eISSN: 1984-3909
Coffee Science, e172012, 2022

Doi: https://doi.org/10.25186/.v17i.2012

Determination of physical and mechanical properties of the coffee branch: An experimental approach

Wellington Washington Andrade de Melo Júnior[1], Fabio Lúcio Santos[1], Francisco Scinocca[1], Pablo Antunes da Rosa[2], Ricardo Rodrigues Magalhães[1]

[1]Universidade Federal de Lavras/UFLA, Departamento de Engenharia/DEG, Lavras, MG, Brasil
[2]Universidade Federal de Santa Catarina/UFSC, Departamento de Engenharia Mecânica, Florianópolis, SC, Brasil
Contact authors: wamelo@outlook.com; fabio.santos@ufla.br; francisco.scinocca@ufla.br; pablo.antunes@outlook.de; ricardorm@ufla.br
Received in February 4, 2022 and approved in August 5, 2022

ABSTRACT

In order to reduce the human efforts during manual harvesting and increase the operational capacity and quality, the mechanization of the harvesting operation has been significantly increasing in the last few years for coffee crops. Therefore, for the design of coffee harvesting machines, the physical and mechanical properties of coffee branches are of utmost importance for harvesting machines projects. In this way, using an experimental approach, the present paper analyzes the variability of physical and mechanical properties in the coffee branches, of the Coffea arabica L., cultivar Catuaí-Vermelho (IAC 144). The branches were collected in different positions, along the orthotropic branch: upper, middle and lower parts of the plant. The mass, volume, specific mass, and modulus of elasticity of the collected specimens were determined considering their position in the plant and position along the branches. According to the position in the plant, no significant differences were found between the specific mass averages for the upper, middle, and lower parts of the plant. The research obtained an average of 1.24 GPa with a standard deviation of 0.13 GPa for the elasticity modulus. A significant increase in the elasticity modulus could be noted in the branches from the top to the bottom of the plant in the present research.

Key words: Mechanized harvest; tensile test; elasticity modulus variation; coffee plant analysis; coffee branch analysis.

1 INTRODUCTION

According to the International Coffee Organization (International Coffee Organization - ICO, 2020), the World production for the 2018/2019 harvest was over 170 million bags of coffee (60 kg per bag). In particular, Brazil deserves a prominent place in the World production scenario, since it is the World leader in production and exports, and the country ranks second as the largest consumer of the product. Therefore, the First Crop Survey of 2020 carried out by the Brazilian National Supply Company (Companhia Nacional de Abastecimento - CONAB, 2020) with an estimate of production, presenting a positive biennially, reaching between 57 million and 62 million bags produced, generating jobs and contributing significantly to the country's economy.

In order to obtain high-quality coffee, associated with cost reduction and increased productivity in its process, best practices and innovative technologies should be employed. Likewise, the quality and price of agricultural products have changed over the years, based on the customer's decision, which involves brand, purity seal, and qualitative criteria such as flavor and aroma, placed in powder or capsule (Stocker et al., 2019). On the other hand, the quality of the coffee product is highly related to several factors, such as cultural treatments, harvesting process, post-processing, and processing (Boaventura et al., 2018; Guimarães; Castro Júnior; Andrade, 2016; Prieto et al., 2008). According to Santos et al. (2010b), losses in quality can vary from 10 to 20% in terms of appearance, 40% in relation to drink, and up to 60% for bad drink coffee.

Therefore, the continuous improvement of equipment employed in coffee harvesting is essential to operational cost reduction, since it is considered the costliest in the production chain of the crop (Oliveira et al., 2007b; Santinato, 2014). Cunha et al. (2016) and Santinato et al. (2015) highlighted the decrease in costs when replacing manual harvesting labor with mechanized harvesters. According to Oliveira et al. (2007a), the reduction in total operating costs with mechanized harvesting exceeds 60% when compared to manual harvesting.

Several types of research involving mechanization were developed, mainly in the flatter areas of the cerrado, which can be implanted even in irrigated crops. (Ortega; Jesus, 2011; Cassia et al., 2013; Tavares et al., 2016). However, research and development in harvesting machines for mountainous regions are also studied (Oliveira et al., 2014). In the same way, the use of portable harvesters for semi-mechanized harvesting also proves to be a good alternative for reducing the demand for labor, in more mountainous regions (Mejía; Tascón; Uribe, 2013).

During the harvesting phase, the plant architecture influences directly in its process, since the fruit stage of maturation is linked to the quality of the drink that will be obtained. This phase can be described in stages: first harvesting or picking fruits; followed by sweeping and gathering, ending with shaking the fruits. In the initial phase, all fruits can be harvested, or only the mature ones selectively obtained (Souza; Queiroz; Rafull, 2006).

