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GENETIC PARAMETERS AND CORRELATIONS OF GROWTH AND WOOD PROPERTIES IN *Peltophorum dubium*[1]

PARÂMETROS E CORRELAÇÕES GENÉTICAS PARA CRESCIMENTO E PROPRIEDADES DA MADEIRA EM *Peltophorum dubium*[1]

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ABSTRACT - The forestry industry uses wood property to assess wood quality and determine the appropriate industrial applications of wood. Understanding the narrow-sense average heritability among progenies (h_m^2) and genetic correlations (r_g) between traits is essential to guide selection of the best progenies in tree improvement. In this study, growth and 16 wood traits at three different positions (pith (PI), middle (MI), and near to the bark (BA)) were measured in a 32-year-old *Peltophorum dubium* provenance and progeny test established in São Paulo State, Brazil. Traits diameter (DBH) and height (H), and wood traits volumetric retraction (β_v), anisotropy index (β_t/β_r), basic (ρ_{bas}) and apparent (ρ_{pab}) wood density, compressive strength (f_{c0}), modulus of rupture (MOR), modulus of elasticity (MOE), shear parallel grain (f_{v0}), vessel element length (VEL), vessel diameter (VDI), vessel density (VDE), fiber length (FL), fiber wall thickness (FWT), ray height (RH), ray length (RL), and ray frequency (RF) were used to estimate the h_m^2 and r_g between traits aiming to select the best families for increase growth and wood quality. Significant differences among progenies were detected for average positions of wood properties ρ_{bas}, ρ_{ap}, and MOE, ρ_{bas}, ρ_{ap}, f_{c0}, and FL at PI, and VDI and FL at MI positions. The h_m^2 for these traits was moderate (0.417–0.452). The pairwise r_g of these traits ranged from moderate to high positives, indicating that selection on any one trait will result in indirect positive genetic gains in the others. This selection strategy is expected to produce wood that is suitable for various uses in the construction and furniture industries.

Keywords: Tropical tree; Commercial wood; Wood properties; REML/BLUP; Heritability.

RESUMO - A indústria florestal utiliza as propriedades tecnológicas da madeira para avaliar a qualidade e determinar as aplicações industriais apropriadas da madeira. Compreender as herdabilidades no sentido estrito entre progenies (h_m^2) e as correlações genéticas (r_g) entre caracteres é essencial para orientar a seleção das melhores progênies no melhoramento florestal. Caracteres de crescimento e 16 de propriedades da madeira, em três posições diferentes (medula (PI), meio (MI) e próximo à casca (BA)) foram medidos em um teste de procedências e progênies de *Peltophorum dubium* de 32 anos, estabelecido no estado de São Paulo, Brasil. Os caracteres de crescimento diâmetro (DAP) e altura (H) e de propriedades da madeira retração volumétrica (β_v), índice de anisotropia (β_t/β_r), densidade básica (ρ_{bas}) e aparente (ρ_{pab}), resistência à compressão (f_{c0}), módulo de ruptura (MOR) e elasticidade (MOE), grão paralelo ao cisalhamento (f_{v0}), comprimento do elemento de vaso (VEL), diâmetro do vaso (VDI), densidade do vaso (VDE), comprimento da fibra (FL), espessura da parede da fibra (FWT), altura do raio (RH), comprimento do raio (RL) e frequência de raios (RF) foram mensurado para estimar a h_m^2 e r_g entre as caracteres com o objetivo de selecionar as melhores progênies para fins de aumentar o crescimento e a qualidade da madeira. Diferenças significativas entre as progênies foram detectadas para as posições médias das propriedades da madeira ρ_{bas}, ρ_{ap} e MOE, ρ_{bas}, ρ_{ap}, f_{c0} e FL na posição PI, e VDI e FL na posição MI. h_m^2 para esses caracteres foi moderada (0,417–0,452). A r_g entre esses caracteres variou de positivamente moderadas a altas, indicando que a seleção em qualquer um deles resultará em ganhos genéticos positivos indiretos nos demais. Espera-se que essa estratégia de seleção produza madeira adequada para diversos usos nas indústrias de construção e móveis.

Palavras-chave: Árvore tropical; Madeira comercial; Propriedades da madeira; REML/BLUP; Herdabilidade.

