Elasticity modulus and damping ratio of macaw palm rachillas

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ABSTRACT: *The macaw palm has been identified as a prime feed stock for biodiesel industries in the near future coming decades. However, there are no machines for harvesting and detaching fruits in the biofuel industry; hence, the study of the dynamic behavior of the fruit-rachilla system would aid in the development of such machines. Thus, this study seeks to determine the modulus of elasticity and the damping ratio of four different plant accessions obtained from the Active Germplasm Bank of the Universidade Federal de Viçosa (UFV). Tensile testing was conducted to determine the modulus of elasticity. From the graphical results of tension versus specific strain, it was possible to determine the modulus of elasticity by using the tangent method. To determine the damping ratio, the logarithmic decrement method was performed using vibration testing. Vibration test consisted of a generated impulse of 100% of the amplitude of acceleration that was used to excite the system. The acquisition of the generated information was performed by a piezoelectric accelerometer. The average modulus of elasticity ranged from 2.22 to 3.17MPa, and the average damping ratios ranged from 0.04 to 0.08. Thus, the macaw fruit-rachilla was an under-damped system.*
Key words: *Acrocomia aculeata, dynamic behavior, mechanical properties.*

Módulo de elasticidade e razão de amortecimento das ráquilas da macaúba

RESUMO: *A macaúba tem sido apontada como uma das principais matérias-primas para a indústria de biodiesel nas próximas décadas. No entanto, não existem máquinas para colheita ou destacamento dos frutos na usina e o estudo do comportamento dinâmico do sistema fruto-ráquila nortearia o desenvolvimento dessas máquinas. Dessa forma, objetivou-se determinar o módulo de elasticidade e a razão de amortecimento de quatro acessos provindos do Banco Ativo de Germoplasma da UFV. Foi realizado teste de tração para determinar o módulo de elasticidade. A partir dos resultados obtidos na forma gráfica, tensão versus deformação específica, foi determinado o módulo de elasticidade pelo método da tangente. Para determinar a razão de amortecimento, foi empregado o método do decremento logarítmico, realizado por meio de teste de vibração. O teste de vibração constituiu-se de um impulso para excitar o sistema. A aquisição das informações geradas foi realizada por meio de acelerômetro piezelétrico. O módulo de elasticidade médio ficou entre 2,22 e 3,17MPa e as razões de amortecimento médias ficaram entre 0,04 e 0,08. Concluiu-se que o sistema fruto-ráquila da macaúba é subamortecido.*
Palavras-chave: *Acrocomia aculeata, comportamento dinâmico, propriedades mecânicas.*

INTRODUCTION

Owing to the difficulty of reaching the macaw palm clusters, fruit is harvested by cutting the bunches with a scythe and catching them in a surrounding net as they fall to the ground, or picking up the detached fruit from the ground. To detach the fruit in a factory, or in the field, it may be possible to employ machines that use the principle of mechanical vibration. However, there are no machines available on the market for this purpose; hence, the study of the dynamic behavior of the fruit-rachilla system would aid in the development of such machines.

Among the mechanical properties relevant to the study of the dynamic behavior of the macaw palm fruit-rachilla system, the modulus of elasticity of the rachilla is of utmost importance, as a material, which undergoes elastic deformation when subjected to tension.

Generally, in biological materials the tensile deformation behavior is influenced by time, and we can characterize a material as viscoelastic. In such cases, viscoelastic materials do not present elastic constants; but, rather, deformation is a function of time (LAURENTI, 1997). In practice, there are few elastically isotropic materials; however, many materials are considered isotropic for the purpose of elastic deformation analysis.

In view of the need to develop new technologies for the macaw palm to become

commercially profitable to agricultural producers, we must invest in the development of harvesting methods and machines for subsequent harvesting and processing of the fruit. In particular, harvesting machines that harvest by creating mechanical vibrations. Two of the necessary parameters for the study of dynamic behavior of an object are the modulus of elasticity and the damping ratio; and the results of this study will aid in the development of harvesters using mechanical vibration. Thus, our objective is to determine the properties in the fruit-rachilla system to aid in the study of its dynamic behavior.