The fruit in the mature stage, also known as cherry or ripe fruit, is considered the ideal point of harvest. The detachment of green fruits is undesirable, considering that only ripe fruits have all the chemical characteristics necessary to obtain a good quality coffee (Oliveira et al., 2017, Prieto et al., 2014, Angélico et al., 2011). For this reason, is important to selective harvesting and adequate removal of impurities in the post-harvest phase or even processing. Thus, mechanized coffee harvesting is considered efficient when there is maximum detachment of ripe fruits, low double harvest rates, in addition to low defoliation and branch breaking, as observed by Souza et al. (2005).

In this way, the force required to detach the ripe fruit is a parameter that influences an efficient mechanized harvest. Silva et al. (2010) presented differences in the strength of detachment between unripe and ripe fruits, over the maturation period, and even between cultivars. The authors observed an increase in the strength of detachment of unripe fruits, when compared to ripe fruits, from: 20 to 35% for the cultivars Mundo Novo, 17 to 26% for Icatú and, from 27 to 34% for Catuaí. Additionally, Li et al. (2013) found that the detachment strength of the fruits does not depend only on the adjustments to the harvesters, but also on climatic and nutritional factors of the plants, which, because it is biological material, reacts when subjected to different levels of external efforts.

The dynamic behavior of coffee plant has been studied through laboratory, field experiments, or even from computer simulations using mathematical models, with analytical and numerical approaches (Ciro, 2001; Aristzábal; Oliveros; Alvares, 2003; Santos et al., 2010a, 2010b).

The finite element method is a computational tool that allows the solution of a system of differential equations, allowing a significant improvement in the modeling of physical systems. This method was employed by Carvalho, Magalhães and Santos (2016) to evaluate the mechanical behavior of a coffee plant. Tinoco et al. (2014) and Santos et al. (2015) had conclude that mathematical modeling contributes significantly to the study of selective harvesting and aid in the development of agricultural machinery and equipment. However, this process needs to be studied in detail, such as the influence of rod vibration and the speed of the harvester on the mechanized coffee harvesting process (Oliveira et al., 2017).

However, Wu et al. (2016), observed the variation of properties such as modulus of elasticity, specific mass, and Poisson's ratio in the modeling of multibody mechanical systems, due the uncertainties of the material's properties. Villibor et al. (2019) presented the importance of identifying the physical-geometric-mechanical properties of the coffee plant and analyzing its variations, since they significantly influence the results obtained in the computer simulations. Coelho et al. (2016) presented the analysis of the influence of the variability of mechanical properties and employing the stochastic finite element method. The natural frequencies of the coffee system had presented a spectral result. Other authors had presented a huge variability in the physical properties of the branch-peduncle-fruit system and, with this, changes in the dynamic response of the system (Coelho et al., 2015; Tinoco et al., 2014).

The present research was developed with the objective of determining experimentally the physical-mechanical properties of the branch of the coffee plant. An evaluation of the branch position in the plant was studied in detail along the plant architecture. This important information can be employed in future stochastic modeling research, as a database. In the same way, another important justification for the present research, is to quantify the variability in the physical-mechanical properties of the branch of the coffee plant, using an experimental approach. The statistical results obtained, could serve to improve and optimize harvesting machines.

2 MATERIAL AND METHODS

The present research was carried out in an experimental field in the southern region of the state of Minas Gerais, Brazil. Plagiotropic branches of Coffea arabica L., cultivar Catuaí-Vermelho (IAC 144), were collected close to the orthotropic branch using pruning shears. The plants were selected randomly, avoiding removing branches, even in different positions along the plants demarcated. The samples were collected in the morning and the tests performed during the same day of the collection, from May / 2019 to June / 2019. Sprouts coming out of the orthotropic branch, which is not considered plagiotropic, were withdrawn from the experiments.

In order to analyze the variation of physical and mechanical properties in the coffee plant, branches were collected in different positions, along the orthotropic branch: upper, middle and lower thirds, as presented in Figure 1. The branches were chosen visually, analyzing the characteristics of the material, since different parts present greater or lesser wood development. Twenty repetitions were collected for each position in the coffee plant.

The branches collected had the size to make at least two specimens. As they have smaller dimensions than the minimum ones for making standardized specimens, a non-standardized tensile test was chosen, however, adopted form the Brazilian Standards NBR 7190 (ABNT, 1997). The specimens were made according to the dimensions shown in Figure 2 and, subsequently, identified according to their Position Reference (PR) in the branch. The PR1 is close to the cut made next to the orthotropic branch; the PR2 is near the free end of the branch. The specimens were prepared with 20 mm at their ends, which were used to fix the specimens close to the claws of the universal testing machine.

