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EVALUATION OF GENETIC PARAMETERS FOR GROWTH TRAITS AND WOOD PROPERTIES IN CLONES OF *Hevea brasiliensis*[1]

AVALIAÇÃO DE PARÂMETROS GENÉTICOS PARA CARACTERES DE CRESCIMENTO E PROPRIEDADES DA MADEIRA EM CLONES DE *Hevea brasiliensis*[1]

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ABSTRACT - *Hevea brasiliensis* (Willd. ex A.Juss.) is a forest species with potential for commercial planting for both latex and timber production after the end of the latex production cycle. This study aimed to determine the genetic variability of growth traits and wood properties in a 33-year-old clonal plantation of *H. brasiliensis* in the region of Selvíria, state of Mato Grosso do Sul, Brazil. Significant differences were detected among the clones for DBH and total tree height. For the physical wood properties, only volumetric shrinkage showed a significant difference between clones; however, significant differences were found for all anatomical dimensions and mechanical properties. Clone IAN717 stood out for the highest growth, while RRIM600 had the lowest growth. In terms of wood properties, clone RRIM600 exhibited highest mechanical resistance, while GT1 showed the lowest resistance. Most wood properties varied in the pith-to-bark direction, with the lowest values found in the pith region and the highest in the bark region, except for vessel frequency, where the opposite trend occurred. The highest heritability coefficients were observed for DBH, volumetric shrinkage in the bark region, vessel element diameter in the intermediate region, and vessel frequency in the bark region as expected. The genetic correlation coefficient was high, positive, and significant between traits such as shear strength x modulus of rupture, modulus of elasticity x modulus of rupture, and volumetric shrinkage x modulus of rupture. This indicates that selection for one trait may result in indirect gains in another.

Keywords: Clonal test; Rubber tree; Genetic improvement; Wood quality.

RESUMO - *Hevea brasiliensis* (Willd. ex A. Juss.) é uma espécie de valor comercial, tanto para a produção de látex quanto para madeira ao final do ciclo produtivo do látex. Este estudo teve como objetivo determinar a variabilidade genética de caracteres de crescimento e propriedades da madeira de um plantio clonal de *H. brasiliensis*, com 33 anos de idade, na região de Selvíria, estado de MS, Brasil. Diferenças significativas foram detectadas entre clones para DAP e altura total das árvores. Para as propriedades físicas da madeira, diferenças significativas entre clones foram detectadas somente para a retração volumétrica; no entanto, diferenças significativas foram observadas para todas as dimensões anatômicas e propriedades mecânicas. O clone IAN717 apresentou o maior crescimento e o RRIM600 apresentou o menor crescimento. Em termos de propriedades da madeira, o clone RRIM600 mostrou maior resistência mecânica e o GT1 a menor resistência. A maioria das propriedades da madeira variou no sentido medula-casca, onde os menores valores foram encontrados na região da medula e os maiores na região da casca, com exceção da frequência de vasos, onde ocorreu o contrário, como esperado. O coeficiente de herdabilidade foi maior para DAP, retração volumétrica na região da casca, diâmetro de elemento de vaso na região intermediária e frequência de vaso na região da casca. O coeficiente de correlação genética foi alto, positivo e significativo entre os caracteres resistência ao cisalhamento x módulo de ruptura, módulo de elasticidade x módulo de ruptura, e retração volumétrica x módulo de ruptura, indicando que a seleção em um caráter pode trazer ganhos indiretos em outro.

Palavras-chave: Teste clonal; Seringueira; Melhoramento genético; Qualidade da madeira.

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1 INTRODUCTION

In Brazil, native tree species are rarely cultivated in commercial plantations. However, the growing demand for timber has stimulated the search for new species with silvicultural potential. In this context, native species may be advantageous over exotic ones due to their good adaptability (Vidaurre et al. 2018), as it presents rapid growth and adaptation to a large part of the Brazilian territory (Silva et al. 2020). The species is valued not only for its latex production, but also for its valuable timber after the latex extraction cycle (Boadu et al. 2022), which can be used to manufacture doors, windows, beams, columns, panels, household utensils and plywood (Haridasan 1989; Okino et al. 2004).