MATERIALS AND METHODS

The fruit and rachillas used in the experiment were collected from the Active Germplasm Bank of the Universidade Federal de Viçosa (UFV), and its border. Four different palm accessions were used, identified as BD 27 (from the region of Abaeté/MG), BD 40 (from the region of Pitangui – Martinho Campos/ MG), BGP 29 (from the region of Prudente de Moraes – Matozinhos/ MG), and BGP 35 (from the region of Mirandópolis/ SP). Accessions that had fruit bunches available at the time of the experiment were chosen.

Determination of properties was performed for clusters with green fruit. Two clusters were cut from each palm, and measurements were taken within 24h after collection in the agricultural mechanization laboratory of UFV. Physical properties of the rachillas and fruit were determined in order to characterize the systems, using the average of each accession. To accomplish this task, we used 30, 25, 34, and 29 fruits for accessions BD 27, BD 40, BGP 29, and BGP 35, respectively, and 10 rachillas from each accession. Three diameters, a, b, and c, were measured for each fruit, corresponding to the largest, intermediate, and smallest dimensions, respectively. The average diameter of the rachillas were obtained from the average of three diameters measured along the rachilla, one in the intermediate portion and the other two at the extremities. Measurements were taken with Mitutoyo digital calipers with a resolution of 0.01mm.

The average volume of the rachillas were determined by water column displacement using 100mL graduated beakers. The volume of the fruit was estimated from characteristic dimensions by means of Equation 1 (MOHSENIN, 1986).

$$V = \frac{\pi(abc)}{6} \, 10^{-3} \tag{1}$$

In which,
V = fruit volume, cm³;
a, b, c = characteristic dimensions, mm.

To determine the average mass of the fruit and rachillas, a digital precision scale with a precision of 0.001g was used. The specific mass was obtained from the mass to volume ratio.

Ten rachillas from each accession were used to determine the modulus of elasticity of rachillas. These rachillas were different from those used for the determination of the physical properties. Rachillas were of standard length, having an intermediate portion of 12cm.

Ten rachillas were used to determine the damping ratio. These rachillas were different from those used to determine the modulus of elasticity, though from the same accessions, and had a standard length of 13cm for accessions BD27 and BGP 35, and 11cm for accessions BD 40 and BGP 29. Length of rachillas had different standard sizes, owing to the limitation of the actual sizes available in the different accessions.

Rachillas were considered to be elastically isotropic materials for experimental purposes. The rachilla test body was subjected to tensile testing by fixing it between the grips of an INSTRON universal testing machine, model 3365, with a 5kN load capacity, with the intermediate 5cm of the test body being the portion tested.

The test bodies were subjected to a preload of 2N and, the tests began immediately with a speed of 3mmmin⁻¹ until rupture of the body. Test speed was defined after carrying out the pre-tests and is in accordancd with the range of 2.5 to 30mmmin⁻¹ used by ASABE (American Society of Agricultural and Biological Engineers) in compression testing of vegetable material. Average modulus of elasticity for each accession was determined using the tangent method on the stress-strain curve at 0 to 3%.

The logarithmic decrement method was used to determine the damping ratio of the fruit-rachilla system in accordance with Equation 2 proposed by RAO (2008).

$$\delta = \ln \frac{x_i}{x_{i+1}} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \tag{2}$$

In which,
δ = logarithmic decrement;
ζ = damping ratio of the system;
x_i = amplitude of the signal for time i, ms⁻²;
x_{i+1} = amplitude of successive signal at x_i, ms⁻².

Logarithmic decrement method was performed by vibration testing with a generated impulse of 100% of the amplitude of acceleration,

the equivalent of five times the acceleration of gravity (g_r). To agitate the fruit-rachilla system, Ling Dynamic Systems (LDS) vibration test system instrumentation was used, comprising a DACTRON brand COMET$_{USB}$ signal generator, a PA 1000L amplifier, and a V-555 model electromagnetic shaker manufactured by LDS. The fruit-rachilla system was secured to a fixed support at the base of the movable shaker. The fruit was attached to the rachilla between the intermediate portion and the end opposite to the support.

