

Modeling Fruit Removal Force and Vibration Thresholds for Selective Harvesting of Robusta Coffee

Muhammad Taufiq^{1*}, Idah Andriyani¹, Akbar Setyo Pambudi¹

¹Department of Agricultural Engineering, Faculty of Agricultural Technology, Universitas Jember, Jember, East Java, Indonesia.

Email*): taufiqmuhammad@unej.ac.id

Received:
13 July 2026

Revised:
8 September 2026

Accepted:
20 September 2026

Published:
29 September 2026

DOI:
10.29303/jrpb.v14i2.1246

Available at:
<http://jrpb.unram.ac.id/>

Abstract: This study developed a preliminary FRF-based model for screening selective vibratory harvesting conditions in robusta coffee. A total of 450 individual fruits were measured from five coffee plants, with 30 red, 30 orange, and 30 green fruits sampled from each plant. For biological-replicate analysis and empirical model fitting, the 30 fruit measurements within each plant-by-maturity combination were averaged, yielding 15 plant-level observations, while the individual-fruit data were retained to characterize within-maturity FRF distributions. Maturity was treated as a categorical predictor with red fruit as the reference class, and fruit mass was included as a covariate. The categorical model closely represented the available plant-level means ($R^2 = 0.9996$; RMSE = 0.038 N): after adjustment for fruit mass, orange and green fruits had FRF values 2.433 N and 4.499 N higher than red fruits, respectively, whereas the mass coefficient was small and not significant ($p = 0.606$). Mean individual-fruit FRF values were 3.533 N for red, 5.966 N for orange, and 8.033 N for green fruits. Using the individual-fruit FRF distributions, the simulation predicted a selective force window of approximately 3.92–5.73 N. Under the idealized point-mass harmonic assumption, this force interval corresponds to approximately 105.4–127.4 Hz at a local amplitude of 3 mm. Because these equivalent frequencies imply very high theoretical local accelerations, they should be interpreted as design-stage screening values rather than field-validated harvester settings.

Keywords: coffee harvesting; detachment force; fruit removal force; robusta coffee; vibration threshold

INTRODUCTION

Background

There are two types of coffee widely cultivated by farmers in Indonesia Arabica and Robusta (Pratopo et al., 2023). Robusta coffee remains one of the most important beverage commodities in tropical agriculture because it supports farmer income, export value, and rural employment while supplying a large segment of the global coffee market (Prasetyo et al., 2022). Fruit maturity at harvest strongly affects beverage quality, processing stability, and the economic value of the final product (Lestari et al., 2024). Mechanical harvesting therefore must not only improve labor efficiency but also preserve selective removal of ripe fruits. Recent coffee literature has emphasized that harvesting strategy, fruit maturity, and post-harvest handling jointly determine the quality trajectory of coffee lots from the field to the cup (Campuzano-Duque et al., 2021; Freitas et al., 2024; Osorio et al., 2024).

Coffee quality is significantly influenced by the harvesting and post-harvest handling practices employed (Rinaldi et al., 2024). Selective harvesting is especially difficult in robusta coffee because clusters on the same branch often contain red, orange, and green fruits at the same time (Wibowo & Palupi, 2022). This heterogeneity creates a direct engineering problem because the harvester must transmit sufficient energy to detach ripe fruits without forcing the

removal of less mature fruits (de Deus Godinho Filho et al., 2025). A purely empirical adjustment of machine frequency is rarely enough when the underlying mechanical response of the fruit-branch system is not quantified (Meneses et al., 2024). Studies on coffee fruit detachment force and machine response increasingly show that maturity-specific mechanical characterization is essential for selective harvest design (Souza et al., 2023).

Fruit removal force, commonly abbreviated as FRF, is one of the most informative variables for describing harvest selectivity because it directly expresses the resistance of the fruit-peduncle attachment to external loading (Zhou et al., 2025). A lower FRF indicates that a fruit can be detached more easily under mechanical action, whereas a higher FRF implies that more vibration energy is needed. The usefulness of FRF becomes greater when it is integrated with fruit mass, since inertial detachment under vibration depends on both resistance and the mass subjected to acceleration. Coffee-specific studies have confirmed that ripening generally reduces attachment resistance, which creates a mechanical basis for selective vibratory harvesting (Bizimungu et al., 2022; de Melo Júnior et al., 2023).

The dynamics of detachment under vibration can be simplified conceptually by considering that an oscillating branch or fruit-bearing segment transmits acceleration to the fruit (Sola-Guirado et al., 2023). The resulting inertial force grows with vibration amplitude, frequency, and fruit mass, meaning that a machine can be designed to operate in a narrow force window where ripe fruits are detached and unripe fruits remain attached (Homayouni et al., 2022). Similar dynamic logic has been used in olives, pistachios, and citrus, where branch response, resonance behavior, and vibration transmissibility determine the success of selective mechanical harvesting. These advances in tree and fruit dynamics provide a useful comparative framework for coffee research (Castro-Garcia et al., 2020).

Recent advances in coffee engineering have expanded from field harvesting trials to modal analysis, transmissibility studies, machine-learning classification of detachment force, and three-dimensional computational modelling of coffee branches (Pereira et al., 2025b). However, several of these dynamic studies, including Pereira et al. (2025a, 2025b) and Zhou et al. (2025), were conducted on *Coffea arabica* and are used here only as a comparative framework for general vibration principles. Their numerical vibration settings are not assumed to transfer directly to *Coffea canephora* because branch architecture, peduncle characteristics, fruit size, and attachment behavior may differ between species. In the present study, the species-specific mechanical inputs are therefore the measured robusta FRF and fruit-mass data, while Arabica and other fruit-crop studies are used only to support the general dynamic interpretation. Despite recent advances, a simple framework that directly converts maturity-specific robusta FRF distributions into force and equivalent-frequency screening thresholds remains limited. The present study addresses this conceptual gap by treating detachment force as the central mechanical constraint rather than as a secondary descriptive result.

The novelty of this study lies in integrating maturity-specific robusta FRF and fruit mass into a transparent engineering screening model that (i) treats maturity as a categorical mechanical factor, (ii) retains the observed individual-fruit FRF distributions when constructing maturity-specific detachment probability curves, and (iii) converts those distributions into a predicted selective force window and corresponding idealized vibration thresholds. The framework is intended as a low-complexity design-stage tool for identifying candidate conditions that can later be tested using instrumented branches and physical harvesting prototypes.