Brazil has no tradition of industrial use of *H. brasiliensis*, except for latex extraction (Ramos et al. 2016), although international studies report the use of its wood for the production of sawnwood after the latex production cycle, which occurs between 25 and 30 years old (Palma 2010, Dourado et al. 2018). Plantations that are 25 to 30 years old can produce logs with a diameter greater than 15 cm, suitable for the production of sawnwood and panels (Dhamodaram 2008). Depending on the genetic material, *H. brasiliensis* plantations average DBH can reach approximately 35 cm at the end of their latex production life (Peries 1980). Smaller diameter logs can serve as a source of bioenergy, due to their low ash content (Amorim et al. 2020). However, due to its rapid growth, its wood often presents quality problems, such as a high percentage of sapwood, leading to reduced resistance to decay, dimensional instability and lower physical-mechanical strength (Shukla and Sharma 2018). Therefore, the wood properties of *H. brasiliensis* need to be studied to determine the most suitable end uses after latex extraction, as these properties directly influence wood quality (Naji et al. 2012). However, there are few studies on the wood quality of *H. brasiliensis* and there is a need for more research to explore its industrial potential, as well as genetic improvement studies to increase wood quality and plantation productivity (Gonçalves et al. 2001).

This study aimed to determine the genetic variability of growth and wood propertie traits of a 33-year-old clonal plantation of *H. brasiliensis* in Selvíria, MS, Brazil.

2 MATERIAL AND METHODS

2.1 Sampling and Experimental Design

In this study, five *H. brasiliensis* clones from Selvíria, State of Mato Grosso do Sul, Brazil, were analyzed. The terrain is characterized as moderately flat and undulating and the local climate is classified as type Aw, according to the Köppen classification, with an average annual temperature of 23°C and an average annual precipitation of 1,440 mm (Alvares et al. 2013). The soil is classified as dystrophic Red Oxisol (LVd), typically clayey, moderately deep, hypodystrophic, alic, kaolinitic, ferric, compacted, very deep, and moderately acidic (Rossi 2017). The assessed clones were as follows: LCB510, RRIM600, IAM717, IAN873, and GT1 (control). The experimental design was a randomized block design, consisting of five treatments (clones), five replications, and linear plots of 10 plants, with a spacing of 8m x 2.5m. Firstly, an inventory of the experiment was conducted, and based on the DBH distribution, the mean DBH class was selected for sampling. For the study of wood properties, 25 trees of 33-year-old *H. brasiliensis* were sampled, one from each clone, selected within each block. Trees were chosen from the mean DBH class in each plot. The growth traits evaluated were the diameter at breast heigh (DBH, cm) and total height (TH, m).

From the selected trees, the first one-meter-long log was removed, properly identified, and marked. These logs were then transported to the Wood Engineering Laboratory at ESALQ/USP, in Piracicaba, State of São Paulo, for processing. Three radial positions were established: i) the position closest to the trunk center, designated as the pith; ii) a middle position; and iii) a position close to the bark. A 7cm thick central plank was removed from each of the logs. Three 4cm x 4cm x 1cm strips were taken from the planks: near the pith, in the intermediate region and near the bark. A specimen was taken from each position to determine the physical, mechanical, and anatomical properties.

2.2 Wood Physical Properties

Apparent density (ρ_{ap}): Samples measuring 2cm x 2cm x 3cm were obtained from the battens and dried until they reached a 12% moisture content to determine the apparent density. The dimensions were measured with a digital caliper with a sensitivity of 0.01cm, and the mass of the specimens was obtained using a semi-analytical digital scale with a sensitivity of 0.01g, following the NBR

7190-1 standard (ABNT 2022a). Basic density (ρ_{bas}): For basic density determination, samples measuring 3cm x 2cm x 5cm were used, and the hydrostatic balance method was employed, following NBR 11941 (ABNT 2003). Dimensional Variation of Wood: volumetric (β_v), radial (β_r), tangential (β_t) shrinkages, and anisotropy coefficient (β_t/β_r) were determined using samples measuring 3cm x 2cm x 5cm, according to the NBR 7190-1 standard (ABNT 2022a).