For data acquisition, we used anLW174002 uniaxial piezometric accelerometer with sensitivity of 100.7mV g_r^{-1} and a National Instruments NI cDAQ9234 data acquisition module. The accelerometer was of low mass, thus not significantly altering the dynamics of the fruit-rachilla system. The accelerometer was fixed vertically to the fruit to measure the system´s vertical acceleration. The generated data were processed to produce a graph of the two successive amplitudes of the signal (X_i and X_{i+1}) for the calculation of the average damping ratio (ζ) of each accession (Equation 2). Data were subjected to descriptive statistical analysis with the aid of the R computer programming language.

RESULTS AND DISCUSSION

The characteristic dimensions of the fruit show greater variation among different accessions than within the same accession (Table 1). Some

Active Germplasm Bank macaw palms from the states of Minas Gerais and São Paulo were morphologically characterized in a study carried out by PLATA RUEDA (2014). A high degree of divergence was observed among the progenies studied, and those from the State of São Paulo formed a genetically distinct group different than those from Minas Gerais.

The behavior observed in the tensile tests presented a well-defined elastic deformation interval, as expected (Figure 1).
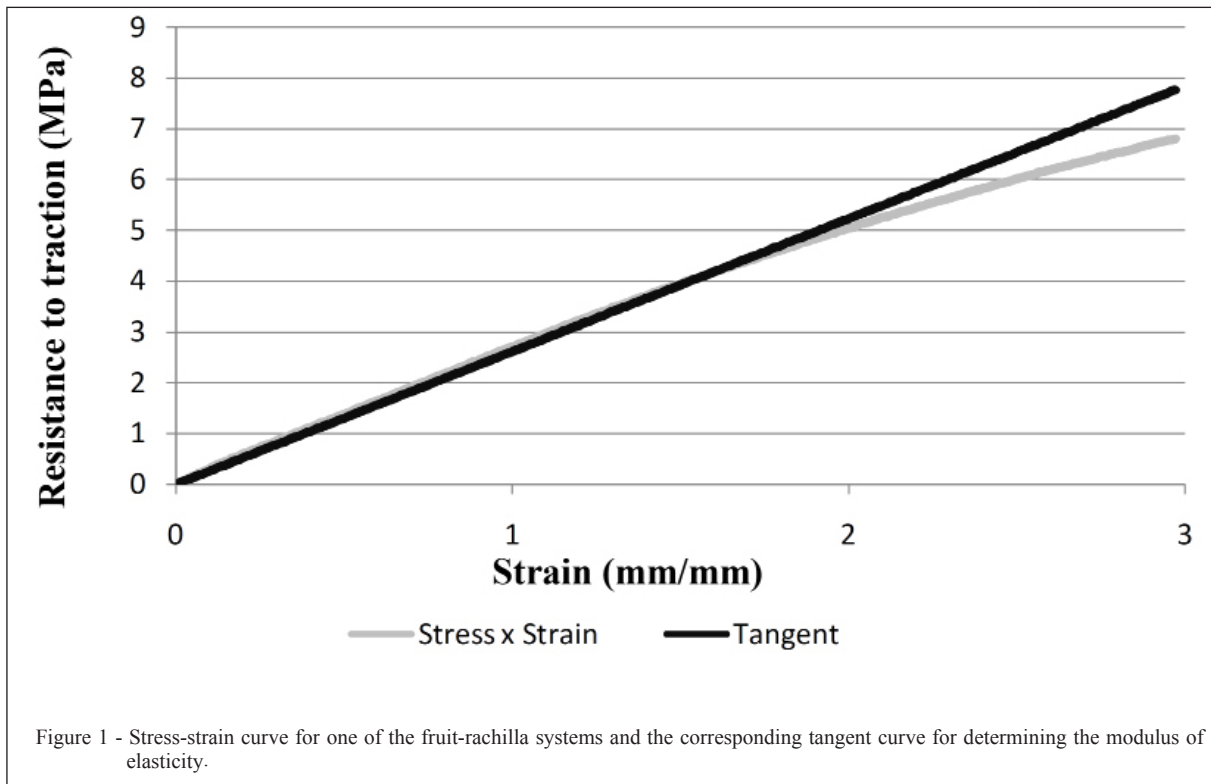
Using these results, it was possible to determine the modulus of elasticity for each accession (Table 2). According to PIMENTEL GOMES (1987), coefficient of variation values up to 10% are considered low for agricultural products; and values between 10 and 20% are medium, between 20 and 30% are high, and above 30% are very high. Modulus of elasticity presented a CV greater than 10% for all accessions, reaching 40.33% in accession BGP 35, which is considered very high both within the same accession and among different accessions. This variation can be attributed to shapes of tested bodies, which were considered cylindrical for the tests, though they were not entirely regular, thus influencing the results.