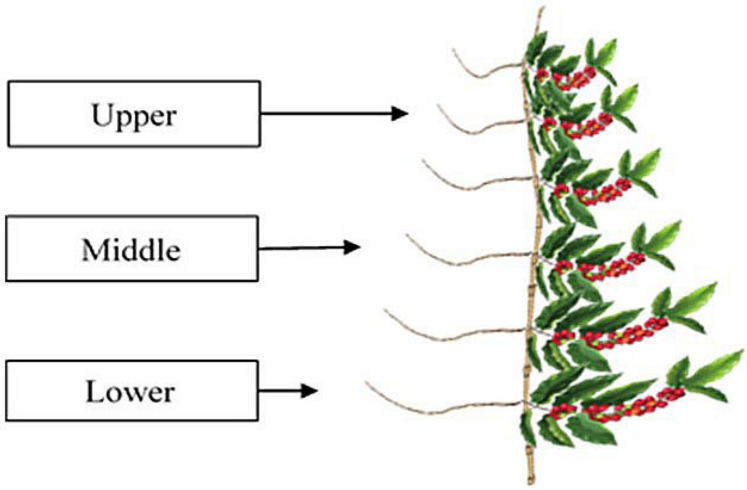

Figure 1: Position collected from branches on the plant.

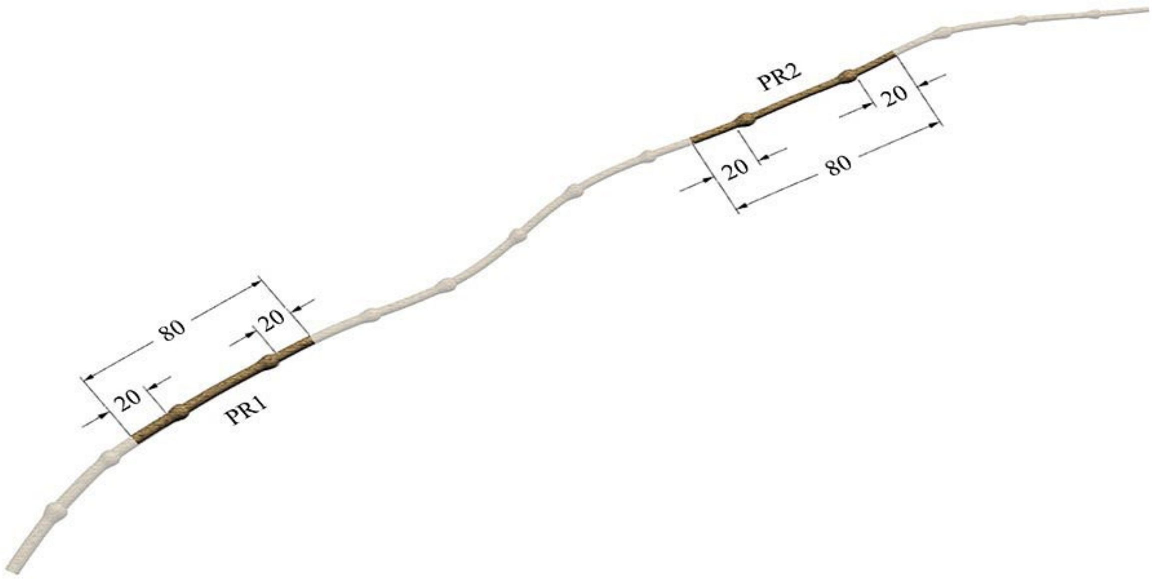

Figure 2: Method of obtaining the specimens, PR1 and PR2 (measured in millimeters).

The mass, volume, specific mass and modulus of elasticity of the collected specimens were determined considering their position in the plant (PP) and position along the branch (PR). The masses of the specimens were determined using a semi-analytical digital scale, model AD500, manufactured by Marte Científica®, with a resolution of 0.001 g. The immersion method was used to determine the volume, with the aid of a 10 mL beaker with 0.1 mL resolution. The specific mass of the branches was given by the ratio between the experimental values of mass and volume. For the determination of the modulus of elasticity, the universal testing machine, model EMIC 23-20, manufactured by Instron®, equipped with a maximum load cell of 20 kN was used. In the machine, the specimens were subjected to tensile tests, parallel to the fibers, fixed by claws at the ends and subjected to loading in the central region, as shown in Figure 3 (a). A pre-load of 2 N was applied for the previous tensioning of the samples and the test was carried out at a displacement rate of 0.01 $m.min^{-1}$ with a time duration corresponding to the linearity output, after maximum tension. The Figure 3(b) presents the fiber direction details.