2.3 Mechanical Properties of Wood

All mechanical tests were conducted with dry samples, which were kept in a controlled environment until they reached approximately 12% moisture content, the standard reference condition according to NBR 7190-3 (ABNT 2022b). To determine the compressive strength parallel to the fibers (f_{c0}), specimens measuring 2cm x 2cm x 3cm were used, totalizing 24 units. Compression tests were carried out on a universal testing machine, following the adapted NBR 7190-3 standard (ABNT 2022b). For assessing tangential shear strength (f_{v0}) across the growth rings, specimens with nominal dimensions of 2cm x 2cm x 3cm and a shear area of 4cm² were used, in accordance with the adapted NBR 7190-3 standard (ABNT 2022b). The modulus of rupture (MOR) and modulus of elasticity in static bending (MOE) were tested simultaneously on specimens measuring 2cm x 2cm x 35cm, extracted from each batten. The tests were performed using the same universal testing machine, following the adapted NBR 7190-3 standard (ABNT 2022b).

2.4 Anatomical Dimensions

For determining anatomical dimensions, additional specimens measuring 2cm x 2cm x 3cm were prepared, and small fragments were macerated using the modified Franklin method (Berlyn and Miksche 1976). Measurements were performed using a microscope equipped with a digital camera and image analysis software. Photographs were taken of 25 different vessels and fibers, and Image-Pro Plus 6.0 software was used to measure fiber wall thickness (FWT), vessel diameter (VD), and vessel frequency (VF), following the methodology recommended by IAWA (1989).

2.5 Statistical Analysis and Estimate of Genetic Parameters

The F-test of analysis of variance was used to determine whether there were significant differences among clones for each trait. The Tukey test was used to determine whether there were significant differences in trait means between pairs of clones. These analyses were performed using SAS software (SAS 1999).

Analysis of variance for each trait were carried out by the REML/BLUP procedure (restricted maximum likelihood/best linear unbiased prediction), using the mixed linear model methodology, model 96 of the SELEGEN software (Resende 2016). Components of variance were estimated for each trait using the additive linear model, $y = Xr + Zg + e$, where: y is the data vector, r is the vector of repetition effects (assumed to be fixed) added to the overall mean, g is the vector of genotypic effects (assumed to be fixed), and e is the vector of errors (random). X and Y represent the incidence matrices for the said effects. The estimated components of variance were: genotypic variance among clones (δ_g^2), residual variance (σ_e^2), and individual phenotypic variance (σ_f^2). The estimated parameters were: broad sense mean heritability (include additive and dominant genetic variation) among clones (H_{mc}^2):

$$H_{mc}^2 = \delta_g^2/[\delta_g^2 + (\frac{\sigma_e^2}{J})], \quad \text{Eq. 1}$$

coefficient of genetic variation among clones ($CV_g\%$):

$$CV_{gi}\%=100(\sqrt{\delta_g^2}/m), \quad \text{Eq. 2}$$

coefficient of experiemental variation ($CV_{exp}\%$):

$$CV_{exp}\%=100(\sqrt{\sigma_e^2}/m), \quad \text{Eq. 3}$$

and the coefficient of relative variation (CV_r):

$$CV_r = CV_g\%/CV_e\% \quad \text{Eq.4}$$

where $CV_e\%$ is the coeffient of experimental variation.

The genetic correlation (r_g) between the traits was also estimated:

$$r_g = COV_g(x, y)/\sqrt{\delta_{g(x)}^2 \delta_{g(y)}^2}, \quad \text{Eq. 5}$$

where $COV_g(x, y)$ is the genetic covariance between trait x and y; $\delta^2_{g(x)}$ and $\delta^2_{g(y)}$ are the genetic variance for the variable x and y, respectively.

3 RESULTS AND DISCUSSION

3.1 Trait development and variation

Significant ($P< 0.01$) differences among clones detected were for DBH and total height traits (HT) traits (Table 1). Clone IAN717 stood out with the highest DBH and HT values, while clones RRIM600 and IAN873 had the lowest values for these growth traits. These results are similar to those obtained by Lima et al. (2015), who found that clones RRIM600 and IAN873 were the least productive in terms of volumetric wood growth when compared to other clones in the Mococa region, State of São Paulo, Brazil. However, these clones are the main ones used commercially for latex production in Brazil (Lima et al. 2023).

Table 1. Summary of analysis of variance and genetic parameters for growth traits in *Hevea brasiliensis* clones.

Tabela 1. Análise resumida de variância e parâmetros genéticos para caracteres de crescimento em clones de *Hevea brasiliensis*.