In general, time influences stress–strain behavior in biological materials, though, the fruit-rachilla system was considered elastic and isotropic for elastic deformation analysis since it presented a well-defined elastic portion. The great variation in

Table 1 - Statistical description of the characteristic dimensions of the fruit and rachillas: mass, volume, and specific mass of the rachillas; and mass, volume, and specific mass of the fruit, based on the overall average of all accessions.

	a (mm)	b (mm)	c (mm)	d (mm)
Average	43.29	42.85	41.07	3.74
Standard deviation	3.38	3.48	3.55	0.48
CV (%)	7.80	8.13	8.64	12.94
	m_r (g)	V_r (cm^3)	ρ_r (gcm^{-3})	
Average	2.32	3.65	0.65	
Standard deviation	0.67	0.82	0.20	
CV (%)	28.92	22.34	30.11	
	m_f (g)	V_f (cm^3)	ρ_f (gcm^{-3})	
Average	44.38	4.06	1.10	
Standard deviation	10.63	0.98	0.09	
CV (%)	23.95	24.17	8.35	

a– largest dimension of the fruit; b–intermediate dimension of the fruit; c– smallest dimension of the fruit; d–average dimension of the rachillas; CV–coefficient of variation; m_r – average mass of rachillas; V_r – average volume of rachillas; ρ_r – average specific mass of rachillas; m_f– average mass of fruit; V_f – average volume of fruit; ρ_f – average specific mass of fruit.

Figure 1 - Stress-strain curve for one of the fruit-rachilla systems and the corresponding tangent curve for determining the modulus of elasticity.

the modulus of elasticity may also be related to this characteristic, given that it is an approximation.

For soya, RIBEIRO et al. (2007) reported values for the modulus of elasticity, analyzing different axes, to be between 10.2 and 23.1MPa for moist grains. In a study on coffee stalks, using green fruit, COELHO et al. (2015) reported a modulus of elasticity of 3.91MPa.

The decay observed after the impulse corresponds to the behavior of an under-damped body (Figure 2), in which the mass oscillates with amplitudes that diminish exponentially until movement ceases.

Damping ratios obtained confirm that the fruit-rachilla system is under-damped given that the average values were always below one (Table 3), as determined by COELHO et al. (2015) for coffee plant branch stems.

When a system undergoes forced vibration, its amplitude tends to increase when near a state of resonance; however, damping tends to diminish the energy transmitted. In mechanical harvesting by mechanical vibration, as in the case of coffee, with the right combination of frequency and amplitude of vibration, it is possible to transfer enough vibrational energy to dislodge the fruit (FERREIRA JÚNIOR et

Table 2 - Statistical description of the modulus of elasticity for accessions BD 27, BD 40, BGP 29 and BGP 35.

