REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

WOOD PROPERTIES OF *Pinus patula* FROM DIFFERENT PROVENANCES PLANTED IN ITAPEVA, SP, BRAZIL

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Received for publication: 09/02/2023 – Accepted for publication: 24/09/2024

Resumo

Propriedades da madeira de Pinus patula de diferentes procedências plantadas em Itapeva, SP, Brasil. Desde as décadas de 60 e 70, *Pinus* spp. têm sido uma alternativa às espécies nativas do Brasil para certos usos na indústria madeireira. Assim, se justifica a importância de saber quais espécies de *Pinus* são as mais indicadas para o plantio em diferentes localidades do Brasil. No presente estudo, objetivamos ampliar o conhecimento da madeira de *Pinus patula* de diferentes procedências de sementes plantadas em Itapeva, São Paulo, Brasil, estudando a variabilidade em propriedades físicas, mecânicas e anatômicas e comparando-as com *Pinus elliottii* var. *elliottii*, espécie já utilizada tradicionalmente pela indústria madeireira brasileira. Espera-se que nossos achados forneçam subsídios para novos estudos voltados ao melhoramento genético de *P. patula* e, assim, contribuam para suprir a demanda por matérias-primas de boa qualidade. Para tanto, aos 31 anos foram coletadas 25 árvores, cinco de cada espécie/procedência. Não encontramos diferença entre os materiais estudados para espessura da parede das traqueídes, resistência à compressão paralela às fibras, resistência ao cisalhamento tangencial aos anéis de crescimento e módulo de ruptura. *Pinus elliottii* apresentou menor comprimento de traqueíde em comparação com as procedências de *Pinus patula*. Todas as propriedades avaliadas aumentaram em direção à casca, mas a partir da posição de 75%, os valores de todas as propriedades tenderam a se estabilizar, indicando maior presença de lenho adulto. Nossos resultados mostram que *Pinus patula* pode ser indicado para fins estruturais.
Palavras-chave: Propriedades mecânicas, Propriedades físicas, Anatomia da madeira, Pinus

Abstract

Since the 60's and 70's, *Pinus* spp. have been an alternative for certain industrial uses to the native species of Brazil. Thus, the importance of knowing which of the *Pinus* species are the most suitable for planting in different locations in Brazil is justified. In the present study, we aim to expand the knowledge of *Pinus patula* wood from different seed provenances planted in Itapeva, São Paulo, Brazil, by studying the variability in physical, mechanical and anatomical properties and comparing them to *Pinus elliottii* var., species traditionally used by the Brazilian wood industry. It is expected that our findings will provide support for new studies aimed at the genetic improvement of *P. patula* and thus contribute to supplying the demand for good quality raw materials. For this purpose, 31-year-old *Pinus patula* and *Pinus elliottii* var. *elliotti*. wood was collected from 25 trees, five from each species/provenance. We found no difference among the studied materials for tracheid wall thickness, compressive strength parallel to the grain, shear strength parallel to the grain and modulus of rupture. *Pinus elliottii* showed shorter tracheid length compared to *Pinus patula* provenances. All properties evaluated increased towards the bark, but from the 75% position, the values of all properties tended to stabilize, indicating a greater presence of adult wood. Our results show that *Pinus patula* may be indicated for structural purposes.
Keywords: Mechanical properties, Physical properties, Wood anatomy, Pine

INTRODUCTION

Overexploitation of Brazil's native species has depleted its wood stocks, which led to government incentives for the introduction of rapid-growth exotic species in the 1960s and 1970s, aiming to supply the timber industry. Among the implanted species, *Pinus* spp. saw increased demand, including *Pinus patula* Schltdl & Cham. (patula pine), a potential species for large-scale use in the timber sector (SHIMIZU; SEBBENN, 2008).

The original provenance of *P. patula* is from Mexico (UNITED STATES DEPARTMENT OF AGRICULTURE - USDA, 2023) where it grows in regions with humid summers and dry winters, without water deficit, and altitudes between 1,400 and 3,200 m. *Pinus patula* is widely cultivated in tropical and subtropical regions of the world. The species is largely used for plantations in tropical and subtropical regions of the world, including South America, Central and Southern Africa, Indonesia, Australia, and New Zealand In Africa, *P. patula*

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plantations is well represented in different countries, and probably being the most widely planted pine in tropical Africa (TADESSE; FONSECA, 2022).

In Brazil, commercial plantations should be situated at altitudes above 1,000 m because *Pinus* spp. planted at low altitude suffers from “foxtail” characterized by low apical growth and accentuated incidence of branches. This results in low-lying wood susceptible to attack by defoliating insects and fungi when trees are exposed to such silvicultural operations as pruning (SHIMIZU; SEBBENN, 2008). When planted in favorable conditions, *P. patula* tends to have growth superior to *Pinus elliottii* and *Pinus taeda*, standing out in the production of cellulosic paste (low resin content) and mechanical processing, however, in Brazil, *P. patula* is limited to sawn wood production (SHIMIZU; SEBBENN, 2008).