Clone	**DBH (cm)**	**TH (m)**
IAN717	27.0[a]	20.94[a]
LCB510	25.2[ab]	16.94[b]
GT1	25.0[ab]	18.76[ab]
RRIM600	24.1[b]	18.76[ab]
IAN873	23.3[b]	17.94[ab]
Mean	24.92*	18.68*
Broad sence mean heritability among clones: H^2_{mc}	0.859	0.619
Coefficient of genetic variation: CV_g%	5.2	6.5
Coefficient of experimental variation CV_e%	4.8	11.1

* $P< 0.05$; Means followed by different letters in the same column differ among themselves by the Tukey test at 5% level of significance.

* P< 0,05; Médias seguidas de letras diferentes na mesma coluna diferem entre si pelo teste de Tukey ao nível de significância de 5%.

Regarding the physical properties, only volumetric shrinkage (β_v) presented significant differences ($P < 0.01$) among clones, with clone RRIM600 showing the highest mean value and clone GT1 the lowest (Table 2). For anatomical dimensions, significant differences ($P < 0.01$) among clones were detected for all traits. Clone GT1 presented a significantly higher mean for fiber length (FL), vessel element length (VEL), fiber wall thickness (FWT), and vessel diameter (DV), while clone IAN873 presented the lowest values for these traits. For mechanical properties, all traits also showed significant differences ($P < 0.01$) among clones, with clone RRIM600 having the highest mean values for all traits and clone GT1 having the lowest for compression parallel to the grain (f_{c0}), modulus of rupture (MOR), and modulus of elasticity (MOE), while clone IAN717 had the lowest for shear parallel to the grain (f_{v0}).

Table 2. Analysis of variance of basic density (ρ_{ap}), apparent density (ρ_{ap}), volumetric shrinkage (β_v), anisotropy coefficient ($\beta_t\beta_r$), fiber length (FL), vessel element length (VEL), fiber wall thickness (FWT), vessel frequency (VF), vessel diameter (VD), compression parallel to the grain (f_{c0}), modulus of rupture (MOR), modulus of elasticity (MOE), and shear parallel to grain (f_{v0}) traits of *Hevea brasiliensis* clones.

Tabela 2. Análise de variância da densidade básica (ρ_{ap}), densidade aparente (ρ_{ap}), contração volumétrica (β_v), coeficiente de anisotropia ($\beta_t\beta_r$), comprimento da fibra (FL), comprimento do elemento de vaso (VEL), espessura da parede da fibra (FWT), frequência do vaso (VF), diâmetro do vaso (VD), compressão paralela ao grão (f_{c0}), módulo de ruptura (MOR) e módulo de elasticidade (MOE) e cisalhamento paralelo ao grão (f_{v0}) em clones de *Hevea brasiliensis*.