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1 INTRODUCTION

The forestry industry uses wood property to assess wood quality and determine the appropriate industrial applications of wood. Among all wood properties, wood density is used in the forestry industry as an indicator of wood quality. Not only is it easy to measure, but it is also directly associated with the productivity and quality of charcoal and cellulose and the physical-mechanical strength of paper (Bouffier et al. 2009). Furthermore, wood density is a trait that presents moderate to high genetic control, often with heritability values > 0.3 and sometimes > 0.7 (Fukatsu et al. 2015; Nabais et al. 2018; Riva et al. 2020; Zhang et al. 2022; Masendra et al. 2023; Poupon et al. 2023; Longui et al. 2024). As such, wood density has been the focus of breeding programs for several tree species around the world to improve wood quality (Sotelo-Montes et al. 2006; Hung et al. 2015; Soro et al. 2022; Poupon et al. 2023).

However, other wood properties are also important and genetic control studies are needed to support the breeding of wood quality, including: volumetric shrinkage (β_v), anisotropy coefficient (β_t/β_r), fiber length (FL), vessel element length (VEL), fiber wall thickness (FWT), vessel frequency (VF), vessel diameter (VDI), compressive strength (f_{c0}), shear parallel to the grain (f_{v0}), modulus of rupture (MOR), and modulus of elasticity (MOE). For example, the physical properties β_v and β_t/β_r are important parameters to determine the appropriate industrial application of wood, ensuring the quality and longevity of wood products. Wood mechanical property as f_{c0}, MOR, MOE, and f_{v0} are used to classify wood into strength classes, indicating the most suitable species for structural projects (Eufrade Junior et al. 2015). Studies have also shown that these traits are generally under strong genetic control (Hong et al. 2014; Chen et al. 2016; Li et al. 2017; Hassegawa et al. 2019; Fundova et al. 2020; Zhang et al. 2022; Takahashi et al. 2023; Lima et al. 2024), suggesting the possibility for breeding.

In tree breeding programs, improving multiple traits simultaneously can be beneficial. Genetic correlation analyses between traits can act as a reference for the breeding of multiple traits. Growth traits such as diameter at breast heigh (DBH) and tree height (H) are generally easier and faster to measure than wood traits and are often chosen for direct selection, particularly DBH. Furthermore, most forest yield models are based on growth traits (Climent et al. 2024). Consequently, if we aim to improve populations for several traits at the same time, it is essential to know the genetic correlation between DBH and H and wood traits. Specifically, understanding the genetic correlation between growth and wood properties is critical because traits that present a negative genetic correlation (i.e., the higher one trait, the lower the other) complicate or impede efforts to conduct simultaneous selection for such traits. Therefore, it is important to estimate the genetic correlation between growth and wood traits for the improvement of both.

Forest plantations of native species play an important role in the commercial production of hardwood. *Peltophorum dubium* (Spreng.) Taub. (Caesalpinaceae) is a deciduous, heliophyte neotropical tree with potential for commercial reforestation due to its rapid growth. Its wood is moderately durable, resistant to rot, and has a high commercial value. The wood is used in civil construction, as beams, rafters, and slats, and in the manufacture of doors, windows, and floors. It is also a medicinal plant (Carvalho 1994). The species occurs naturally in dense primary forests as well as secondary formations, with a natural distribution between latitudes of 7º S (Paraíba state, Brazil) and 30º 25' S in Uruguay (Carvalho 1994). Adult individuals in natural populations are 10 to 25 m tall and 35 to 90 cm in DBH, but in exceptional cases the species can reach 40 m in height and 300 cm DBH. The trunk is cylindrical, straight or slightly curved, with a stem up to 15 m long (Carvalho 1994). Although some studies have been carried out in *P. dubium* on the genetic variation and control of DBH, H, and stem form (Sebbenn et al. 1999; Senna et al. 2012; Bassan et al. 2022), no studies have assessed the genetic variation and control of the wood's anatomical, physical, and mechanical properties, or the genetic correlations with growth traits. This information is fundamental for the genetic improvement of the species.

The aim of this study was to support breeding programs for the species by analyzing the genetic variation, heritability, and genetic correlation between growth and physical, mechanical, and anatomical properties of the wood in a 32-year-old *P. dubium* provenance and progeny test planted in Luiz Antônio, São Paulo state, Brazil. We also assessed the genetic correlation between wood traits measured at three radial positions in the trunk: Pith (PI), middle (MI), and near to the bark (BA).