According to Kronka *et al*. (2005), the regions with the best conditions for *P. patula* development are in the Serra da Mantiqueira, a mountain range that extends across the three states of São Paulo, Minas Gerais and Rio de Janeiro. Grown in suitable regions, it can reach a mean annual increment (MAI) of 40 m^3 ha^{-1} $year^{-1}$ in a rotation of 30 years, higher than other *Pinus* species, however, the average pine productivity in Brazil in 2022 was 30.9 m^3 ha^{-1} $year^{-1}$ (INDÚSTRIA BRASILEIRA DE ÁRVORES - IBÁ, 2022). In this sense, it is interesting to study wood properties of *P. patula* to maximize its uses.

The younger *P. patula* wood presents desirable characteristics for cellulose and paper production based on its calculated quality parameters. Although this species has the potential to adapt to climatic and environmental conditions, its use is restricted to segments of the paper industry (MODES *et al*., 2019). However, older. *Pinus patula* has the potential to replace *P. taeda* wood for lamination (TAVARES *et al*., 2018). Wood quality of *P. patula* is only sparsely studied in Brazil, except for radial variation in wood properties and anatomy, making it difficult to identify its potential industrial use.

In the present study, we characterize the variation of physical, mechanical, and anatomical properties *P. patula* wood from different provenances and comparing them to *P. elliottii* var. *elliottii*, specie with a certain tradition of use by the Brazilian wood industry.

MATERIAL AND METHODS

Study area and sampling

In this study, seeds of four different populations from *P. patula* were collected in Mexico, and one population from *P. elliottii* var. *elliottii* was collected in 1983 at the Estação Experimental de Itapetininga in the municipality of Itapetininga, São Paulo State, Brazil (23º42’ S, 47º57’ W, elevation 500m, (Table 1). Then, seedlings were produced and planted in 1984 at the Estação Experimental de Itapeva (EEI) in the municipality of Itapeva, São Paulo State, Brazil (24º02’S, 49º06’W, elevation 740 m, INSTITUTO DE PESQUISAS AMBIENTAIS, 2023) (Figure 1). The EEI climate is tropical type (Cfa), temperate, with mild summer and average annual precipitation of 1,289 mm, and the annual average temperature is 18.9°C (ALVARES *et al*., 2013). The soil is typical Dystrophic Red Latosol (LVd) and slightly hilly topography.

Then, seedlings were produced and all planted in Itapeva, São Paulo, Brazil (Table 1).

Table 1. Collection sites of *Pinus patula* and *Pinus elliottii* var. *elliotti*, mean of the diameter at breast height (DBH), and total height (TH) of tree samples.
Tabela 1. Locais de coleta de *Pinus patula* e *Pinus elliottii* var. *elliotti*, média do diâmetro à altura do peito (DBH) e altura total (TH) das árvores amostradas.

Treatment	Species	Provenance	Country	Altitude (m)	DBH (cm)	TH (m)
Provenance 1	*P. patula*	Huauchinango, Pueblo	Mexico	2030	32.18	27.23
Provenance 2	*P. patula*	Zacualtipán, Hidalgo	Mexico	2000	32.33	25.87
Provenance 3	*P. patula*	La Venta, Q,f.	Mexico	2500	29.26	26.26
Provenance 4	*P. patula*	Tianguistenango, Hidalgo	Mexico	1700	30.09	26.81
Control	*P. elliottii*	Itapetinga SP	Brazil	500	32.18	30.61

The experiment was installed in a spacing level of 3 m x 2 m and randomized block design. It was composed of five treatments, distributed in five replications, with 25 plants per rectangular plots (5 x 5), and nine useful plants in the center of the plot.

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ISSN 1982-4688
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Initially, a forest inventory of the populations was carried out, thus obtaining the mean DBH (diameter at breast height, 1.30cm from the ground) and total height (TH, m) of the populations (Table 1). For the study of wood properties, 31-year-old *Pinus patula* and *Pinus elliottii* var. *elliotti*. wood was collected from 25 trees, five from each species/provenance, selected within each block among useful plants.

For mechanical tests, a log (1.10 m length) was cut at the region immediately above breast height (DBH) from each tree. From each log, a central board (7 cm thick) was sawed. From these boards, three battens of 4 cm × 4 cm × 1 m were removed, as representative of positions 0, 50 and 100% of the log radius. Specific samples were removed from the battens for each mechanical test.