During the elasticity modulus tests, the 60 samples were submitted to tensile stress until rupture. Specific stress and strain values were measured. Based on these data, stress-strain graphs were created and the elasticity modulus was calculated in the elastic zone for each sample, using the tangent method, only in the elastic region of the curve (Garcia; Spim; Santos, 2012).

The data were submitted to analysis of variance, according to a completely randomized design, in a 2x3 factorial scheme, with 20 repetitions (total of 60 samples). The factors considered in the analysis were two positions along the branch, as showed in Figure 2, and three positions on the plant, as showed in Figure 1. The effect of the factors studied on the behavior of the specific mass and the modulus of elasticity was analyzed using the Tukey test, considering a significance level of 5%. The R software (R Core Team, 2020) was used to perform the statistical analysis.

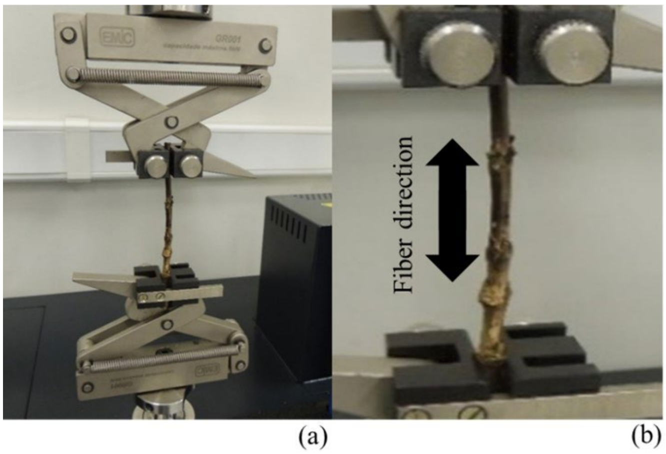

Figure 3: (a) Experimental configuration, specimen fixed in two claws for tensile test; (b) Fiber Direction Details.

3 RESULTS

The specimens of the branch had an average specific mass equal to 0.945 $g.cm^{-3}$ with a standard deviation of 0.049 $g.cm^{-3}$. For the specific mass averages, no significant differences were observed for the factors position in the plant (PP) and position in the branch (PR) and, consequently, their interaction, according to the F test, as shown in Table 1.

The results of the descriptive statistics for the specific mass of the branches, considering the position in the plant (PP) and position along the branch (PR) are presented in summary form in Table 2 and in Figure 4. According to the classification criterion proposed by Warrick and Nielsen (1980), the values of the Variance Coefficient (VC) for average specific mass revealed to be of low dispersion (<12%). Thus, the data set can be considered as homogeneous, validating the comparison between the values of this response variable.

The elasticity modulus average found in the present research was 1.24 GPa with a standard deviation of 0.13 GPa. The stress-strain curve deformation for each position in the plant branch is presented Figure 5. The values found correspond to the linear elastic part of the tensile test.

Table 1: Results for the analysis of variance regarding the influence of the factors position in the plant and position in the branch on the specific mass of the branches.

Variation source	DOF	SQ	QM	F	F critical	Pr>Fc
PP	2	0.002744	0.0013717	0.635349	3.075853	0.531616
PR	1	0.006640	0.0066398	3.075353	3.92433	0.082175
PP x PR	2	0.001939	0.0009696	0.449096	3.075853	0.639329
Residual	114	0.246132	0.0021590			
Total	119	0.257455				
VC = 4.88%						

Legend: VC = Variation coefficient.

Table 2: Descriptive statistics referring to the specific mass of the branches in relation to the position on the plant and position along the branch.

	Upper		Middle		Lower		Total
	PR1	PR2	PR1	PR2	PR1	PR2	
Average	0.950	0.969	0.949	0.952	0.937	0.959	0.942
St. deviation	0.053	0.051	0.041	0.030	0.053	0.046	0.049
Variance	0.003	0.003	0.002	0.00	0.003	0.002	0.002
CV	5.58%	5.26%	4.32%	3.15%	5.65%	4.79%	

Legend: CV= Variation Coefficient in relation to the total specific mass average.

In Table 3, it is possible to observe the results for analysis of variance considering the modulus of elasticity for the factors position in the plant and position in the branch. It is noted that the interaction between the factors position in the plant (PP) and position along the branch (PR) showed a significant difference. Thus, the deployment and analysis of the influence of factors on the elasticity module of the branch proceeded is presented in Table 4.