	BD 27	BD 40	BGP 29	BGP 35	All accessions
	2.95	3.02	3.17	2.22	2.84
Standard deviation	0.52	0.98	0.85	0.89	0.91
CV (%)	17.73	32.42	26.88	40.33	32.00

E – Modulus of elasticity; CV – coefficient of variation; BD 27 – accession from Abaeté/ MG; BD 40 – accession from Pitangui-Martinho Campos/ MG; BGP 29 – accession from de Prudente de Moraes Matozinhos/ MG; BGP 35 – accession from Mirandopólis/ SP.

Figure 2 - Decay curve obtained in experiment on fruit-rachilla system.
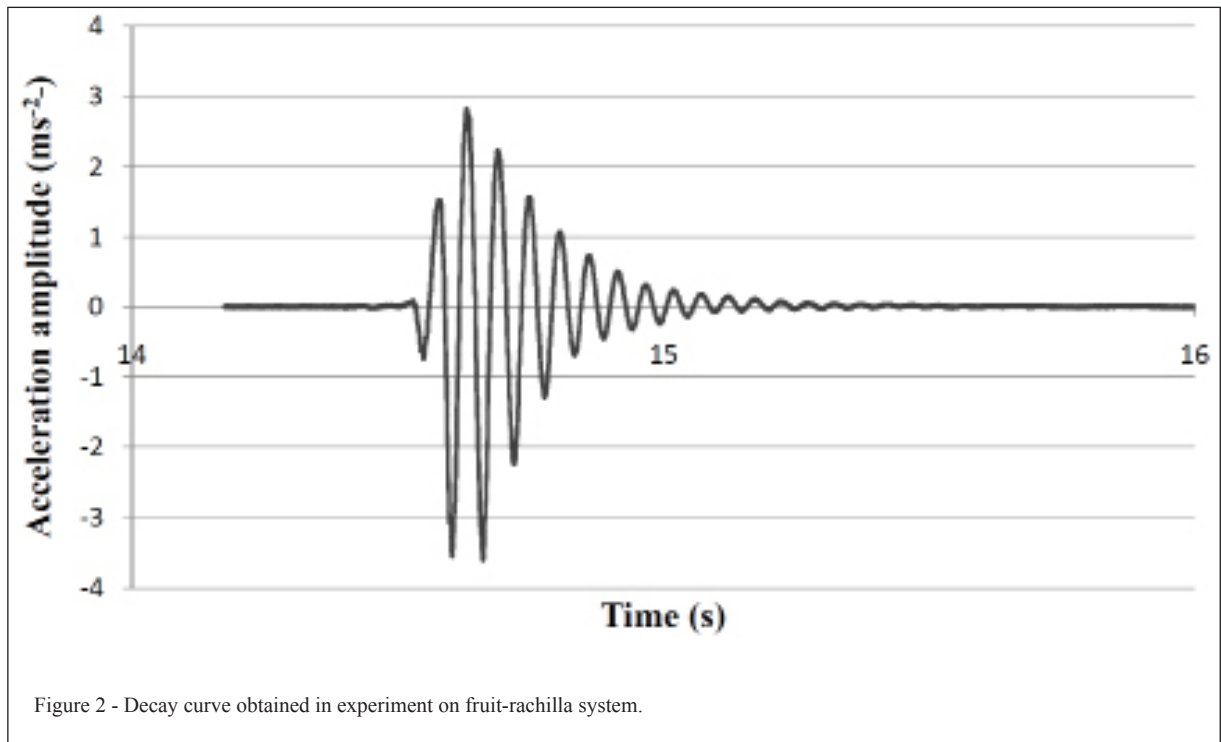
al., 2016). In the case of under-damped systems, the greater the damping ratio, the lower the free vibration amplitude. With a lower damping ratio of the system, there is a tendency for the damped natural frequency to approach the undamped natural frequency, which occurred in the fruit-rachilla systems studied, given that the average damping ratio was less than 0.1 in all accessions (RAO, 2008).

Rachillas are a component of the macaw palm fruit cluster; though under studied, they are of fundamental importance for mechanization projects using the principle of vibration to harvest or detach fruit from the clusters. CIRO (2001) determined the mechanical and geometrical properties of the Columbia variety coffee fruit-stalk system in three stages of maturation and

Table 3 - Damping ratio of the fruit-rachilla system (FR) for accessions BD 27, BD 40, BGP 29, and BGP 35, determined experimentally.