2 MATERIAL AND METHODS

2.1 Site, experimental design, and sampling

This study was carried out in a provenances and progenies test planted in 1982 at the Luiz Antônio Experimental Station (21°40' S, 47°49' W, elevation of 550 m, high altitude tropical climate (Cwa), mean annual temperature of 23.5°C, mean annual precipitation of 1340 mm, and red latosol), in the state of São Paulo, Brazil. We used open-pollinated plants originated from seeds collected from three natural populations of *P. dubium*: i) seeds from 24 trees in the city of Alvorada do Sul (22°46' S, 51°13' W, elevation of 320 m), state of Paraná; ii) seeds from 20 trees in the city of Bauru (22°18' S, 49°03' W, elevation of 530 m), São Paulo; and iii) seeds from three trees in the city of Ribeirão Preto (21°11' S, 47°51' W, elevation of 530 m), São Paulo (Galão et al. 2023). The provenance and progeny test was established using a compact family block design, completely randomized within blocks (six blocks), with 47 treatments (progenies), and linear plots of five plants at a spacing of 2 m x 3 m.

All traits were measured for 30 trees from 17 randomly selected progenies of two provenances: 15 trees from 10 progenies of Alvorada do Sul provenance, and 15 trees from seven progenies of Bauru provenance. For each progeny, samples were collected from one to three trees, one individual per plot and block. Samples were randomly collected from only part of the trial progenies in order to represent the genetic variation among the progenies established in the experiment and to preserve the majority of trees within the families for future selection with the aim of transforming the trial into a seed orchard for the production of improved seeds for greater growth and better wood quality. A 1.3 m log was removed from the base of each tree, and a central plank was cut from each log to obtain wood samples for analysis. Samples measuring 4 cm × 4 cm × 1 m were taken from this plank, near three radial positions: (i) the region closest to the pith (PI), (ii) an intermediate position (MI), and (iii) the region near the bark (BA). A specimen was taken from each position to assess the physical-mechanical properties and anatomical features. Eighteen traits were measured: two growth traits, DBH and tree height (H); four physical wood properties, volumetric shrinkage (β_v), index of wood anisotropy (β_t/β_r), basic wood density (ρ_{bas}), and apparent density (ρ_{ap}); four mechanical wood properties, compressive strength (f_{c0}), modulus of rupture (MOR), modulus of elasticity (MOE), and shear parallel to the grain (f_{v0}); and eight anatomical wood properties, vessel element length (VEL), vessel diameter (VDI), vessel density (VDE), fiber length (FL), fiber wall thickness (FWT), ray height (RH), ray length (RL) and ray frequency (RF). The anatomical analysis was performed at the Wood Anatomy Laboratory of the Forestry Science Department of the School of Agricultural Sciences (FCA), UNESP, Botucatu Campus, Brazil. The mechanical and physical properties tests were conducted at the Materials Testing Laboratory of the Rural Engineering Department of the School of Agricultural Sciences – FCA, UNESP, Botucatu, Brazil.

2.2 Wood physical properties

Wood density at 12% equilibrium moisture content (EMC) was determined according to NBR7190-1 standard (ABNT 2022a), with an adaptation in the recommended specimen dimensions (2 cm x 2 cm x 3 cm). Samples were conditioned in a room at a constant temperature (21°C) and relative humidity (65%). In these conditions, mass was determined using an analytical scale, and volume was calculated as the product of their dimensions, obtained with a micrometer. Basic wood density (ρ_{bas}) was assessed as the ratio between dry mass and saturated volume. Specimens (5 cm x 3 cm x 2 cm) were immersed in water and considered saturated when they presented constant mass during monitoring in the laboratory. Subsequently, the saturation volume was obtained by the hydrostatic balance method and were dried in an oven at 105 ± 2°C to obtain the dry mass. Volumetric shrinkage (β_v) was obtained from the same samples as those used for basic density (ABNT 2022a). Samples were saturated in water, their dimensions measured with calipers (accuracy = 0.001 mm), taking three measurements per direction, and then oven-dried at 105 ± 3°C, followed by measurement of the dry volume of each sample. The anisotropy index (β_t/β_r) and β_v were determined as:

$$\frac{\beta_t}{\beta_r} = \frac{\varepsilon r_3}{\varepsilon r_2}, \qquad \text{Eq. 1}$$

$$\beta_v = (V_s - V_d)/V_d, \qquad \text{Eq. 2}$$

where V_s and V_d are the saturation and dry volume, respectively, and $\mathcal{E}r_2$ and $\mathcal{E}r_3$ are the percentage of radial and tangential retraction, respectively.

2.3 Wood mechanical properties

Samples were tested for f_{v0}, f_{c0}, MOR, and MOE according to ABNT (2022b). Tests were conducted in a computer-controlled 300 kN electromechanical testing machine, and strain was evaluated using a standard mechanical strain gauge extensometer (accuracy of 0.001 mm). We used a loading speed of 2.5 MPa/min (shear strength) and 10 MPa/min (compression and bending). Initial results of strength and elastic properties (modulus of elasticity) were corrected to EMC (12%) using a conversion coefficient of 3% (of variation per 1% of MC variation) for strength properties and 2% for elastic properties.