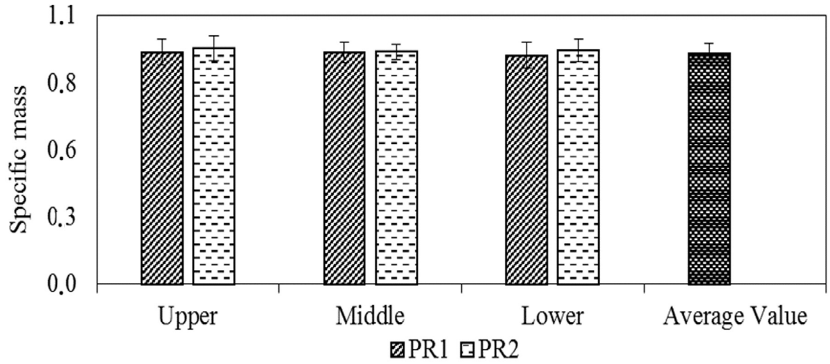

Figure 4: Specific mass average per position in the plant.

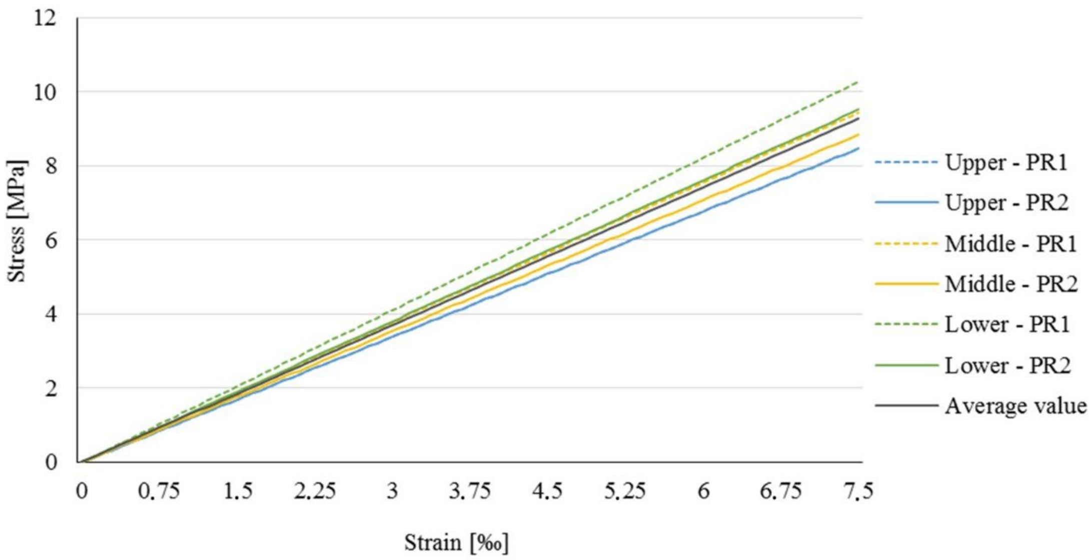

Figure 5: Stress-strain curve of the specimens in relation to the position in the plant.

Table 3: Results for the analysis of variance regarding the influence of the factors position on the plant and position on the branch on the elasticity module of the branches

Variation Source variação	GDL	SQ	QM	F	F critical	Pr>Fc
PP	2	262378	131189	18,21409	3.168246	0.000001
PR	1	20873	20873	2,897932	4.019541	0.094444
PP x PR	2	73103	36552	5,074781	3.18246	0.009559
Residual	114	388942	7203			
Total	119	745296				
VC = 6,88%						

Legend: VC = Variation coefficient. Analogously to the criterion used for specific mass (Warrick; Nielsen, 1980), the value of the coefficient variation found for the elasticity modulus can be considered as having low dispersion in relation to the mean (<12%). Such a measure must be considered, because the lower the VC value, the more the data is concentrated around the average, that is, a more homogeneous set.

Table 4: Breakdown - Position on the plant within each level of Position on the branch

	Branch position	
Plant Position	PR1 [GPa]	PR2 [GPa]
Upper	1.13Aa	1.19Aa
Middle	1.26Ab	1.18Aa
Lower	1.37Ac	1.27Ba

Legend: Means followed by the same uppercase letters in the row and lowercase letters in the column are statistically equal by the Tukey test ($p < 0.05$).

4 DISCUSSION

Coelho et al. (2015) determined the specific mass for the branch equals to 0.900 g.cm^{-3}. The results found by Coelho et al. (2015), for the variety Catuaí Vermelho IAC 144, was below that found in the present research, as presented in Table 2 and in Figure 4. The discrepancy can be explained by the type of management of the coffee field, age difference, in addition to adverse weather conditions (Aristzábal; Oliveros; Alvares, 2003; Rodríguez et al., 2006). Additionally, the study by Coelho et al. (2015) contemplated a smaller number of samples and used a random collection method, which may have influenced the involuntary acquisition of branches with more or less woody part, due to the great variability existing in the plant.