ζ (adimensional)	BD 27	BD 40	BGP 29	BGP 35
FR 1	0.01	0.12	0.08	0.04
FR 2	-	0.05	0.06	0.23
FR 3	-	0.08	0.08	-
FR 4	0.02	0.11	0.09	0.06
FR 5	0.06	-	0.06	0.04
FR 6	0.05	0.10	0.02	0.05
FR 7	0.03	0.07	0.07	0.03
FR 8	0.07	-	0.02	0.06
FR 9	0.10	-	0.07	-
FR 10	0.01	0.05	0.05	0.08
Average	0.04	0.08	0.06	0.07

FR – fruit-rachilla system; ζ – damping ratio; BD 27 – accession from Abaeté/ MG; BD 40 – accession from Pitangui-Martinho Campos/ MG; BGP 29 – accession from Prudente de Moraes Matozinhos/ MG; BGP 35 – accession from Mirandopólis/ SP.

analyzed the dynamic behavior of the system. The author established that the dynamic behavior is highly dependent on the mechanical and geometric properties. FILGUEIRAS (2001), after determining the mechanical and geometric properties of a coffee plant and analyzing its dynamic behavior, established through sensitivity analysis the significant influence of the diameter of branches and trunks in natural vibration frequencies.

In view of the fact that studies on coffee showed that the mechanical and geometrical properties of the fruit-stalk system influence its dynamic behavior, it was expected that the geometric variation of the fruit and rachillas would also directly influence the dynamic behavior of the macaw palm fruit-rachilla system. This should occur as the natural frequencies vary in accordance with the rigidity of the system, which in turn is determined by its geometry and e distribution of the mass in the system.

CONCLUSION

The modulus of elasticity obtained is within the expected range for vegetable material with elastic behavior. The fruit-rachilla systems are under-damped for the different accessions as they present an average damping ratio of less than one.

ACKNOWLEDGEMENTS

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Erratum

In the "Elasticity modulus and damping ratio of macaw palm rachillas" published in Ciência Rural, volume 47, number 2, DOI http://dx.doi.org/10.1590/0103-8478cr20160289.

In the Abstract, where it reads:

The average modulus of elasticity ranged from 2.22 to 3.17MPa

Read it:

The average modulus of elasticity ranged from 194 to 293.3MPa

In the Resumo, where it reads:

O módulo de elasticidade médio ficou entre 2,22 e 3,17MPa

Read it:

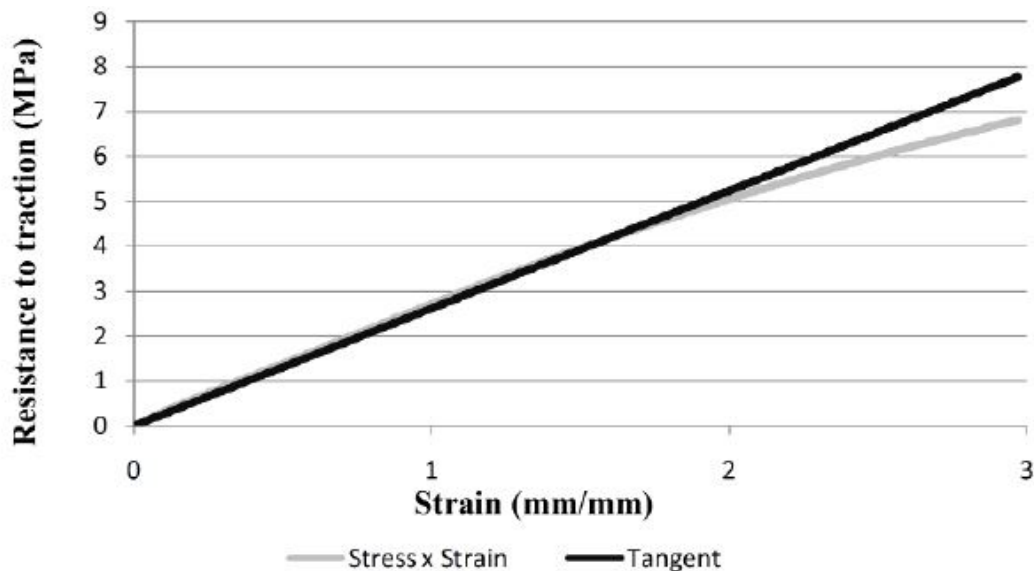O módulo de elasticidade médio ficou entre 194 e 293,3MPa