Objective study

The objective of this study was to model robusta coffee fruit removal force and equivalent vibration thresholds for selective harvesting. The specific aims were to quantify

maturity-dependent FRF and fruit-mass patterns, test whether FRF differed significantly among maturity stages, construct a categorical empirical FRF model, simulate idealized dynamic detachment thresholds, evaluate model fit and literature-based plausibility, and identify a predicted force window in which ripe-fruit recovery and harvest purity simultaneously met predefined criteria. The resulting ranges are intended as preliminary screening values for future experimental harvester development rather than as validated machine settings.

MATERIALS AND METHODS

Experimental Site and Plant Material

Fruit samples were collected from a managed robusta coffee (*Coffea canephora*) plantation located in Pakis Village, Sukorambi District, Jember Regency, East Java, Indonesia, during June–July 2025. The coffee trees within the experimental plantation had been established during the same planting period and were approximately eight years old at the time of sampling. The sampled trees were fruit-bearing, visually healthy, and showed a low incidence of pests and diseases. Routine plantation management included fertilization, pruning, pesticide application, and field sanitation to minimize weed growth, accumulated plant residues, and potential habitats for pests and disease-causing organisms. Five fruit-bearing coffee trees were randomly selected from the plantation.

The primary plant materials used in this study were robusta coffee cherries representing three maturity stages based on fruit color: red (ripe), orange (intermediate maturity), and green (unripe). From each tree, 30 red, 30 orange, and 30 green cherries were sampled, resulting in 90 individual fruits per tree. Thus, a total of 450 individual fruits were evaluated, comprising 150 fruits for each maturity stage. The main instruments consisted of a digital force gauge with a maximum capacity of 5 kg and an accuracy of 0.01 N, and a digital weighing scale with a maximum capacity of 500 g and an accuracy of 0.01 g. Fruit removal force (FRF) was measured individually using the digital force gauge, while the fresh mass of each fruit was determined using the digital weighing scale. The resulting FRF and fruit-mass data were organized and processed using Microsoft Excel. Statistical analyses and empirical model development were subsequently performed using IBM SPSS Statistics version 27.

FRF and Fruit Mass Observation

Fruit removal force (FRF) was measured individually using the digital force gauge by applying a controlled tensile pull to each fruit until detachment from the peduncle occurred. Fresh fruit mass was determined immediately after FRF measurement using the digital weighing scale. Fruit maturity was classified visually as red (ripe), orange (intermediate maturity), and green (unripe). This operational classification follows the progressive color change used to describe *Coffea canephora* maturation, in which fruits develop from green through an intermediate color-break stage toward red/cherry maturity (Privat et al., 2008; Costa et al., 2020).

The 30 fruits within each plant-by-maturity combination were treated as fruit-level subsamples rather than independent biological replicates. For inferential comparison and empirical FRF model fitting, the 30 measurements were averaged to obtain one plant-level mean for each maturity class, resulting in 15 plant-by-maturity observations (5 plants $\times$ 3 maturity classes). This structure retained the coffee tree as the biological replication level and avoided treating fruits collected from the same plant as independent plant replicates. The complete set of 450 individual observations was retained separately to quantify within-maturity FRF variation and to construct maturity-specific detachment-probability curves.

FRF was treated as the reference mechanical response that had to be overcome by the harvester, whereas fruit mass was treated as the inertial component that modulates the

dynamic force generated during vibration. Red fruits represented the main target of selective harvest because they best match commercial maturity. Orange fruits were interpreted as an intermediate stage that should preferably remain attached or be detached only minimally, while green fruits were strictly undesirable in a selective harvest. This maturity classification allowed the dataset to be translated from visual field observation into engineering variables suitable for simulation.

Modeling System

The literature study was conducted to explain the real phenomenon modelled in this research, namely the relationship among fruit maturity level, fruit removal force (FRF), and mechanical harvesting parameters. Recent studies indicate that the physical and mechanical characteristics of coffee fruits change during ripening, so fruit color can be used as an initial practical indicator for separating maturity categories before mechanical analysis is performed (Buitrago-Osorio et al., 2022; Ghonimy et al., 2025; Zhou et al., 2025). This phenomenon is important because fruits on a single coffee branch often ripen asynchronously, causing red, orange, and green fruits to occur simultaneously on the same bearing node. Mechanical harvesting without selectivity may therefore detach fruits from different maturity stages at the same time, reduce harvest uniformity, and lower the quality potential of the harvested coffee lot. The reviewed literature also emphasizes that FRF is a key mechanical variable for determining harvest timing, maturity classification, and the adjustment of coffee harvesting machines (de Deus Godinho Filho et al., 2025; Meneses et al., 2024).

The real system represented in the model can be understood as a fruit-peduncle-branch structure that receives tensile force under static loading and inertial force under dynamic vibration (Gomes et al., 2020). Under static conditions, a fruit detaches when the tensile load transmitted to the peduncle exceeds its FRF threshold. Under dynamic conditions, detachment may occur when harmonic vibration from a shaker rod, clamp, or vibrating harvesting head generates acceleration large enough to produce an inertial force greater than the attachment resistance of the fruit. Vibration transmissibility in the coffee fruit-peduncle-branch system is therefore essential for understanding how frequency and amplitude determine the efficiency of mechanical energy transfer from the machine to the fruit (Villibor et al., 2023). Previous studies on coffee vibration dynamics have shown that maturation stage, excitation frequency, vibration amplitude, and branch configuration influence the probability of fruit detachment and the potential selectivity of the harvesting operation (de Melo Júnior et al., 2023).