	Physical properties				**Anatomical dimensions**					**Mechanical properties**			
Source of variation	**ρ_{ap} (kg m^{-3})**	**ρ_{bas} (kg m^{-3})**	**β_v (%)**	**$\beta_t\beta_r$**	**FL (µm)**	**VEL (µm)**	**FWT (µm)**	**VF (n°mm^{-2})**	**VD (µm)**	**f_{c0} (MPa)**	**MOR (MPa)**	**MOE (MPa)**	**f_{v0} (MPa)**
Clone	2537	2357	27.89^{**}	0.36	101255^{**}	53051^{**}	1.32^{**}	2.17^{**}	2090^{**}	270^{**}	1933^{**}	35908037^{**}	17.22^{**}
Radial position	2735^{**}	2476	16.84**	0.89	618329^{**}	113853^{**}	2.93^{**}	18.03^{**}	9181^{**}	26.81	1147	41716363^{**}	4.45
Clone													
IAN717	672	565	7.35^{c}	1.48	1230^{ab}	740^{b}	4.35^{bc}	2.60^{b}	188^{a}	41^{b}	66^{b}	9611^{ab}	14.15^{b}
LCB510	650	594	7.84^{bc}	1.68	1232^{ab}	774^{b}	4.79^{a}	3.06^{ab}	179^{ab}	43^{ab}	75^{ab}	10275^{ab}	14.70^{ab}
GT1	646	565	6.77^{c}	1.69	1332^{a}	856^{a}	4.30^{c}	3.40^{ab}	196^{a}	38^{b}	65^{b}	7811^{b}	14.83^{ab}
RRIM600	666	583	10.02^{a}	1.63	1190^{b}	726^{b}	4.73^{ab}	3.01^{ab}	183^{ab}	49^{a}	93^{a}	12094^{a}	16.91^{a}
IAN873	643	573	9.31^{ab}	1.92	1175^{b}	704^{b}	4.09^{c}	3.59^{a}	164^{b}	44^{ab}	78^{ab}	10426^{ab}	15.64^{ab}
Radial position													
Pith	644^{b}	565	7.31^{b}	1.48	1082^{c}	694^{c}	4.11^{c}	4.02^{c}	162^{c}	43	68	8763^{c}	15.39
Middle	656^{ab}	578	8.73^{a}	1.70	1246^{b}	757^{b}	4.46^{b}	3.04^{b}	184^{b}	42	78	1002^{ab}	15.58
Bark	665^{a}	585	8.74^{a}	1.85	1397^{a}	829^{a}	4.79^{a}	2.33^{a}	200^{a}	44	80	1135^{a}	14.77
Mean	655	576.7	8.26	1.68	124	760	4.46	3.14	182.4	43.2	76	10043	15.25
CV_e %	4.6	5.1	18.5	45.7	12.7	9.6	8.4	28.5	10.42	14.2	26.59	28.84	16.63

**P< 0.01 by F test; Means followed by different letters in the same column differ among themselves by the Tukey test at 5% level of significance; CV_e= coefficient of experimental variation.

**P< 0,01 pelo teste F; Médias seguidas de letras diferentes na mesma coluna diferem entre si pelo teste de Tukey ao nível de significância de 5%; CVe= coeficiente de variação experimental.

The mean wood density values of *H. brasiliensis* obtained were similar to those observed in clone RRIM600 by Raia et al. (2022). The cell dimensions obtained were consistent with the literature, based on research involving clones GT1, IAN873, RRIM600, and other 12-year-old materials. These clones were grouped into three distinct categories based on density and cell dimensions. Regarding fiber quality indices for pulp and paper production, clone IAN873 was considered one of the best materials (Amorim et al. 2021). The values obtained for density, volumetric shrinkage, and mechanical strength of wood from clones GT1 and RRIM600 were consistent with those observed by Eufrade Junior et al. (2015), who, based on their findings, recommended the wood of clones GT1 and RRIM600 for use in small and secondary structures, light construction, interior building components, general utilities (frames), wood-based panels and furniture. Due to the fiber traits of *H. brasiliensis* wood, it can also be used in paper manufacturing, which would help reduce pressure on natural forests while promoting conservation and sustainable forest use (Boadu et al. 2022).

Regarding radial position (Table 3), significant differences ($P < 0.01$) among clones were detected for the physical properties traits basic density (ρ_{ap}) and β_v, while the highest mean values were observed at bark position (BA) and the lowest at pith position (PI); for all anatomical dimension traits, while the highest mean values for FL, VEL, FWT, and VD traits were also observed at BA and the lowest at PI position, and the opposite was observed for vessel frequency (VF) trait; and for mechanical properties for MOE trait, while the highest mean value was also observed at BA and the lowest at PI position. This occurred because juvenile wood in the pith region exhibits higher physiological activity, which results in the production of a greater number of narrower vessels (Lima et al. 2023).

3.2 Genetic parameters

In this study, it means broad sense heritability among clones (H^2_{mc}) values ≤ 0.1 were considered as very low, ranging from > 0.1 to ≤ 0.25 as low, > 0.25 to ≤ 0.5 as moderate, > 0.5 to ≤ 0.75 as high, and > 0.75 as very high. For both growth traits (Table 1), H^2_{mc} was high for TH (0.619) and very high for DBH (0.859). These values are higher than those reported for TH (0.002) and DBH (0.3) at 19-year-old *H. brasiliensis* clones (Lima et al. 2015), but similar to those estimated for the panel opening height girth in 10-year-old *H. brasiliensis* clones reported from three sites (0.77–0.887) in State of São Paulo (Gonçalves et al. 2006). The observed differences may be attributed to different experimental conditions among the studies, such as environmental characteristics of the sites (altitude, soil, soil temperature), clone age, and number and type of clones tested. In agreement, other studies with *H. brasiliensis* also found that the estimated genetic parameters for growth traits indicate favorable conditions for selection, contributing to promising genetic advances in breeding programs (Lima et al. 2015; Gonçalves et al. 2006; Chaendeakattu and Mydin 2018; Dourado et al. 2018).