2.4 Wood anatomical properties

Samples (1.5 cm^3 blocks) were softened in boiling water and glycerin (4:1) for approximately 1 h. Transverse and longitudinal sections of 12–15 µm in thickness were cut using a sliding microtome. Sections were bleached with sodium hypochlorite (60%) and washed thoroughly in water. We prepared permanent slides. Sections were double stained with aqueous 1% safranin and aqueous 1% astra blue (1:9). We mounted slides permanently in synthetic resin (Entellan®). Measurements followed the recommendations of the IAWA (1989).

2.5 Data analyses

Our genetic analyses were performed at the progenies level as only 21 individuals from 8 progenies (2–3 individuals/progeny) were measured for the traits. Furthermore, the main focus of the study was to investigate the genetic heritability of wood traits, which were obtained by destructive method (i.e., felling the tree). The restricted maximum likelihood/best linear unbiased prediction (REML/BLUP) method was used to estimate components of variance and genetic parameters using the SELEGEN-REML/BLUP software (Resende 2016) based on model 111 (Mixed mating system: randomized blocks, open-pollinated progenies, one plant per plot), and using the mean self-fertilization rate of 0.326, calculated among four populations of the species (Mori et al. 2013). Components of variance and genetic parameters were estimated, ignoring the effect of provenances, as:

$$y = X_r + Z_a + \text{e}, \qquad \text{Eq. 3}$$

where y is the data vector, r is the vector of blocks effect (assumed to be fixed) added to the general mean, a is the individual additive genetic effects (assumed to be random), and e is the vector of (random) errors or residuals. Uppercase letters represent the incidence matrices for the aforementioned effects. The estimated variance components were genetic variance among progenies (σ_f^2), addictive genetic variance among progenies ($\sigma_a^2 = \sigma_f^2/\rho$, where ρ is the average coefficient of relatedness among plants within progenies), and environmental variance (σ_e^2). The estimated parameters were: Narrow-sense average heritability among progenies:

$$h_f^2 = [(\tfrac{1}{4})\sigma_a^2]/(\sigma_f^2 + \sigma_e^2) \qquad \text{Eq. 4}$$

where b is the number of blocks; coefficient of relative variation,

$$CV_r = CV_g\%/CV_e\%, \qquad \text{Eq. 5}$$

where $CV_g\%$ is the coefficient of genetic variation among progenies:

$$V_g\% = 100(\sqrt{\sigma_f^2}/x) \qquad \text{Eq. 6}$$

and $CV_e\%$ is the coefficient of environmental variation,

$$CV_e\% = 100(\sqrt{\sigma_e^2}/x), \qquad \text{Eq. 7}$$

where x is the mean of the trait under analysis.

Genetic correlations (r_g) were calculated pairwise between growth and average (PI, MI, and BA) anatomical, physical, and mechanical wood traits, as well as for each anatomical, physical, and mechanical wood trait between PI, MI, and BA:

$$r_g = Cov_{f(x,y)}/\sqrt{\sigma_{fx}^2\sigma_{fy}^2}, \qquad \text{Eq. 8}$$

where $Cov_{f(x,y)}$ is the genetic covariance between trait x and y, respectively. The statistical significance of r_g was determined using the t-test with n-2 degrees of freedom, $t = (r_g/\sqrt{1 - r_g^2}))\sqrt{n-2}$, where n is the number of progeny (Cruz and Regazzi 1997).

3 RESULTS AND DISCUSSION

3.1 Mean traits and variation

This study investigated the genetic variation, progenies-mean heritability (h_m^2), and correlations between growth and wood property traits in a 32-year-old *P. dubium* provenance and progeny test. The mean growth was 15.97 cm for DBH and 16.4 m for H (Table 1), indicating a mean annual increment (MAI) of 0.499 cm (15.97 cm/32 years) and 0.513 m (16.4 cm/32 years) for DBH and H, respectively, at 32-years-of-age. The MAI for DBH at 32 years decreased strongly in comparison to that reported for 1 to 11 years of age (1.9–0.96 cm) in the same trial (Sebbenn et al. 1999). Consequently, if this growth rate per year is maintained, it would take about 180 years for trees to reach 90 cm DBH and up to 602 years to reach the maximum of 300 cm DBH reported for the species (Carvalho 1994).