The plant position factor, as expected, presented significant differences between the levels of position in the branch (Figure 1). The values obtained for PR1, with the averages presented in the unfolding of the effect of the factor interaction in Table 4, were significant. For PR2, the means found were statistically equal.

The values found for the branches are increasing from the top of the plant to the bottom, which demonstrates greater rigidity in this fraction of the plant, as presented in Figure 5 and in Table 4. In general, the lower branches had a larger part of the wood and a larger diameter, while the upper branches had smaller diameters and more of the new branch, with a less developed woody part. Latorraca et al. (2000) observed that the properties of woody bodies vary according to the growth of the tree. The authors explain that, with advancing age, there is a consequent increase in cell wall thickness and a decrease in cell width.

Several researchers have analyzed the influence of juvenile and mature woods. In their work, they explained this difference in the elasticity module, being similar to that found in the present paper. (Evans; Senft; Green, 2000; Rowell; Han; Rowell, 2000; Mcalister; Clark; Saucier, 1997; Kretschmann; Bendtsen, 1992). Juvenile wood is characterized, in general, by its lower density, thinner cell walls and less resistance. Similar to what happens in juvenile woods, the elasticity modulus is directly affected by branches containing less developed woody part.

Coelho et al. (2015) found 1.94 GPa with standard deviation 0.62 GPa for Catuaí Vermelho IAC 144. The authors used the mechanical flexion test as a method of obtaining the branch elasticity module. Unlike the method employed in the present research, the authors used samples of 250 mm in length, bi supported on the extremities, submitted to loading in the central region. The test speed was 1.0 mm s^{-1} and the displacements were captured using a digital camera. The elasticity modulus was determined by average of video processing and analysis of the 10 mm deformation arrow value and the corresponding bending force. The method used by the authors and the one used in this study can explain the differentiation in the values found for VC, of 31.96% and 10.48%, respectively. The use of a dedicated machine for the test proved to be effective in obtaining values with a low dispersion index, thus contributing to more accurate data for this research line.

The average of the elasticity modulus for the Catuaí Vermelho branch determined by Coelho et al. (2017) was 4.64 GPa. The authors used an algorithm that compared the natural frequencies determined experimentally with those simulated using the finite element method. The differences found by the author and those determined in this study can be explained due to the sensitivity and assumptions of the algorithm used in determining the elasticity modulus.

According to Villibor et al. (2019), it is extremely important to identify the stiffness properties of the coffee fruit-peduncle-branch system, at different stages of maturation, since it is a parameter that influences the modeling and results of computer simulations. Still according to the authors, the coffee peduncle and its stiffness vary in relation to the direction of the fibers, the same can be observed for the wood of orthotropic and plagiotropic branches of the plant. Coelho et al. (2015) state that the water content of the coffee stem can significantly influence its stiffness.

Other researches performed by Aristzábal, Oliveros and Alvares (2003) and Rodríguez et al. (2006) cite climatic parameters, cultural treatments, age of the coffee tree, location, variety, as influences in the divergence of the obtained result. Additionally, as found in the literature, the biological systems, such as the coffee branches, presents a great variability in their physical properties, even though it is the same plant, different sites and maturation stages (Santos et al., 2021; Velloso et al., 2020; Villibor et al., 2019; Coelho et al. 2016; Tinoco et al., 2014;). The results obtained in the present research could be used as a base of knowledge for the design and development of harvesting machines, taking into account the inherent variability observed in the experimental data obtained (Ferreira Júnior et al., 2020).

5 CONCLUSIONS

Regarding the determination of the physical-mechanical properties of the plagiotropic branch of the coffee plant, it can be concluded that:

The specimens of the branch presented a specific mass average of 0.945 $g.cm^{-3}$ with a standard deviation of 0.049 $g.cm^{-3}$.

According to the position in the plant, no significant differences were found between the specific mass averages for the upper, middle, and lower thirds, long the orthotropic branch.

The elasticity modulus average found was 1.24 GPa with a standard deviation of 0.13 GPa. The values found for the mean modulus of elasticity are increasing for the branches from the top to the bottom of the plant.

Finally, this research is extremely important to design optimized harvesting machines. With the experimental data presented, it was possible to quantify the inherent variability of the physical-mechanical properties of the plagiotropic branches along the coffee plant.

6 AUTHORS' CONTRIBUTION

WWAMJ wrote part of the manuscript and conducted the experiment; FLS wrote part of the manuscript, conducted the statistical analysis and supervision; FS wrote part of the manuscript, supported the statistical analysis and supervision; PAR supported the experiment; RRM review the final version and supervision.