The coefficients of genetic variation among clones ($CV_g\%$) for the growth traits DBH and TH were average, ranging from 4.8 to 11.1% (Table 1). For the wood physical properties traits, $CV_g\%$ was high only for the mean and all radial positions (ranging from 10.6–20.9%) and average only for $\beta_t\beta_r$ at the MI position (7.2%), where all estimates for the wood density traits (ρ_{ap}, ρ_{bas}) and $\beta_t\beta_r$ at the PI and BA positions showed low genetic variation among clones (1.1–2.7%). The $CV_g\%$ for the anatomical dimensions traits generally presented average values (4.6-10.2%), except for VF at the PI and MI positions, where high genetic variation among clones was observed (13.0 and 23.1%, respectively). The $CV_g\%$ for mechanical property traits was medium for f_{c0} and f_{v0} (4.0–10.7%) and high for MOR and MOE (11.5–14.4%) on mean and across all positions. These results, in agreement with the heritability, confirm that the tested clone have potential for genetic improvement, given the presence of genetic variation, which is fundamental for the selection of superior genotypes.

The coefficients of relative variation (CV_r) were very low (< 0.2) only for $\beta_t\beta_r$, indicating together with the low values of heritability and coefficient of genetic variation that this trait is not suitable for clone selection. The CV_r was high (≥ 0.5 to ≤ 0.7) or very high (> 0.7) for DBH, TH, β_v, VEL and FWT on average and in all positions, FL on PI, VF on MI, VD on average, PI and MI, f_{c0} on average, PI and BA, MOR on average and MOE on average and BA. Most of the other estimates were moderate (> 0.3 to < 0.5). These results indicated that, except for the $\beta_t\beta_r$ trait, the phenotypic variation of the other wood property traits presents substantial genetic control that can be exploited by selection in genetic improvement programs.

Table 3. Genetic parameters for physical, mechanical, and anatomical wood properties traits in *Hevea brasiliensis* clones.

Tabela 3. Parâmetros genéticos para características físicas, mecânicas e anatômicas da madeira em clones de *Hevea brasiliensis*.

	H^2_{mc}				$CV_g\%$				CV_r			
Trait	**Mean**	**PI**	**MI**	**BA**	**Mean**	**PI**	**MI**	**BA**	**Mean**	**PI**	**MI**	**BA**
Wood physical properties												
ρ_{ap} (kg m^{-3})	0.525	0.333	0.56	0.381	1.4	1.4	2.0	1.5	0.47	0.31	0.49	0.35
ρ_{bas} (kg m^{-3})	0.526	0.344	0.536	0.313	1.6	1.7	2.7	1.1	0.47	0.32	0.48	0.3
β_v (%)	0.888	0.829	0.601	0.853	15.5	20.9	10.6	15.6	1.26	0.99	0.55	1.08
$\beta_t\beta_r$	0.015	0.012	0.073	0.011	1.3	2.3	7.2	1.4	0.06	0.05	0.12	0.05
Anatomical dimensions												
FL (µm)	0.544	0.682	0.485	0.42	4.9	9.9	5.2	4.6	0.49	0.65	0.44	0.38
VEL (µm)	0.847	0.718	0.586	0.768	7.2	6.9	5.9	7.6	1.05	0.71	0.53	0.81
FWT (µm)	0.891	0.624	0.714	0.844	7.3	5.1	5.6	9.7	1.28	0.58	0.71	1.04
VF (nºmm^{-2})	0.493	0.470	0.815	0.522	8.6	13.0	23.1	8.4	0.44	0.42	0.94	0.47
VD (µm)	0.679	0.559	0.903	0.506	5.3	6.8	10.2	5.2	0.65	0.5	1.36	0.45
Mechanical properties												
f_{c0} (MPa)	0.722	0.553	0.416	0.782	8.3	6.6	7.4	10.7	0.72	0.5	0.38	0.85
MOR (MPa)	0.726	0.548	0.535	0.514	12.8	13.6	12.9	11.5	0.73	0.49	0.45	0.46
MOE (MPa)	0.661	0.522	0.520	0.566	1.5	12.2	12.0	14.4	0.62	0.47	0.46	0.51
f_{v0} (MPa)	0.567	0.501	0.483	0.521	4.0	7.8	7.0	7.2	0.31	0.45	0.43	0.47

H^2_{mc} is the broad sense mean heritability among clones; $CV_g\%$ is the coefficient of genetic variation among clones; $CV_r\%$ is the coefficient of relative variation.