Significant differences ($P < 0.05$) were detected among progenies by the deviance analyses for the wood property traits considering the average of the three positions for ρ_{bas}, ρ_{ap}, and MOE (Table 1). Significant differences ($P < 0.05$) among progenies were also detected for traits ρ_{bas}, ρ_{ap}, f_{c0}, and FL at PI position, and VDI and FL at MI position. These results suggest genetic variation among progenies that can be exploited for these traits through selection for genetic improvement of the studied population. In the present study, only a portion of all tested progenies from each provenance (19 progenies per provenance) were sampled, so the genetic variability found herein is likely lower than that present in the trial. Furthermore, previous analyses of the same provenance and progenies test using measurements obtained from all planted progenies, detected significant differences between progenies for DBH from 4 to 11 years of age, height at ages 1 to 5 and 8 to 11 years (Sebbenn et al. 1999), and DBH at 24 years of age (Senna et al. 2012). Thus, the absence of significant differences for growth traits, as well as for other wood traits, may be due to the limited number of progenies or individuals per progeny used for our analyses.

Table 1. Mean for growth, physical, mechanical, and anatomical wood property traits at pith (PI), middle (MI), and bark (BA) positions.

Tabela 1. Média para caracteres de crescimento e caracteres físicos, mecânicas e anatômicos da madeira nas posições medula (PI), meio (MI) e casca (BA).

Trait	Mean			
	PI	MI	BA	Total
Growth				
DBH (cm)	-	-	-	15.97
Height: H (m)	-	-	-	16.4
Physical				
Volumetric retraction: β_v (%)	8.72	9.74	10.96	9.81
Index of anisotropy: β_t/β_r	1.24	1.86	1.82	1.64
Basic density: ρ_{bas} (g cm^{-3})	0.443*	0.501	0.538	0.494*
Apparent density: ρ_{ap} (g cm^{-3})	0.552*	0.623	0.672	0.616*
Mechanical				
Compressive strength: f_{c0} (MPa)	32.4*	33.51	35.72	33.9
Modulus of rupture: MOR (MPa)	53.34	62.94	65.04	60.44
Modulus of elasticity: MOE (MPa)	5729	6819.1	7131	6559.8*
Shear parallel grain f_{v0} (MPa)	10.4	12.52	13.05	11.98

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continuation – Table 1
continuação – Tabela 1

Trait	Mean			
	PI	MI	BA	Total
Vessel density: VDE ($n.mm^{-2}$)	8.3	5.2	5.5	6.31
Vessel diameter: VDI (µm)	102.95	115.95*	119.8	112.91
Anatomical				
Vessel element length: VEL (µm)	293.73	332.93	335.3	320.65
Fiber length: FL (µm)	828.3*	971.3*	1009	936.35
Fiber wall thickness: FWT (µm)	3.01	4.0	3.91	3.64
Ray height: RH (µm)	219.2	201.1	205.8	208.7
Ray length: RL (µm)	15.9	20.74	20.74	19.11
Ray frequency: RF ($n.mm^{-2}$)	9.1	8.9	9.2	9.05

*P< 0.05, with 0.5 degrees of freedom for likelihood ratio test (LRT), χ2 deviance chi-square.

*P< 0,05, com 0,5 graus de liberdade para o teste da razão de verossimilhança (LRT), desvio qui-quadrado (χ^2).

3.2 Genetic parameters

Genetic parameters were discussed only for those traits that show significant differences between progenies (Table 1). In the current study, values of $h_m^2 \leq 0.2$ were considered low, with values ranging from $> 0.2 < h_m^2 \leq 0.5$ considered moderate, and > 0.5 high. Base on Resende and Duarte (2007), values of $r_a < 0.5$ were considered low, values ranging from $0.5 \leq r_a < 0.7$ considered moderate, values ranging from $0.7 \leq r_a < 0.9$ considered high, and ≥ 0.9 as very high. For those traits that show significant differences among progenies (Table 2), progenies-mean heritability (h_m^2), selective accuracy (r_a), and coefficient of relative variation (CV_r) ranged from moderated to high (h_m^2: 0.417–0.452; r_a= 0.646–0.672; CV_r: 0.35–0.37). These results indicate that wood quality traits can be increased through selection among progenies with high values for average position for ρ_{bas}, ρ_{ap}, and MOE and ρ_{bas}, ρ_{ap}, f_{c0}, and FL at PI position, and VDI and FL at MI position. Although, h_m^2 for traits ρ_{bas}, ρ_{ap}, f_{c0}, MOE, and FL decreased from PI to BA and VDI increased from PI to BA positions, values were similar between radial positions (Table 2). Thus, all these wood traits in all positions offer potential for tree improvement through selection among progenies. Similarly, genetic control ranging from moderate to high heritability for wood traits have been found in several other studies, including: ρ_{bas} or ρ_{ap}, ranging from 0.36–0.61 (Santos et al. 2004; Hamilton et al. 2009; Blackburn et al. 2011; Hong et al. 2014; Hung et al. 2016; Longui et al. 2024); f_{c0} o ranging from 0.416–0.782 (Santos et al. 2004; Lima et al. 2024); MOE ranging from 0.3–0.53 (Blackburn et al. 2011; Gaspar et al. 2011; Hung et al. 2016; Kien and Bien 2024); VDI ranging from 0.506–0.903 (Lima et al. 2024); FL, ranging from 0.41–0.682 (Chen et al. 2016; Lima et al. 2024). Consequently, the results confirm that wood properties ρ_{bas}, ρ_{ap}, f_{c0}, MOE, VDI, and FL are on genetic control and can be improved through selection among progenies.