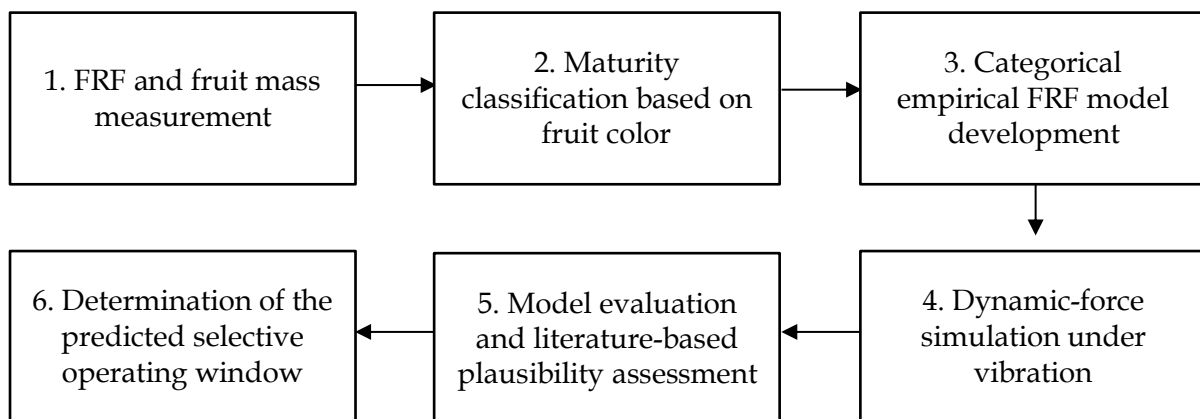


Figure 1. Research workflow for FRF-based selective coffee harvesting simulation

The system workflow begins with FRF and fruit-mass measurement, followed by maturity classification based on fruit color, categorical empirical FRF model development, dynamic-force simulation under vibration, model evaluation and literature-based plausibility assessment, and determination of the predicted selective operating window (Fig. 1). This sequence separates empirical characterization from simulation-based screening and avoids interpreting internal model fit as external experimental validation. The framework simplifies the field condition of robusta coffee into a calculable engineering model while retaining the principal mechanical relationship among fruit attachment resistance, fruit mass, and vibration-induced inertial force (Pereira et al., 2025a; Silva et al., 2025; Zhou et al., 2025).

Assumptions and Limitations

Several assumptions were required to translate the FRF dataset into a design-stage dynamic simulation. For the empirical regression, each plant-level mean was assumed to represent the average mechanical condition of a maturity class within a sampled plant. Maturity was treated as a categorical factor rather than as a continuous ordinal scale, so no equal spacing between red, orange, and green classes was imposed. For the probability simulation, within-class FRF variation was characterized from the 150 individual fruit measurements available for each maturity stage. The principal detachment mechanism was assumed to be inertial, meaning that vibration-generated dynamic force acts as the immediate trigger for fruit removal, although the real fruit-peduncle-branch response is more complex than a simple point-mass system.

A second group of assumptions concerned vibration representation. The simulation examined nominal local displacement amplitudes of 2, 3, and 4 mm and treated the fruit as a point mass subjected to sinusoidal acceleration. The amplitude A in the model therefore represents an idealized displacement amplitude at the fruit-bearing segment rather than a directly measured actuator-to-fruit displacement. Branch damping, resonance, transmissibility, contact losses, and repeated loading were not explicitly modelled. Consequently, the frequency values calculated from the static FRF threshold are equivalent theoretical frequencies under the adopted assumptions and should not be interpreted as validated machine settings.

The main limitations of the study were the small number of independent coffee plants, the use of plant-level averages for the empirical model, the absence of direct branch or fruit acceleration measurements, and the use of static tensile FRF as a first-order surrogate for dynamic detachment resistance. Real field selectivity also depends on branch geometry, damping, resonance, transmissibility, fruit position, peduncle orientation, repeated excitation cycles, fruit and branch damage, power requirement, and operator-machine interaction. Several site and plant descriptors, including clone identity, planting density, tree height, branch diameter, fruit orientation, and peduncle dimensions, were not systematically recorded. These limitations mean that the theoretical frequency ranges are screening outputs that require instrumented prototype and field validation before engineering optimization.

Problem Formulation and Mathematical Model

The first mathematical component was an empirical plant-level FRF model relating fruit removal force to maturity category and fruit mass. Because red, orange, and green fruits represent distinct biological maturity classes and their mechanical spacing is not assumed to be equal, maturity was entered as a categorical predictor rather than as the numerical code 0, 1, and 2. Red fruit was used as the reference category, with separate indicator variables for orange and green fruit. The categorical model was expressed as Eq. (1).

$$FRF = \beta_0 + \beta_O I_{orange} + \beta_G I_{green} + \beta_M M \dots\dots\dots(1)$$

Where β_0 is the intercept for the red reference class, I_{orange} and I_{green} are indicator variables ($I_{orange} = 1$ only for orange fruit; $I_{green} = 1$ only for green fruit), β_O and β_G

represent the adjusted FRF differences of orange and green fruits relative to red fruit, βM is the fruit-mass coefficient, and M is fresh fruit mass in grams.

The second mathematical component described the dynamic force developed during vibration. Assuming sinusoidal excitation, the peak inertial force acting on a fruit can be approximated by the product of fruit mass, vibration amplitude, and angular frequency squared. The relationship was expressed as Eq. (2), where m is fruit mass in kilograms, A is vibration amplitude in meters, and f is vibration frequency in hertz. Dynamic detachment is expected when the applied force equals or exceeds the FRF threshold of the fruit.

$$F = m \cdot (2 \cdot \pi \cdot f)^2 \cdot A \dots\dots\dots(2)$$

To connect FRF variability with harvest selectivity, a maturity-specific detachment probability was defined using the cumulative normal distribution. For each maturity class j , the probability of detachment under an applied dynamic force F_d was expressed as Eq. (3), where μ_j and σ_j are the mean and standard deviation calculated from the 150 individual FRF observations in that maturity class. Using the individual-fruit distributions rather than the standard deviation of five plant means retains the observed within-class biological variation in the probability simulation. This probability formulation is a design-stage approximation and is not an experimentally measured field detachment probability.

$$P_j = \Phi \cdot \left[\frac{(F_d - \mu_j)}{\sigma_j} \right] \dots\dots\dots(3)$$

Selectivity was summarized through two indices. Harvest purity for ripe fruits was defined as the proportion of predicted detached fruits belonging to the red class, while the composite selectivity index J combined red-fruit recovery and purity. The predicted selective operating window was defined as the force interval where both red-fruit recovery and harvest purity were at least 95%. The term “predicted” is used because this interval was derived from the probability criteria and was not obtained from a physical optimization experiment.

$$S = \frac{P_{red}}{(P_{red} + P_{orange} + P_{green})} \dots\dots\dots(4)$$

$$J = P_{red} \cdot S \dots\dots\dots(5)$$

Analysis Method

Descriptive statistics were calculated at two levels. First, the 450 individual fruit observations were summarized by maturity stage to estimate the mean and standard deviation of FRF and fruit mass and to characterize within-stage dispersion. Second, the 30 fruit measurements within each plant-by-maturity combination were averaged to obtain five plant-level means per maturity stage for biological-replicate comparisons and empirical model fitting.