H^2_{mc} é a herdabilidade média no sentido amplo entre clones; $CV_g\%$ é o coeficiente de variação genética entre clones; $CV_r\%$ é o coeficiente de variação relativa.

3.3 Genetic correlations

Genetic correlations (r_g) between traits at the PI and MI, PI and BA, and MI and BA positions were positively higher ($0.5 \geq r_g < 0.7$) or very high ($r_g \geq 0.7$) for β_v, VEL, f_{c0}, and MOE, ranging from 0.63 to 0.96 (Table 4). The r_g was also higher or very higher between traits at the PI and MI and MI and BA positions for ρ_{ap}, FL, FWT, VD, and MOR (0.5–0.86), as well as between PI and MI for ρ_{bas} (0.69) and f_{v0} (0.85). These results indicate that the selection in one of the two positions between these traits will result in the direct selection in the other.

Table 4. Genetic correlations (r_g) between pith (PI), middle (MI) and bark (BA) trunk position for physical, mechanical, and anatomical wood properties in *Hevea brasiliensis* clones.

Tabela 4. Correlações genéticas (r_g) entre a posição do tronco na medula (PI), meio (MI) e casca (BA) para propriedades físicas, mecânicas e anatômicas da madeira em clones de *Hevea brasiliensis*.

Trait	PI *versus* MI	PI *versus* BA	MI *versus* BA
ρ_{ap} (kg m^{-3})	0.57	0.13	0.69
ρ_{bas} (kg m^{-3})	0.69	0.38	0.29
β_v (%)	0.84	0.73	0.96
$\beta_t\beta_r$	0.16	0.02	0.31
FL (µm)	0.80	0.17	0.56
VEL (µm)	0.91	0.68	0.96
FWT (µm)	0.80	0.44	0.86
VF (nºmm^{-2})	0.08	0.07	0.43
VD (µm)	0.50	0.21	0.59
f_{c0} (MPa)	0.92	0.94	0.86
MOR (MPa)	0.85	0.32	0.69
MOE (MPa)	0.72	0.63	0.93
f_{v0} (MPa)	0.85	0.36	0.42

Growth traits can be more easily and quickly measured than wood properties traits. Thus, growth traits are preferable and more important for selection in tree breeding, especially due to the observed positive and very high r_g between DBH x TH (0.71) (Table 5). Genetic correlations for growth (DBH, TH) with other traits was positive and high between DBH x TH, TH x ρ_{ap}, moderated between DBH x ρ_{ap}, DBH x VD, TH x VD, indicating that the increase in one trait by selection will results in a direct increase in the other, where for the other. In contrast, r_g for growth with other traits was negative and high between DBH x β_v, DBH x $\beta_t\beta_r$, and DBH x VF, and negative moderate between DBH x MOE, DBH x f_{v0}, TH x ρ_{ba}, TH x $\beta_t\beta_r$, and TH x VF, indicating that the increase in one trait by selection will results in a direct decrease in the other traits. For the correlation between growth and the other traits, r_g suggest the selection will probably show low or no effect.

Table 5. Genetic correlation (r_g) among growth and wood propriety traits in *Hevea brasiliensis* clones.

Tabela 5. Correlação genética (r_g) entre caracteres de crescimento e propriedade da madeira em clones de *Hevea brasiliensis*.