Table 2. Genetic parameters for a 32-year-old *Peltophorum dubium* provenance and progeny test analyzed for growth, physical, mechanical, and anatomical wood property traits at pith (PI), middle (MI), and bark (BA) positions.

Tabela 2. Parâmetros genéticos para um teste de procedências e progênies de *Peltophorum dubium* de 32 anos de idade, analisado para caracteres de crescimento e caracteres físicos, mecânicas e anatômicos da madeira nas posições medula (PI), meio (MI) e casca (BA).

Trait	h_m^2				r_a				CVr			
	PI	**MI**	**BA**	**Mean**	**PI**	**MI**	**BA**	**Mean**	**PI**	**MI**	**BA**	**Mean**
Growth												
DBH	-	-	-	0.411	-	-	-	0.641	-	-	-	0.34
H	-	-	-	0.396	-	-	-	0.629	-	-	-	0.33
Physical												
β_v	0.402	0.398	0.399	0.391	0.634	0.631	0.63	0.625	0.33	0.33	0.33	0.33
β_t/β_r	0.346	0.384	0.405	0.383	0.588	0.62	0.636	0.619	0.3	0.32	0.34	0.32
ρ_{bas}	0.452	0.432	0.404	0.42	0.672	0.657	0.636	0.648	0.37	0.36	0.34	0.35
ρ_{ap}	0.423	0.416	0.405	0.419	0.65	0.645	0.636	0.647	0.35	0.34	0.34	0.35
Mechanical												
f_{c0}	0.423	0.635	0.386	0.413	0.65	0797	0.621	0.643	0.35	0.54	0.32	0.34
MOR	0.412	0.409	0.388	0.407	0.642	0.64	0.623	0.638	0.34	0.34	0.33	0.34
MOE	0.415	0.406	0.387	0.417	0.644	0.637	0.622	0.646	0.34	0.34	0.32	0.35
f_{v0}	0.4	0.38	0.404	0.395	0.632	0.616	0.636	0.628	0.33	0.32	0.34	0.33
Anatomical												
VEL	0.392	0.418	0.402	0.415	0.626	0.647	0.634	0.644	0.33	0.35	0.33	0.34
VDI	0.377	0.433	0.391	0.412	0.614	0.658	0.625	0.642	0.32	0.36	0.33	0.34
VDE	0.403	0.384	0.414	0.395	0.635	0.62	0.643	0.628	0.34	0.32	0.34	0.33
FL	0.422	0.422	0.376	0.394	0.65	0.65	0.613	0.628	0.35	0.35	0.32	0.3
FWT	0.395	0.376	0.402	0.388	0.628	0.613	0.634	0.623	0.33	0.32	0.33	0.33
RH	0.381	0.397	0.392	0.387	0.617	0.63	0.626	0.623	0.32	0.33	0.33	0.32
RL	0.411	0.342	0.396	0.39	0.641	0.585	0.629	0.624	0.34	0.29	0.33	0.33
RF	0.374	0.386	0.341	0.339	0.612	0.621	0.584	0.582	0.33	0.32	0.29	0.29

h_m^2 and r_a are the progeny-mean-heritability and selective accuracy, respectively; CV_r is the coefficient of relative variation. The abbreviation of the traits is presented in Table 1.

h_m^2 and r_a são a herdabilidade média da progênie e a acurácia seletiva, respectivamente; CV_r é o coeficiente de variação relativa. A abreviação dos caracteres é apresentada na Tabela 1.