Inferential analysis used the five coffee plants as biological replicates. A one-way repeated-measures ANOVA was applied to the plant-level means to test the effect of maturity stage on FRF and fruit mass, followed by paired comparisons with Bonferroni adjustment when appropriate. The empirical FRF model was fitted to the 15 plant-by-maturity means using linear regression with maturity represented by two indicator variables (orange and green) and red fruit as the reference category; fruit mass was included as a covariate. Model fit was summarized using R^2 , RMSE, MAPE, residual inspection, and leave-one-out cross-validation. Because only five independent plants were available, these statistics were interpreted as internal fit to the sampled plant-level dataset rather than as evidence of broad predictive generalizability.

Dynamic threshold analysis calculated the idealized frequency required to generate a peak inertial force equal to the mean FRF of each maturity stage at local amplitudes of 2, 3, and 4 mm. Probability curves were generated from the individual-fruit FRF mean and standard deviation for each maturity class over an applied force range of 2.5–8.5 N. The predicted selective window was selected from the region where red-fruit recovery and harvest

purity were both at least 95%. Equivalent accelerations were also calculated from $a = F/m$ and expressed relative to gravitational acceleration ($g = 9.80665 \text{ m s}^{-2}$) to assess the physical implications of the simulated force-frequency range.

Model Evaluation and Literature-Based Plausibility Assessment

Model evaluation was performed at two complementary levels. First, internal fit of the categorical empirical FRF model to the 15 plant-level observations was examined using R^2 , RMSE, MAPE, residual inspection, and leave-one-out cross-validation. These metrics quantify consistency with the available dataset but do not constitute external validation.

Second, the idealized vibration thresholds were compared with published coffee vibration studies as a literature-based plausibility assessment. This comparison was used only to determine whether the magnitude and trend of the simulated conditions were mechanically plausible; it was not considered experimental validation of the model for the present robusta plants. Arabica-based studies were treated as comparative dynamic references rather than species-specific validation.

Selection of the predicted operating window was based on predefined engineering criteria rather than on an optimization algorithm or experimental response surface. The lower boundary required at least 95% predicted red-fruit recovery, and the upper boundary required predicted harvest purity of at least 95%. The resulting interval is therefore referred to as a predicted selective operating window.

RESULTS AND DISCUSSION

FRF and Fruit Mass Pattern

The FRF data showed a clear maturity gradient. Based on the 450 individual observations, mean FRF was $3.533 \pm 0.233 \text{ N}$ for red fruits, $5.966 \pm 0.143 \text{ N}$ for orange fruits, and $8.033 \pm 0.117 \text{ N}$ for green fruits. At the biological-replicate level, repeated-measures ANOVA confirmed a significant maturity effect on FRF ($F(2,8) = 13,786.46$, $p < 0.001$), and all Bonferroni-adjusted pairwise comparisons among red, orange, and green fruits were significant ($p < 0.001$). In contrast, fruit mass did not differ significantly among maturity stages ($F(2,8) = 0.128$, $p = 0.881$). Within the relatively narrow fruit-mass range observed in this study, maturity-related variation in FRF was therefore substantially greater than variation associated with fruit mass.

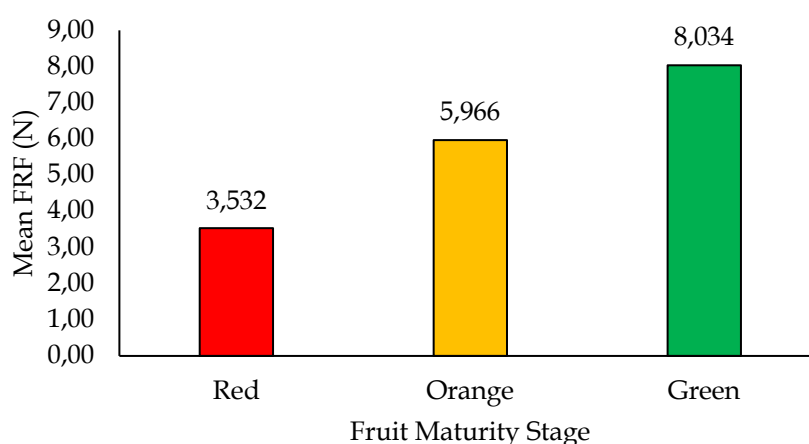


Figure 2. Mean fruit removal force by maturity stage

Table 1. Average FRF and fruit mass on five plant samples for each maturity stage

Plant	Maturity stage	Average FRF (N)	Average Mass (g)
1	Red	3.47	3.02
	Orange	5.96	3.18
	Green	8.03	3.18
2	Red	3.54	2.99
	Orange	5.93	2.89
	Green	8.01	2.80
3	Red	3.56	2.90
	Orange	5.96	2.93
	Green	8.13	2.94
4	Red	3.56	3.05
	Orange	5.96	3.03
	Green	7.98	3.12
5	Red	3.53	2.99
	Orange	6.02	2.89
	Green	8.02	2.78

Table 2. Individual-fruit summary statistics by maturity stage (n = 150 fruits per stage)

Maturity stage	Mean FRF (N)	SD FRF	Mean mass (g)	SD mass	FRF/mass (m s^{-2})	Threshold f at 3 mm (Hz)
Red	3.533	0.233	2.992	0.103	1181.3	100.0
Orange	5.966	0.143	2.984	0.154	1999.3	129.9
Green	8.033	0.117	2.965	0.189	2710.5	151.2

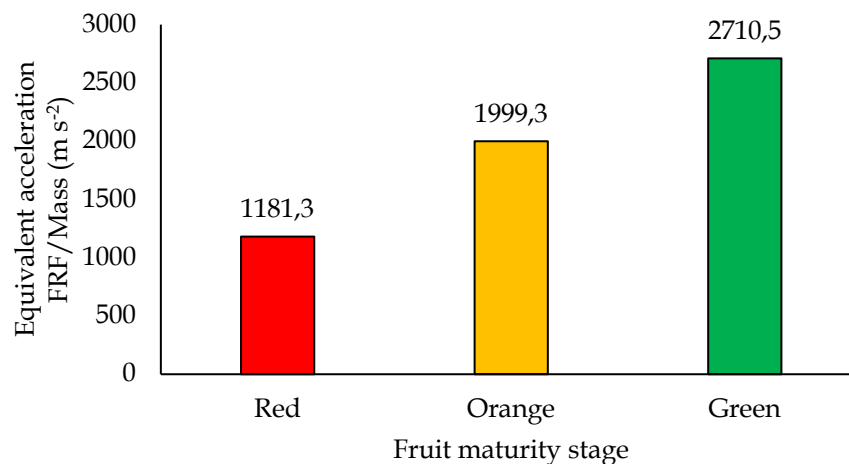


Figure 3. Equivalent acceleration implied by the FRF-to-mass ratio for each maturity stage

The FRF-to-mass ratio is dimensionally equivalent to the acceleration required for inertial force to equal the static FRF threshold. It increased from approximately 1181.3 m s^{-2} for red fruits to 1999.3 m s^{-2} for orange fruits and 2710.5 m s^{-2} for green fruits (Fig. 3), corresponding to about 120.4, 203.9, and 276.3 g, respectively. These values highlight an important limitation of directly equating static tensile FRF with instantaneous inertial detachment: the implied accelerations are extremely high and may not represent practical branch-harvester conditions. Dynamic detachment under repeated excitation, resonance, peduncle fatigue, and non-unity transmissibility may occur differently from the simple point-mass threshold assumed here (Duque-Dussán et al., 2025).