7 REFERENCES

ANGÉLICO, C. L. et al. Diferentes estádios de maturação e tempos de ensacamento sobre a qualidade do café. **Coffee Science**, 6(1):1-10, 2011.

ARISTZÁBAL, I. D.; OLIVEROS, T. C. E.; ALVARES, M. F. Mechanical harvest of coffee applying circular and multidirectional vibrations. **Transactions of the ASAE**, 46:205-209, 2003.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS - ABNT. NBR 7190. **Projeto de Estruturas de Madeira**. Rio de Janeiro. 1997. 107p.

BOAVENTURA, P. S. M. et al. Value co-creation in the specialty coffee value chain: The third-wave coffee movement. **Revista de Administração de Empresas**, 58(3):254-266, 2018.

CARVALHO, E. A. de.; MAGALHÃES, R. R.; SANTOS, F. L. Geometric modeling of a coffee plant for displacements prediction. **Computers and Electronics in Agriculture**, 123:57-63, 2016.

CASSIA, M. T. et al. Quality of mechanized coffee harvesting in circular planting system. **Ciência Rural**, 43(1):28-34, 2013.

CIRO, H. J. Coffee harvesting I: Determination of the natural frequencies of the fruit stem system in coffee tress. **Applied Engineering in Agriculture**, 17(4):475-479, 2001.

COELHO, A. L. F. et al. Determination of geometric, physical and mechanical properties of coffee fruit-stem-branch system, **Revista Brasileira de Engenharia Agrícola e Ambiental**, 19(3):286-292, 2015.

COELHO, A. L. F. et al. Dynamic behavior of the coffee fruit-stem-branch system using stochastic finite element method. **Coffee Science**, 11(1):1-10, 2016.

COELHO, A. L. F. et al. Dynamic test for determining the elastic modulus of coffee fruit-stem-branch system. **Acta Scientiarum. Technology**, 39:579-586, 2017.

COMPANHIA NACIONAL DE ABASTECIMENTO – CONAB. **Acompanhamento da safra brasileira de café**. v. 6- Safra 2020, n. 1 - Primeiro levantamento, Brasília. p. 1-62, 2020.

CUNHA, J. P. B. M. et al. Viabilidade técnica e econômica de diferentes sistemas de colheita do café. **Coffee Science**, 11(3):416-425, 2016.

EVANS, J. W.; SENFT, J. F.; GREEN, D.W. Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. **Forest Products Journal**, 50(7/8):75-87, 2000.

FERREIRA JÚNIOR, L. G. et al. Dynamic behavior of coffee tree branches during mechanical harvest. **Computers and Electronics in Agriculture**, 173:105415, 2020.

GARCIA, A.; SPIM, J. A.; SANTOS, C. A. **Ensaios dos materiais**. 2. ed. Rio de Janeiro: LTC, 2012. 384p.

GUIMARÃES, E. R.; CASTRO JÚNIOR, L. G.; ANDRADE, H. C. C. A. Terceira onda do café em Minas Gerais. **Organizações Rurais & Agroindustriais**, 18(3):214-227, 2016.

INTERNATIONAL COFFEE ORGANIZATION – ICO. **Historical data on the global coffee trade**. 2020. London. Available in:< https://www.ico.org/new_historical.asp>. Access in: August, 22, 2021.

KRETSCHMANN, D. E., BENDTSEN, B. A. Ultimate tensile stress and modulus of elasticity of fast-grown plantation loblolly pine lumber. **Wood and Fiber Science**, 24(2):189-203, 1992.

LATORRACA, J. V.; ALBUQUERQUE, C. E. C. Efeito de rápido crescimento sobre as propriedades da madeira. **Revista Floresta e Ambiente**, 7(1):279-291, 2000.

LI, Z. et al. Internal mechanical damage prediction in tomato compression using multiscale finite element models. **Journal of Food Engineering**, 116(3):639-647, 2013.

MCALISTER, R.; CLARK, A.; SAUCIER, J. Effect of initial spacing on mechanical properties of lumber sawn from unthinned slash pine at age 40. **Forest Products Journal**, 47(7/8):107-109, 1997.

MEJÍA, F. Á.; TASCÓN, C. E. O.; URIBE, J. R. S. Evaluation of mechanical beaters in coffee harvesting. **Revista Facultad Nacional de Agronomía**, 66(1):6919-6928, 2013.

OLIVEIRA, E. et al. Custos operacionais da colheita mecanizada do cafeeiro. **Pesquisa Agropecuária Brasileira**, 42(6):827-831, 2007a.

OLIVEIRA, E. et al. Influence of the mechanized harvest in the coffee production. **Ciência Rural**, 37(5):1466-1470 2007b.