3.3 Genetic parameters

The r_g between growth traits and average wood properties was significantly higher than zero (0.71–0.78) for the trait pairs DBH × H, H × ρ_{bas}, and H × ρ_{ap} (Table 3), while between the wood properties was significantly higher than zero (0.71–0.99) for the pairs ρ_{bas} × ρ_{ap}, ρ_{bas} × f_{c0}, ρ_{bas} × MOR, ρ_{bas} × MOE, ρ_{bas} × f_{v0}, ρ_{ap} × f_{c0}, ρ_{ap} × MOR, ρ_{ap} × MOE, ρ_{pa} × f_{v0}, f_{c0} × f_{v0}, f_{c0} × MOR, f_{c0} × MOE, MOR × MOE, and VEL × FL (Table 3). Thus, a direct selection for an increase in H will result in an increase in the other DBH, ρ_{bas}, and ρ_{ap} traits, the direct selection for an increase in ρ_{bas} or ρ_{ap}, will results in an indirect increase in f_{c0}, MOR, MOE, and f_{v0}, and a direct selection for an increase in VEL will results in an indirect increase in FL.

Several studies found r_g values between DBH × ρ_{bas} or DBH × ρ_{ap}, H × ρ_{bas} or H × ρ_{ap}, that ranged from low to high positive (0.16–0.89) (Sotelo-Montes et al. 2006; Weng et al. 2014; Chen et al. 2018; Zhang et al. 2022; Lima et al. 2024), while other studies have reported values ranging from moderately negative to slightly positive (-0.61 to 0.18: Lenz et al. 2013; Wu et al. 2013; Hung et al. 2015; Li et al. 2017; Fundova et al. 2020; Riva et al. 2020; Longui et al. 2024). Values of r_g were reported as highly positive for the trait pairs, f_{c0} × f_{v0} (1.0), ρ_{bas} × f_{c0} (0.99) (Santos et al. 2004; Li et al. 2017; Huda et al. 2018), ρ_{bas} × f_{v0} (0.75-0.92) (Santos et al. 2004; Li et al. 2017; Huda et al. 2018), ρ_{bas} × MOE (Blackburn et al. 2010; Wu et al. 2013; Hong et al. 2014; Hung et al. 2016; Kien and Bien 2024), f_{c0} × MOR (r_g= 0.64, Li et al. 2017), and MOR × MOE (Li et al. 2017; Kien and Bien 2024). Thus, the simultaneous genetic improvement of the population for multiple traits is possible.

However, although values were not significantly different from zero, r_g was moderate positive between growth traits and average wood properties (0.53–0.63) for the trait pairs DBH × f_{c0}, DBH × f_{v0}, DBH × FWT, H × f_{c0}, and H × FWT, between the wood properties (0.51–0.67) for the pairs β_v × ρ_{bas}, β_v × ρ_{ap}, β_v × f_{v0}, ρ_{bas} × VDE, ρ_{ap} × VDE, f_{c0} × VDI, MOR × f_{v0}, MOE × f_{v0}, f_{v0} × FL, and VEL × VDI, and was moderate negative between β_t/β_r × MOE (-0.62) and β_t/β_r × f_{v0} (-0.64). These results are apparently an artefact of the small sample size in terms of number of progenies (8 progenies). The test-t for six degrees of freedom, r_g values must be at least 0.71 and 0.84 to be significantly different from zero, respectively. Therefore, although the r_g values were not significantly different from zero, they should not be neglected. However, these results also indicate that wood quality studies should be performed using a larger number of progenies and plants within progenies to obtain results that can be statistically verified.

Among the paired traits that presented significant differences between the progenies, r_g ranged from 0.32 to 0.99 (Table 3) and was significantly greater than zero among the traits ρ_{bas} × ρap (0.99), ρ_{bas} × f_{c0} (0.81), ρ_{bas} × MOE (0.77), ρ_{ap} × f_{c0} (0.79), ρ_{ap} × MOE (0.73), and f_{c0} × MOE (0.84). Values of r_g were reported as highly positive for the trait pairs, ρ_{bas} × f_{c0} (0.99) (Santos et al. 2004; Li et al. 2017; Huda et al. 2018), ρ_{bas} × MOE (Blackburn et al. 2010; Wu et al. 2013; Hong et al. 2014; Hung et al. 2016; Kien and Bien 2024), Thus, the simultaneous genetic improvement of the population for multiple traits is possible. These results indicate an indirect positive effect for the paired traits through direct selection, especially for ρbas, which presented the highest r_g values with the other traits. An increase in wood density (ρ_{bas}) results in greater strength and durability of the wood. Meanwhile, an increase in compression strength (f_{c0}) results in wood that can support greater weights without reducing in size. High MOE values result in high strength and low deformation capacity of the wood and qualifying it for use in construction. This makes wood suitable for various uses in the construction and furniture industries.