Empirical FRF Model Performance

Treating maturity as a categorical predictor produced a close fit to the available plant-level dataset. With red fruit as the reference class, the fitted model was $FRF = 3.689 + 2.433 I_{orange} + 4.499 I_{green} - 0.052M$, where M is fruit mass in grams. At a given fruit mass, the model therefore estimates orange-fruit FRF to be 2.433 N higher than red-fruit FRF and green-fruit FRF to be 4.499 N higher than red-fruit FRF. Both maturity coefficients were significant ($p < 0.001$), whereas the mass coefficient was small and not significant ($p = 0.606$). The latter result should be interpreted within the narrow fruit-mass range observed in this dataset and does not imply that fruit mass is generally irrelevant to dynamic detachment.

Table 3. Empirical FRF model coefficients and validation statistics

Metric	Value
Intercept (β_0)	3.689
Orange maturity effect (β_O)	2.433
Green maturity effect (β_G)	4.499
Mass coefficient, g (β_M)	-0.052
Model R^2	0.9996
RMSE (N)	0.038
MAPE (%)	0.53
LOOCV R^2	0.9993
LOOCV RMSE (N)	0.050

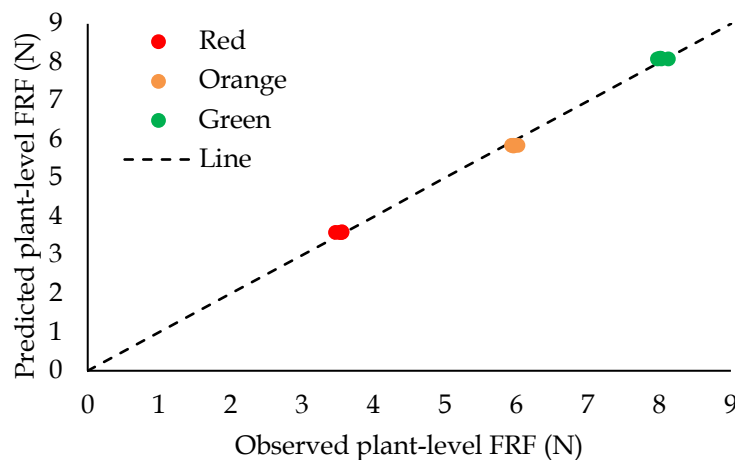


Figure 4. Observed versus predicted plant-level FRF from the categorical empirical model

The categorical model produced $R^2 = 0.9996$, $RMSE = 0.038$ N, $MAPE = 0.53\%$, leave-one-out $R^2 = 0.9993$, and leave-one-out $RMSE = 0.050$ N. Figure 4 shows close agreement between observed and fitted plant-level means. The residuals did not show evidence of departure from normality in the Shapiro-Wilk test ($W = 0.971$, $p = 0.868$). Nevertheless, the very high R^2 should not be interpreted as near-perfect prediction of individual-fruit FRF because the regression was fitted to only 15 plant-by-maturity means and the maturity classes were strongly separated. Plant-level averaging reduces fruit-to-fruit dispersion represented directly in the regression; therefore, the complete individual-fruit FRF distributions were retained separately for the probability simulation.

Dynamic Force Simulation

The dynamic simulation converted mean FRF values into equivalent theoretical frequency thresholds under the idealized point-mass harmonic assumption. At a local amplitude of 3 mm, the thresholds were approximately 99.8 Hz for red fruits, 129.9 Hz for orange fruits, and 151.2 Hz for green fruits (Fig. 5). These frequencies are substantially higher than experimentally investigated coffee-harvesting ranges. Villibor et al. (2023) evaluated 35–55 Hz with amplitudes of 3.5–6.5 mm and noted that commercial coffee harvesters commonly operate near 25 Hz, while Zhou et al. (2025) tested 50–70 Hz and reported field-selective performance around 55 Hz at a much larger amplitude of 10.10 mm in Arabica. Therefore, the present 100–151 Hz values should not be interpreted as immediately practical machine settings; they reveal the consequence of equating static FRF directly with inertial force in a simplified model.

Amplitude sensitivity analysis retained the expected mathematical trade-off between displacement amplitude and equivalent frequency (Table 4). However, the corresponding acceleration requirement is determined by F/m and therefore remains very high. At the 3-mm mean-FRF thresholds, the theoretical local accelerations are approximately 1181, 1999, and 2709 m s^{-2} for red, orange, and green fruit, respectively (about 120, 204, and 276 g). Such accelerations raise concerns regarding branch damage, fruit damage, power demand, resonance, machine vibration, and operator exposure if interpreted literally. Their magnitude reinforces that the present static-FRF point-mass model is a screening abstraction; actual dynamic detachment may be achieved through repeated loading, resonance amplification, fatigue, and complex fruit-peduncle-branch motion at lower actuator frequencies and different amplitudes.