In the Results and Discussion, where it reads:

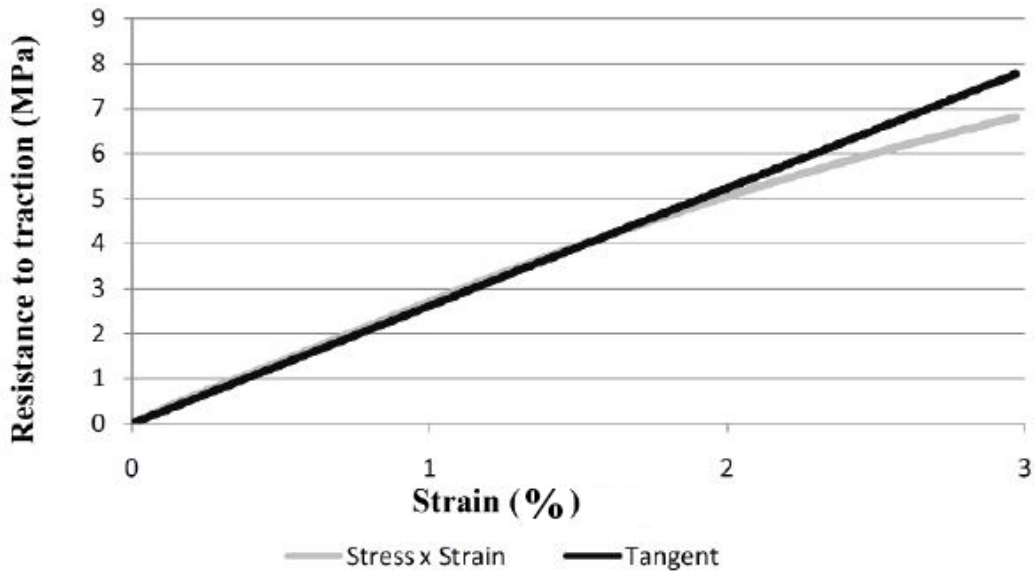Modulus of elasticity presented a CV greater than 10% for all accessions, reaching 40.33%

Read it:

Modulus of elasticity presented a CV greater than 10% for all accessions, reaching 31.4%

Where it reads:

Read it:

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Table header spanning columns: -------E (MPa)-------

E – Modulus of elasticity; CV – coefficient of variation; BD 27 – accession from Abaeté/ MG; BD 40 – accession from Pitangui-Martinho Campos/ MG; BGP 29 – accession from de Prudente de Moraes Matozinhos/ MG; BGP 35 – accession from Mirandopólis/ SP.

Read it:

Table 2 - Statistical description of the modulus of elasticity for accessions BD 27, BD 40, BGP 29 and BGP 35.

	BD 27	BD 40	BGP 29	BGP 35	All accessions
	238.9	260.7	293.3	194	246.9
Standard deviation	38.4	62.7	81.4	60.9	72.4
CV (%)	16.1	24.1	27.7	31.4	29.3

Table header spanning columns: -------E (MPa)-------

E – Modulus of elasticity; CV – coefficient of variation; BD 27 – accession from Abaeté/ MG; BD 40 – accession from Pitangui-Martinho Campos/ MG; BGP 29 – accession from de Prudente de Moraes Matozinhos/ MG; BGP 35 – accession from Mirandopólis/ SP.