Because the h_m^2 for most traits was moderate or high in all radial positions, and although for most traits the highest values were observed in the PI position, the difference in relation to MI and BA is not strong. Thus, selection for wood property traits at all radial positions will result in an indirect positive genetic gain for the others. Due to the fact that for the production of boards the part of the wood close to the bark (BA) is eliminated when the logs are split in the carpentry shops, data and estimates of genetic parameters of the wood properties obtained in the PI and MI positions are in practice the most important for tree improvement.

Table 3. Genetic correlation (r_g) among growth and wood properties traits.

Tabela 3. Correlação genética (r_g) entre caracteres de crescimento e propriedades da madeira.

Trait		**Physical**				**Mechanical**				**Anatomical**							
	H	**β_v**	**β_t/β_r**	**ρ_{bas}**	**ρ_{ap}**	**f_{c0}**	**MOR**	**MOE**	**f_{v0}**	**VEL**	**VDI**	**VDE**	**FL**	**FWT**	**RH**	**RL**	**RF**
Growth																	
DBH	0.78*	-0.07	-0.22	0.31	0.31	0.53	0.06	0.36	0.6	0.07	0.2	0.12	-0.01	0.56	-0.21	0.2	-0.11
H		-0.03	-0.24	0.71*	0.71*	0.63	0.25	0.36	0.47	0.13	0.06	0.26	0.19	0.53	-0.34	0.13	-0.09
Physical																	
β_v			-0.21	0.51	0.53	0.27	0.36	0.15	0.67	0.08	0.11	0.31	0.36	-0.03	-0.11	-0.08	-0.02
β_t/β_r				0.49	0.27	-0.46	-0.44	-0.62	-0.64	-0.21	-0.21	0.04	-0.44	-0.27	0.01	0.42	-0.07
ρ_{bas}					0.99**	0.81*	0.71*	0.77*	0.81*	0.22	0.32	0.56	0.38	0.28	-0.4	-0.09	-0.12
ρ_{ap}						0.79*	0.71*	0.73*	0.83*	0.25	0.32	0.51	0.43	0.24	-0.43	-0.11	-0.14
Mechanical																	
f_{c0}							0.72*	0.84**	0.75*	0.32	0.51	-0.06	0.47	0.18	-0.03	-0.22	0.03
MOR								0.77*	0.51	0.28	0.41	-0.02	0.4	0.01	-0.04	-0.31	-0.03
MOE									0.61	0.22	0.42	-0.23	0.41	0.23	-0.14	-0.15	-0.06
f_{v0}										0.27	0.19	-0.1	0.53	0.26	-0.1	-0.18	-0.11
Anatomical																	
VEL											0.55	0.03	0.73*	-0.15	0.24	-0.31	-0.23
VDI												-0.11	0.44	-0.1	0.34	-0.06	-0.03
VDE													0.16	0.15	-0.23	-0.38	0.31
FL														0.18	0.07	-0.48	-0.03
FWT															-0.29	0.23	-0.09
RH																-0.22	0.38
RL																	-0.16

**P< 0.01 and *P< 0.05 according to the t-test with 6 degrees of freedom. The abbreviation of the traits is presented in Table 1.

**P< 0,01 e *P< 0,05 de acordo com o teste t com 6 graus de liberdade. A abreviação das características está apresentada na Tabela 1.

4 CONCLUSIONS

Our results demonstrate the possibility of simultaneous genetic improvement to increase the quality of multiple wood traits through direct selection for increased average radial positions of ρ_{bas}. We found genetic variation among progenies for average positions of wood properties ρ_{bas}, ρ_{ap}, and MOE, ρ_{bas}, ρ_{ap}, f_{c0}, and FL at PI, and VDI and FL at MI positions. Progenies-mean heritability for these traits is moderate. The pairwise r_g of these traits ranged from moderate to high positives, indicating that selection on any one trait will result in indirect positive genetic gains in the others. Therefore, it is not necessary to measure all of these wood properties to improve wood quality. Direct selection for an increase in the average radial positions of ρ_{bas} will result in an indirect increase in the average positions of the wood properties ρ_{ap} and MOE, ρ_{bas}, ρ_{ap}, f_{c0}, and FL at PI, and VDI and FL at MI positions. This selection strategy is expected to produce wood that is suitable for various uses in the construction and furniture industries.

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6 AUTHORS' CONTRIBUTION

ATDG, ELL and AWB: Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. MLMF, JARM, ILL, MR and AMS: Formal analysis, Methodology, Writing – review & editing.

7 CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest related to the publication of this manuscript.

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