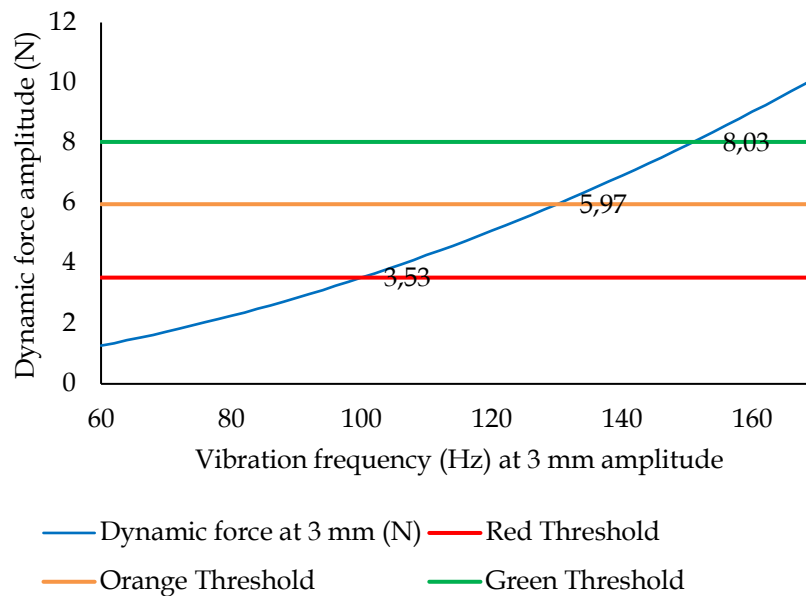


Figure 5. Simulated dynamic force and maturity-specific detachment thresholds

Table 4. Equivalent threshold frequencies for three vibration amplitudes

Maturity stage	2 mm	3 mm	4 mm
Red	122.3	100.0	86.500
Orange	159.1	129.9	112.5
Green	185.3	151.3	131

Model Evaluation and Plausibility of the Dynamic Simulation

Internal model-fit results showed that the categorical empirical model closely reproduced the plant-level maturity pattern, but this represents internal consistency with the

sampled dataset rather than external validation. The probability curves were generated separately from the individual-fruit FRF distributions, so fruit-to-fruit variability was retained in the selectivity simulation even though the empirical regression used plant-level means. The resulting ordering – red-fruit detachment increasing first, followed by orange and then green fruit – is mechanically consistent with the observed FRF gradient but remains to be verified experimentally under controlled vibration.

The predefined 95% criteria were used only to select a predicted operating window. The lower boundary corresponded to 95% predicted red-fruit recovery, and the upper boundary was constrained by maintaining predicted harvest purity at or above 95%. Figure 6 shows the 95% probability reference line. Because the curves are derived from observed FRF distributions rather than measured vibration-detachment trials, the resulting window should be interpreted as a hypothesis for experimental testing (Furriel et al., 2022).

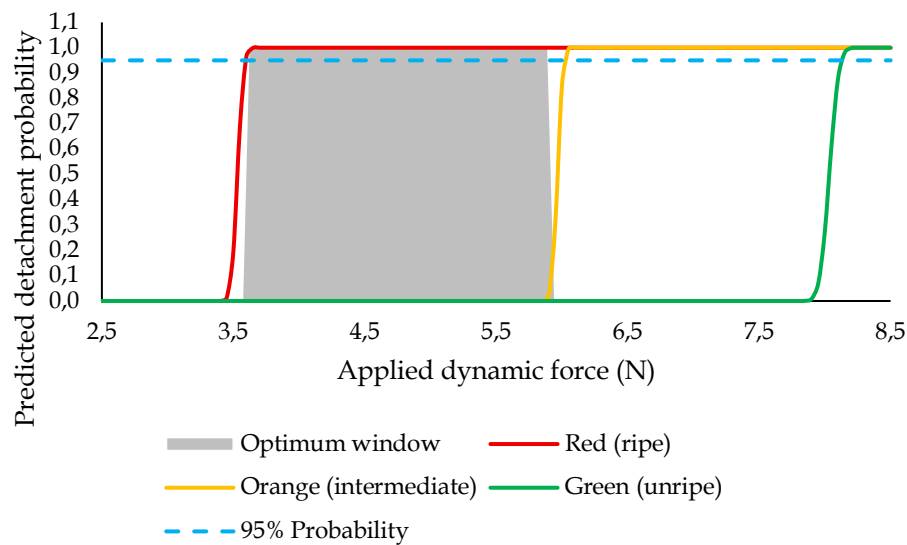


Figure 6. Predicted detachment probability by maturity stage with the 95% criterion and predicted selective window

Predicted Selective Operating Window

The simulation predicted a potential selective operating window of approximately 3.92–5.73 N of dynamic force (Fig. 7). Using the average fruit mass and the idealized local amplitude of 3 mm, this interval corresponds to approximately 105.4–127.4 Hz. The equivalent local acceleration across this window is about 1315–1923 m s^{-2} , or approximately 134–196 g. These values are substantially above the acceleration environment implied by conventional coffee-harvesting frequencies and therefore should not be interpreted as direct machine-control recommendations. Instead, the force window is the more defensible output of the current model, while the frequency conversion is an idealized equivalence that requires experimental transmissibility, resonance, and dynamic-detachment measurements.

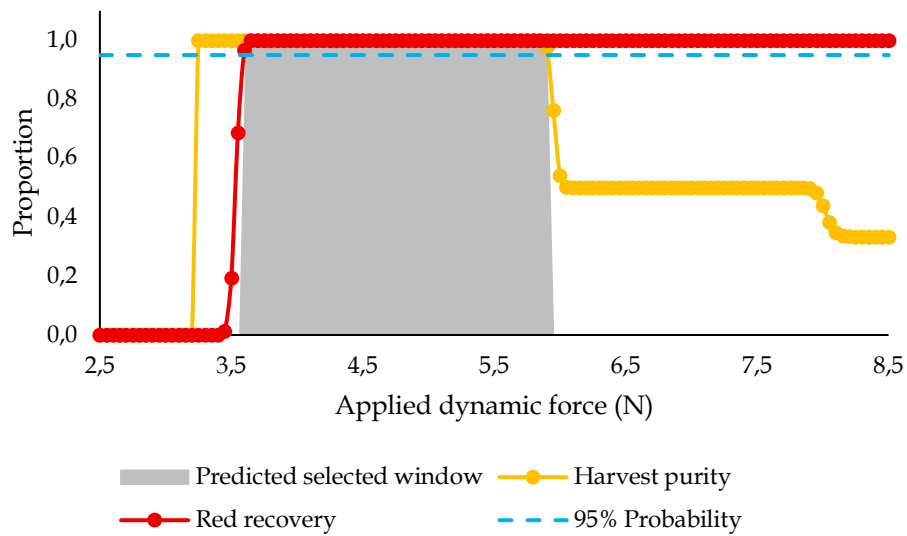


Figure 7. Selection of the predicted selective operating window based on red-fruit recovery and harvest purity

The predicted force interval converts the observed maturity-dependent attachment gradient into a testable engineering hypothesis, but it should be verified at the branch and prototype levels before use in harvester control. Published coffee studies have demonstrated selective responses at substantially lower frequencies when larger amplitudes, repeated loading, branch dynamics, and transmissibility are present (Villibor et al., 2023; Zhou et al., 2025). Future experiments should therefore prioritize direct measurement of branch and fruit acceleration, frequency-response functions, transmissibility, detachment percentage, fruit and branch damage, energy consumption, and operator vibration exposure rather than applying the present equivalent frequencies directly.

