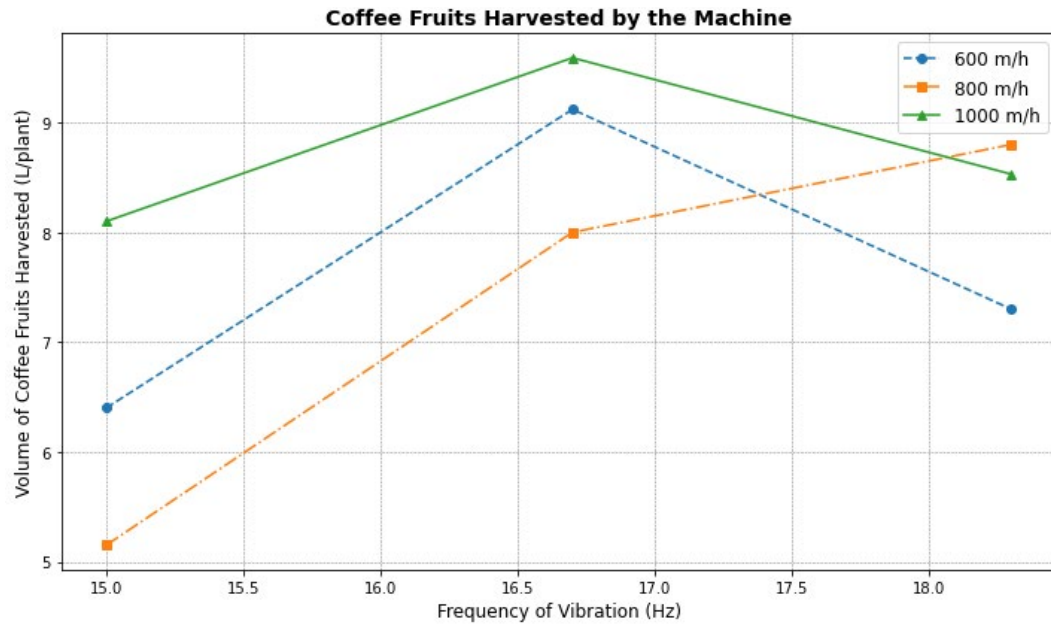


Figure 2: Volume of harvested coffee fruits as a function of the vibration frequency and displacement speed.

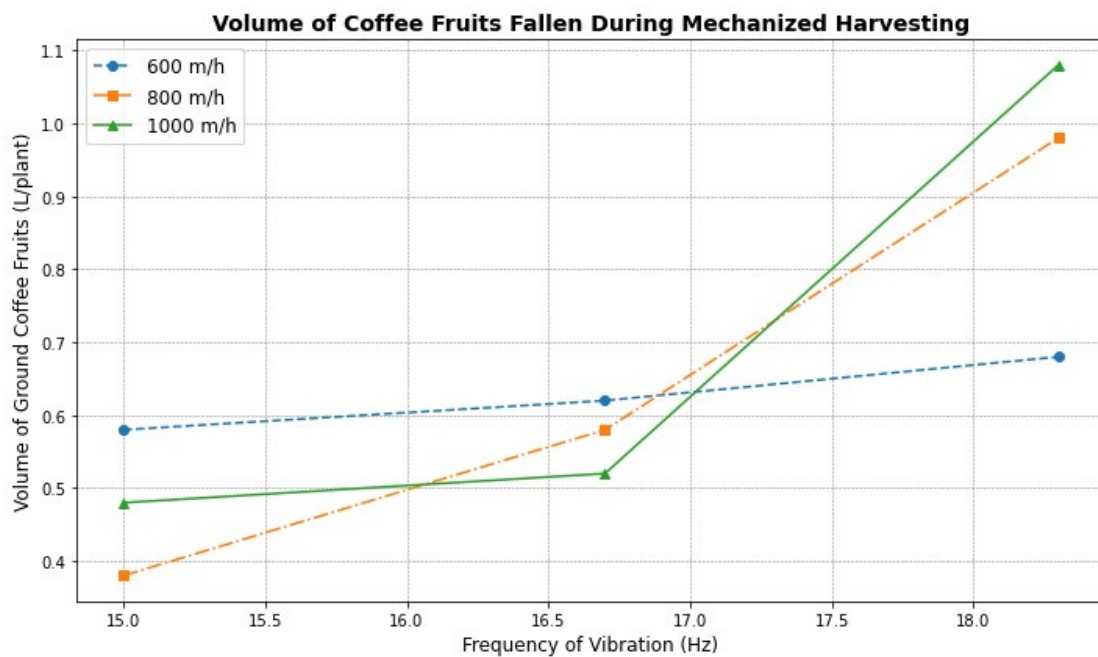


Figure 3: Volume of fallen coffee fruits as a function of displacement speed and rod vibration frequency.

Table 1: ANOVA results for the volume of harvested coffee fruits at different displacement speeds.

Displacement speed (m·h ⁻¹)	Harvested coffee fruits (L·plant ⁻¹)
600	7.65 a
800	7.73 a
1000	8.26 a
CV 16.2 %	

*Results within each row sharing the same letter do not differ significantly at the 5% level, as determined by Tukey's test.

Table 2: ANOVA results for the volume of harvested coffee fruits at different rod vibration frequencies.

Frequency (Hz)	Harvested coffee fruits (L·plant ⁻¹)
15	7.00 a
16.7	8.56 ab
18.3	8.08 b
CV 16.2 %	

*Results within each row sharing the same letter do not differ significantly at the 5% level, as determined by Tukey's test.