	TH	**ρ_{ap}**	**ρ_{bas}**	**β_v**	**$\beta_t\beta_r$**	**FL**	**VEL**	**FWT**	**VF**	**VD**	**f_{c0}**	**MOR**	**MOE**	**f_{v0}**
DBH	0.71	0.64	-0.30	-0.70	-0.80	0.29	0.26	0.12	-0.81	0.62	-0.48	-0.63	-0.39	-0.67
TH		0.80	-0.62	-0.30	-0.67	0.15	-0.01	-0.19	-0.69	0.56	-0.23	-0.35	-0.20	-0.28
ρ_{ap}			-0.12	0.08	-0.72	-0.27	-0.31	0.32	-0.91	0.37	0.29	0.13	0.35	0.01
ρ_{bas}				0.41	0.12	-0.42	-0.22	0.79	-0.02	-0.38	0.60	0.60	0.61	0.33
β_v					0.29	-0.79	-0.77	0.17	0.19	-0.65	0.93	0.94	0.91	0.89
$\beta_t\beta_r$						-0.18	-0.19	-0.43	0.72	-0.61	0.08	0.20	0.06	0.27
FL							-0.37	-0.14	0.16	0.79	-0.74	-0.67	-0.78	-0.43
VEL								0.04	0.16	0.76	-0.69	-0.59	-0.80	-0.40
FWT									-0.45	0.20	0.51	0.47	0.48	0.24
VF										-0.42	-0.10	0.08	-0.19	0.30
VD											-0.46	-0.45	-0.53	-0.30
f_{c0}												0.98	0.98	0.84
MOR													0.92	0.92
MOE														0.73

*P < 0.05 according to t-test with 2 degrees of freedom. Green high r_g > 0.7 or < -0.7, Black medium r_g > 0.4 < 0.7 or > -0.7 and < 0.4 Blue moderate r_g > 0.1 < 0.4 or > -0.4 and < -0.1 Red low r_g -0.1 > r_g < 0.1

*P < 0,05 de acordo com o teste t com 2 graus de liberdade. Verde alto rg > 0,7 ou < -0,7, Preto médio rg > 0,4 < 0,7 ou > -0,7 e < 0,4 Azul moderado rg > 0,1 < 0,4 ou > -0,4 e < -0,1 Vermelho baixo rg -0,1 > rg < 0,1

In general, r_g the most strongly correlated to each other were apparent density and vessel frequency, volumetric shrinkage versus compressive strength, MOR and MOE, compressive strength versus MOR and MOE, as well as MOR versus MOE and shear strength. These correlations were positive and of high magnitude (r_g > 0.7), indicating that the selection of one trait could result in indirect gains in another (Lima et al. 2015). Other positive and negative correlations were also observed. Positive correlations indicate that two traits vary in the same direction, whereas negative correlations suggest that as one trait increases, the other decreases. A high genetic correlation between DBH, height, and wood volume in Eucalyptus spp. clones was observed, suggesting the feasibility of indirect selection for volume gain via DBH (Oliveira et al. 2021).

In another study with wood from *H. brasiliensis* clones, positive genetic correlations were found between growth, fiber diameter, and fiber wall thickness. Thus, selection for growth would likely lead to simultaneous improvement in fiber diameter and wall thickness. However, since a negative relationship was observed between growth and fiber length, achieving vigorous growth and longer fibers simultaneously may not be possible (Chaendaekattu and Mydin 2018). In studies with eucalyptus hybrids, wood traits showed low or even negative correlations. An intermediate and positive correlation was observed between lignin and density, but a negative correlation was found between lignin and cellulose (Soares et al. 2014).

4 CONCLUSIONS

There is genetic variation for growth traits and the majority of wood properties traits among *H. brasiliensis* clones. Clone IAN717 shows the highest growth, while RRIM600 has the lowest growth in Selvíria-MS, Brazil. Clone RRIM600 exhibits the highest mechanical strength, whereas clone GT1 has the lowest. Most wood properties vary along the pith-to-bark direction, with the lowest values observed in the pith region and the highest in the bark region, except for vessel frequency, where the opposite was found.

The highest heritability coefficients were obtained for DBH, volumetric shrinkage, vessel element length, and compression parallel to the grain at the bark region, vessel frequency and vessel diameter at the middle region, and fiber wall thickness at middle and bark position, indicating that these traits have the greatest potential for selection. The genetic correlation coefficient was high, positive, and significant between the traits DBH and HT, shear strength and modulus of rupture, modulus of elasticity and modulus of rupture, and volumetric shrinkage and modulus of rupture, suggesting that selection for one trait can lead to indirect gains in another.

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