Table 5. Predicted operating zones derived from the idealized force-frequency relationship

Operating zone	Dynamic force (N)	Equivalent frequency at 3 mm (Hz)	Expected response	Interpretation
Predicted selective window	3.92–5.73	105.4–127.4	High predicted red recovery and harvest purity	Experimental screening only
Transition zone	5.73–8.03	127.4–151.2	Orange-fruit contribution increases; harvest purity declines	Model exploration only
Non-selective zone	>8.03	>151.2	Green-fruit detachment becomes increasingly likely	Not suitable for selective screening

CONCLUSION

This study showed a significant maturity-dependent gradient in robusta coffee fruit removal force, with individual-fruit means of 3.533 N for red, 5.966 N for orange, and 8.033 N for green fruit. A categorical plant-level FRF model, using red fruit as the reference category and separate indicators for orange and green fruit, closely represented the 15 plant-by-maturity means ($R^2 = 0.9996$; RMSE = 0.038 N), while the complete individual-fruit FRF

distributions were retained to represent within-class variation in the probability simulation. Under the assumptions of the simplified point-mass harmonic model, the simulation predicted a potential selective force window of approximately 3.92–5.73 N, equivalent to about 105.4–127.4 Hz at a local amplitude of 3 mm. Because these equivalent frequencies imply theoretical local accelerations of roughly 134–196 g and because damping, resonance, transmissibility, repeated loading, and branch geometry were not measured directly, the frequency range should not be interpreted as a validated machine operating specification. The predicted force window may serve as an initial design guideline for future instrumented branch tests and prototype development, including direct measurements of acceleration, transmissibility, detachment percentage, fruit and branch damage, power demand, and operator vibration exposure.

ACKNOWLEDGEMENTS

This research was financially supported by an internal grant from Universitas Jember under the KERIS-DIMAS Grant scheme, based on the Rector's Decree of Universitas Jember No. 8375/DST/UN25/KP/2026, dated May 5, 2026, concerning the recipients of the Internal Research Resource Program Grant of Universitas Jember for the 2026 fiscal year. This research was conducted under the Research Assignment Agreement No. 4238/DST/UN25.C1/LT/2026, dated May 5, 2026, issued by the Institute for Research and Community Service, Universitas Jember. The authors also like to express their sincere gratitude to the Agricultural Tools and Machinery and Food Engineering Laboratory, Agricultural Engineering Study Program, Faculty of Agricultural Technology, Universitas Jember, for providing the laboratory facilities used by the researchers during this study. The authors would also gratefully acknowledge to Mr. Muarif, a farmer and producer of Rengganis Coffee from Pakis Village, Sukorambi District, Jember Regency, for his valuable support and assistance during this study.

CONFLICT OF INTEREST

The authors declare that they have no competing financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

REFERENCES

- Bizimungu, G., Ahouansou, R. H., & Semassou, C. (2022). Physical and mechanical properties of coffee cherries and beans in Africa: Review and the State of arts. *Food Science and Technology*. <https://doi.org/10.13189/fst.2022.100301>
- Buitrago-Osorio, J., Tinoco, H. A., Perdomo-Hurtado, L., Rincon-Jimenez, A., Ocampo, O., Berrio, L. V., Pineda, M. F., & Lopez-Guzman, J. (2022). Physical-mechanical characterization of coffee fruits *Coffea arabica* L. var. Castillo classified by a colorimetry approach. *Materialia*, 21, 101330. <https://doi.org/10.1016/j.mtla.2022.101330>
- Campuzano-Duque, L. F., Herrera, J. C., Ged, C., & Blair, M. W. (2021). Bases for the establishment of robusta coffee (*Coffea canephora*) as a new crop for Colombia. *Agronomy*, 11(12), 2550. <https://doi.org/10.3390/agronomy11122550>
- Castro-Garcia, S., Aragon-Rodriguez, F., Arias-Calderón, R., Sola-Guirado, R. R., & Gil-Ribes, J. A. (2020). The contribution of fruit and leaves to the dynamic response of secondary branches of orange trees. *Biosystems Engineering*, 193, 149–156. <https://doi.org/10.1016/j.biosystemseng.2020.02.019>
- Costa, A. G., de Sousa, D. A. G., Paes, J. L., Cunha, J. P. B., & de Oliveira, M. V. M. (2020). Classification of robusta coffee fruits at different maturation stages using colorimetric