An analysis of variance (ANOVA) was conducted to examine the effects of displacement speed and rod vibration frequency on the volume of harvested coffee fruits. The results revealed a significant main effect of vibration frequency ($F(2,27) = 8.70$, $p=0.001$), indicating that changes in frequency significantly influenced the harvested volume. However, no significant effects were observed for displacement speed ($F(2,27) = 1.94$, $p=0.164$) or the interaction between speed and frequency ($F(4,27) = 0.74$, $p=0.573$).

4 DISCUSSION

Mechanized coffee harvesting is a critical stage for quality coffee production but it is also the most expensive stage too. Furthermore, it is a key factor influencing product quality (Silva et al., 2016). Therefore, selecting optimal harvester settings and understanding their impact on the harvesting process require extensive research.

The exposure time of coffee plants to the vibrating mechanism increases as the harvester's displacement speed decreases. However, at the lowest speed ($600 \text{ m}\cdot\text{h}^{-1}$), harvesting efficiency varied with increasing rod vibration frequencies. In contrast, Kazama et al. (2020) examined harvester settings based on management zones defined by crop yield and ripeness status. They tested harvester speeds ranging from $500 \text{ m}\cdot\text{h}^{-1}$ to $1000 \text{ m}\cdot\text{h}^{-1}$ and frequencies ranging from 8.33 Hz to 15.83 Hz. Their results revealed that the volume of harvested coffee did not vary across the selected settings. Their study recommended higher speeds for economic efficiency, contrasting with our findings, where higher frequencies at identical speeds notably influenced the harvested volume. This discrepancy may be attributed to differences in harvester models, experimental conditions, and cultivar characteristics.

At a displacement speed of $800 \text{ m}\cdot\text{h}^{-1}$, the harvester exhibited the lowest efficiency across all investigated frequencies, potentially due to suboptimal exposure times. The highest harvesting efficiency value (98.75%) was achieved at a displacement speed of $1000 \text{ m}\cdot\text{h}^{-1}$ and rod vibration frequency of 16.7 Hz. Santinato et al. (2014) reported harvesting efficiencies varying between 70% and 80% across low- and high-yield seasons. Their tests at frequencies of 12.49 Hz and 15.83 Hz revealed that in low-yield seasons, the frequency of 12.49 Hz caused less damage to the coffee plants. Conversely, in high-yield seasons, the frequency of 15.83 Hz achieved better harvesting efficiency without increasing plant damage, highlighting the interaction between yield potential and optimal vibration settings.

Comparatively, using a K3 harvester model, with a displacement speed of $1300 \text{ m}\cdot\text{h}^{-1}$ and vibration frequencies of 13.34 Hz, 15.00 Hz, and 16.67 Hz, Silva, F. C. et al.

(2013) obtained harvesting efficiencies varying from 80% to 93%. The authors conclude that with a single pass of the harvester, harvesting efficiency increases as the vibration intensity of the rods is elevated. In our study, despite lower displacement speeds ($600 \text{ m}\cdot\text{h}^{-1}$ to $1000 \text{ m}\cdot\text{h}^{-1}$), efficiencies ranged from 82.38% to 98.75%, indicating that modern harvester models or adjusted settings may achieve comparable or superior performance at similar frequency and reduced speeds. These findings are consistent with those reported by Oliveira et al. (2007), where, at a fixed displacement speed, higher rod vibration intensity resulted in increased harvesting efficiency without a corresponding rise in harvest losses. However, during the second pass of the harvester, an increase in displacement speed did not affect fruit detachment efficiency but led to higher harvest losses. Among the vibration frequencies tested in this study, 16.7 Hz and 18.3 Hz demonstrated the best harvesting efficiencies for the Topázio cultivar. However, these results may vary depending on the coffee cultivar, as noted by Silva, F. C. et al. (2013), who examined the operational performance of mechanical harvesting across two progenies.

Additionally, extrapolating these results to other harvester models requires caution. Differences in machine design, rod configurations, and operational parameters can significantly influence outcomes. For instance, harvesting efficiency on sloped terrains was reported to decrease substantially, with values between 53.56% and 66.08% on slopes of 10% to 30% (Santinato et al., 2016). Thus, while the current findings provide valuable insights, further research comparing various harvester models across diverse terrains and cultivars is warranted to confirm broader applicability. This study highlights the importance of selecting optimal harvester settings to improve operational performance while minimizing losses and damage to coffee plants.

Future studies can assess the fuel consumption associated with different displacement speeds and vibration frequencies to determine optimal settings. Thus, examine how different speeds and vibration frequencies impact the quality of harvested coffee fruits. In addition, future studies should investigate cultivar-specific adjustments to enhance generalizability.

5 AUTHORS' CONTRIBUTIONS

Conceptual Idea: Amancio, M.E.; Volpato, C.E.S.; Barbosa, R.L.; Methodology design: Amancio, M.E.; Volpato, C.E.S.; Barbosa, R.L.; Data collection: Amancio, M.E.; Abreu, A.L.; Correia, K.L.R. Data analysis and interpretation: Amancio, M.E.; Zanella, M.A. Dadalto, J.P.; Volpato, C.E.S. and Writing and editing: Amancio, M.E.; Zanella, M.A.; Dadalto, J.P.

6 CONCLUSIONS

According to the findings of this study, increasing the displacement speed and vibration frequency of the harvester did not improve harvesting efficiency. Increasing the harvester's displacement speed and vibration frequency did not improve efficiency but increased fruit losses. Rod vibration frequency directly influenced the harvested volume, with significant differences between 15 Hz and 18.3 Hz. The highest yield occurred at 1000 m·h⁻¹ and 16.7 Hz, while the lowest fruit loss was observed at 800 m·h⁻¹ and 15 Hz.

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