OLIVEIRA, E. et al. The influence of the stick's vibration and the speed in the displacement of the harvester machine on mechanized coffee harvest process. **Engenharia Agrícola**, 27(3):714-721, 2017.

OLIVEIRA, M. V. M. et al. Computer-aided design of a coffee-dragging device. **Ciências Agrárias**, 35(5):2373-2382, 2014.

ORTEGA, A. C.; JESUS, C. M. Território café do cerrado: transformações na estrutura produtiva e seus impactos sobre o pessoal ocupado. **Revista de Economia e Sociologia Rural**, 49(3):771-800, 2011.

PRIETO, M. et al. Concepto de calidad en la industria agroalimentaria. **Interciência**, 33(4):258-264, 2008.

R CORE TEAM. **A language and environment for statistical computing**. version 4.0.0. 2021. Available in. <https://cran-r.c3sl.ufpr.br/bin/windows/base/old/4.0.0>. Access in: August, 10, 2022.

RODRÍGUEZ, A. M. et al. Determinácion de propriedades físico-mecánicas de los frutos de café (*Coffea arábica* variedade Catuai) relacionadas con la cosecha mecanizada. **Revista Ciências Técnicas Agropecuárias**, 15(3):22-27, 2006.

ROWELL, R. M.; HAN, J. S.; ROWELL, J. S. Characterization and factors effecting fiber properties. In: FROLLINI, E.; LEÃO, A. L.; MATTOSO, L. H. C. (Ed.). **Natural polymers and agrofibers composites**. São Carlos: IQSC/USP, p.115-33, 2000.

SANTINATO, F. **Café de qualidade**. Cultivar Máquinas. 2014. Available in. < https://revistacultivar.com.br/revistas/materias/439>. Access in: April, 09, 2021.

SANTINATO, F. et al. Análise econômica da colheita mecanizada do café utilizando repetidas operações da colhedora. **Coffee Science**, 10(3):402-411, 2015.

SANTOS, F. L. et al. Analysis of the coffee harvesting process using an electromagnetic shaker. **Acta Scientiarum. Agronomy**, 32(3):373-378, 2010a.

SANTOS, F. L. et al. Efeito da frequência e amplitude de vibração sobre a derriça de frutos de café. **Revista Brasileira de Engenharia Agricola e Ambiental**, 14(4):426-431, 2010b.

SANTOS, F. L. et al. Simulation of the dynamic behavior of the coffee fruit-stem system using finite element method. **Acta Scientiarum. Technology**, 37(1):11-17, 2015.

SANTOS, F. L. et al. Modal properties of macaw palm fruit-rachilla system: An approach by the stochastic finite element method (SFEM). **Computers and Electronics in Agriculture**, 184: 106099, 2021.

SILVA, F. C. et al. Behavior of the coffee fruit detachment force throughout the harvest period. **Ciência e Agrotecnologia**, 34(2):468-474, 2010.

SOUZA, C. M. A. et al. Performance of fruits portable harvester in the detachment of coffee plant. **Engenharia Agrícola**, 25(3):791-800, 2005.

SOUZA, C. M. A.; QUEIROZ, D. M. de.; RAFULL, L. Z. D. Portable harvester in the total and selective harvesting of coffee fruits. **Pesquisa Agropecuária Brasileira**, 41(11):1637-1642, 2006.

STOCKER, F. et al. Multicriteria analysis in purchasing decision: Study of coffee consumer behavior. **Brazilian Journal of Development**, 5(9):17018-17041, 2019.

TAVARES, T. O. et al. Operational performance of the mechanized picking of coffee in four soil slope. **African Journal of Agricultural Research**, 11(48):4857-4863, 2016.

TINOCO, H. A. et al. Finite element modal analysis of the fruit-peduncle of *Coffea arabica* L. var. Colombia estimating its geometrical and mechanical properties. **Computers and Electronics in Agriculture**, 108:17-27, 2014.

VELLOSO, N. S. et al. Modal properties of coffee plants via numerical simulation. **Computers and Electronics in Agriculture**, 175:105552, 2020.

VILLIBOR, G. P. et al. Dynamic behavior of coffee fruit-stem system using modeling of flexible bodies. **Computers and Electronics in Agriculture**, v. 166:105009, 2019.

WARRICK, A. W.; NIELSEN, D. R. Spatial variability of soil physical properties in the field. In: HILLEL, D. (Ed). **Aplications of soil physics**. New York: Academic, 319-344, 1980.

WU, J. et al. Dynamic computation of flexible multibody system with uncertain material properties. **Non-linear Dynamics**, 85:1231-1254, 2016.