- characteristics. *Engenharia Agrícola*, 40(4), 518–525. <https://doi.org/10.1590/1809-4430-Eng.Agric.v40n4p518-525/2020>
- de Deus Godinho Filho, J., Souza, J. B. C., de Almeida, S. L. H., Junior, L. A. R. R., de Oliveira Vieira, I. C., de Oliveira Tavares, T., & da Silva, R. P. (2025). Spatial and temporal variability of coffee fruit detachment force in relation to maturity aiming at smart harvesting. *Smart Agricultural Technology*, 101394. <https://doi.org/10.1016/j.atech.2025.101394>
- de Melo Júnior, W. W. A., Santos, F. L., & Scinocca, F. (2023). Modal analysis of the coffee fruit-peduncle-branch system coffee fruit-peduncle-branch system. *Smart Agricultural Technology*, 4, 100217. <https://doi.org/10.1016/j.atech.2023.100217>
- Duque-Dussán, E., Rincón-Jimenez, A., Tinoco, H. A., Cardona, C. I., Ibarra, C. A., & Rodríguez-Sotelo, J. L. (2025). Determination of Elastic Properties of Coffea arabica L. var. Castillo Bean-Mesocarp Using Finite Element Analysis and Experimental Methods. *Journal of Food Process Engineering*, 48(12), e70303.
- Freitas, V. V., Borges, L. L. R., Vidigal, M. C. T. R., dos Santos, M. H., & Stringheta, P. C. (2024). Coffee: A comprehensive overview of origin, market, and the quality process. *Trends in Food Science & Technology*, 146, 104411. <https://doi.org/10.1016/j.tifs.2024.104411>
- Furriel, G. P., Furriel, B. C. R. S., Coimbra, A. P., & Calixto, W. P. (2022). Acoustics applied in the development of equipment for precision agriculture: Coffee handling and harvesting. *Computers and Electronics in Agriculture*, 198, 106981. <https://doi.org/10.1016/j.compag.2022.106981>
- Ghonimy, M., Alayouni, R., Alshehry, G., Barakat, H., & Ibrahim, M. M. (2025). Integrated Physical-Mechanical Characterization of Fruits for Enhancing Post-Harvest Quality and Handling Efficiency. *Foods*, 14(14), 2521. <https://doi.org/10.3390/foods14142521>
- Gomes, E. Q., Santos, F. L., Nascimento, M., & Velloso, N. S. (2020). Effect of the impact of rigid rods on coffee fruit detachment efficiency by mechanical vibrations. *Coffee Science*. <https://doi.org/10.25186/.v15i.1747>
- Homayouni, T., Gholami, A., Toudeshki, A., Afsah-Hejri, L., & Ehsani, R. (2022). Estimation of proper shaking parameters for pistachio trees based on their trunk size. *Biosystems Engineering*, 216, 121–131. <https://doi.org/10.1016/j.biosystemseng.2022.02.008>
- Lestari, D. I., Amilia, W., Rusdianto, A. S., Choiron, M., & Mahardika, N. S. (2024). Marketing Strategy Planning of Kahyangan Coffee Using Marketing Mix in Coffee Shops. *JSEP (Journal of Social and Agricultural Economics)*, 16(3), 287–300. <https://doi.org/10.19184/jsep.v16i3.43030>
- Meneses, M. D., dos Santos Carreira, V., de Almeida Moreira, B. R., do Vale, W. G., de Souza Rolim, G., & da Silva, R. P. (2024). Machine learning models for classifying coffee fruits detachment force. *Agronomy Journal*, 116(5), 2362–2369. <https://doi.org/10.1002/agj2.21633>
- Osorio, V., Pabón, J., & Medina, R. (2024). Impact of fruit reserve conditions from harvest to processing on the chemical composition and quality of coffee. *Frontiers in Sustainable Food Systems*, 8, 1425599. <https://doi.org/10.3389/fsufs.2024.1425599>
- Pereira, M. R., Santos, F. L., Scinocca, F., Tinoco, H. A., & Villibor, G. P. (2025a). Determination of the Modal Properties of the Coffee Plant (Coffea arabica L.): A Study Under Field Conditions. *AgriEngineering*, 7(11), 364. <https://doi.org/10.3390/agriengineering7110364>
- Pereira, M. R., Santos, F. L., Scinocca, F., Tinoco, H. A., & Villibor, G. P. (2025b). Evaluation of the transmissibility of vibration and dynamic behaviour of coffee plants under field conditions. *Biosystems Engineering*, 250, 225–235. <https://doi.org/10.1016/j.biosystemseng.2025.01.002>
- Prasetyo, E., Listiyaningsih, D., Setiadi, A., Mukson, M., Roessali, W., & Ekowati, T. (2022).

- Factors determining income and product type of Robusta coffee farming in Central Java, Indonesia. *International Social Science Journal*, 72(245), 737–748. <https://doi.org/10.1111/issj.12362>
- Pratopo, L. H., Thoriq, A., & Ciptaningtyas, D. (2023). Financial Feasibility Analysis of Arabica Powder Coffee in Drip Bag Packaging (Case Study of Berdikari Farmer Group, Sumedang District). *Jurnal Ilmiah Rekayasa Pertanian Dan Biosistem*, 11(2), 188–200. <https://doi.org/10.29303/jrpb.v11i2.470>
- Privat, I., Foucrier, S., Prins, A., Epalle, T., Eychenne, M., Kandalaf, L., Caillet, V., Lin, C., Tanksley, S., Foyer, C. H., & McCarthy, J. (2008). Differential regulation of grain sucrose accumulation and metabolism in *Coffea arabica* (Arabica) and *Coffea canephora* (Robusta) revealed through gene expression and enzyme activity analysis. *New Phytologist*, 178(4), 781–797. <https://doi.org/10.1111/j.1469-8137.2008.02425.x>
- Rinaldi, M., Salim, I., Azis, A., & Mursalim, M. (2024). Rancang Model Sistem Mobile untuk Mesin Pengupas Kopi (Pulper). *Jurnal Ilmiah Rekayasa Pertanian Dan Biosistem*, 12(1), 14–25. <https://doi.org/10.29303/jrpb.v12i1.537>
- Silva, D. S. e, Magalhães, R. R., Santos, F. L., Bonesio, M. de R., & Silva, S. P. da. (2025). Three-Dimensional Scanning and Computational Simulation of Coffee Tree Branches. *Agriculture*, 15(13), 1326. <https://doi.org/10.3390/agriculture15131326>
- Sola-Guirado, R. R., Sanchez-Cachinero, P., & Blanco-Roldan, G. (2023). Simultaneous trunk and branch shaking in an over-the-row olive harvester. *Biosystems Engineering*, 231, 92–103. <https://doi.org/10.1016/j.biosystemseng.2023.06.005>
- Souza, G. S. de, Bouzan, A., Infantini, M. B., Silva, S. de A., & Almeida, R. F. de. (2023). Mechanized harvesting of conilon coffee plants using a self-propelled machine. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 27, 140–148. <https://doi.org/10.1590/1807-1929/agriambi.v27n2p140-148>
- Villibor, G. P., Santos, F. L., Queiroz, D. M., Khoury, J. K., & Pinto, F. A. C. (2023). Vibration Transmissibility of the Coffee Fruit-Peduncle System: a Forced Vibration Study of High Frequency Aiming Mechanical Harvesting. *Engenharia Agrícola*, 43(1), e20220201. <https://doi.org/10.1590/1809-4430-Eng.Agric.v43n1e20210201/2023>
- Wibowo, Y., & Palupi, C. B. (2022). Analisis nilai tambah pengolahan biji kopi arabika (studi kasus: rumah kopi banjarsengon, Jember). *Jurnal Agroteknologi*, 16(1), 37–48. <https://doi.org/10.19184/j-agt.v16i01.28209>
- Zhou, S., Yu, Y., Su, W., Wang, H., Yuan, B., & Que, Y. (2025). Determining the Vibration Parameters for Coffee Harvesting Through the Vibration of Fruit-Bearing Branches: Field Trials and Validation. *Agriculture*, 15(10), 1036. <https://doi.org/10.3390/agriculture15101036>