In the evaluation of the physical and anatomical properties of the sampled trees, 7 cm thick discs were removed from the DBH, properly identified, and, subsequently, measured for their diameter lengths with and without bark. From the discs, a sample block was removed from the pith to the bark. In this block, five points representing positions 0, 25, 50, 75 and 100% of the disc radius were sampled.

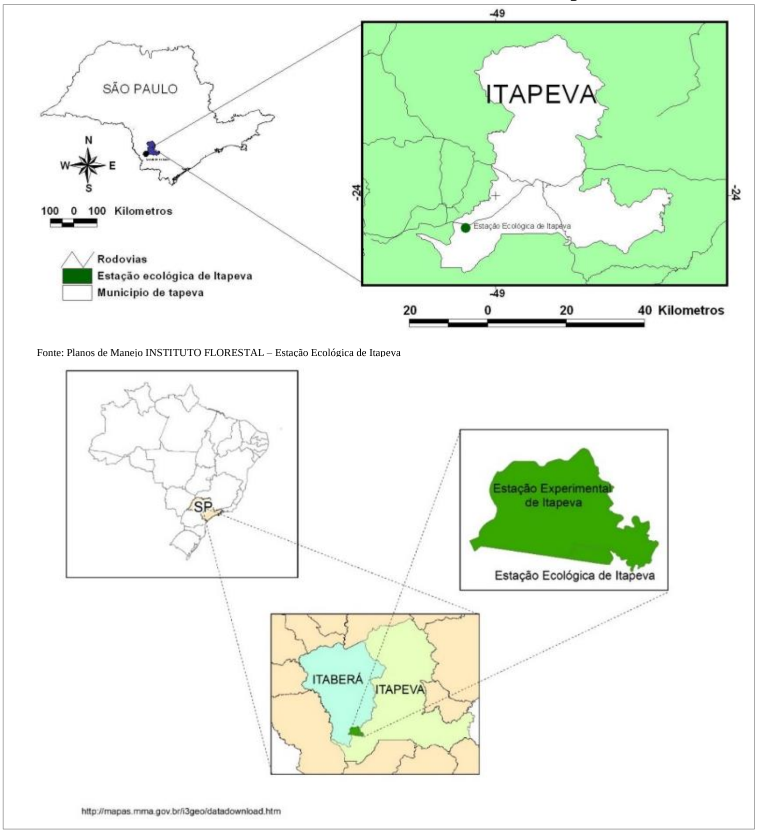

Figure 1 - Location of the planting site in the Estação Experimental de Itapeva, São Paulo State, Brazil.
Figura 1 - Localização da área de instalação do plantio na Estação Experimental de Itapeva, São Paulo, Brasil.

Wood properties

Mechanical properties were determined at 12% of wood moisture content, and mechanical tests (compression strength parallel to the grain, shear strength parallel to grain, modulus of elasticity, and modulus of rupture) were carried out with the aid of a universal mechanical machine.

NBR 7190 standard (ABNT, 1997) was used for analyzing the following properties: apparent density (AD), compression strength parallel to the grain (f_{c0}) with a stress application rate of 10 MPa.min^{-1}, shear strength parallel to the grain (f_{v0}) with some modifications, modulus of elasticity (MOE) and modulus of rupture (MOR) nevertheless some adaptations were made. NBR 11941 ABNT (2003) was used to obtain basic density (BD), according to the hydrostatic balance method.

Wood anatomy

Samples were taken from sampled discs to carry out analyses of macro- and microscopic wood structure. Wood dissociation was prepared according to Franklin (1945), which made it possible to measure tracheid dimensions using the methodology recommended by IAWA (2004). Thus, using a trinocular microscope with a camera, images of slides were obtained, and using "Image Pro-Plus" software, tracheid length and tracheid wall thickness were measured.

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Statistical analyses

In the analysis of variance aiming to detect differences between species, the F test was used according to the experimental design in randomized blocks in plots entirely at random to analyze the mechanical, physical, and anatomical properties. The Tukey test was applied whenever a significant difference was observed, at the level of 5% probability of some treatment in the F test. For radial variation analyses, descriptive statistics were used for the mechanical properties, anatomical and physical properties and correction test and graphics.

RESULTS

Apparent density, basic density, tracheid length and modulus of rupture differed significantly between provenances (Table 2). No statistically significant difference among *P. patula* provenances and *P. elliottii* var. *elliotti* was found for tracheid wall thickness, compression strength parallel to the grain, shear strength parallel to the grain and modulus of elasticity in static bending (Table 2).

Table 2. Analysis of variance of physical and mechanical wood properties, and tracheid features of 31-year-old *Pinus patula* and *Pinus elliottii* var. *elliotti*.

Tabela 2. Análise de variância das propriedades físicas, propriedades mecânicas e características das traqueídes da madeira de *Pinus patula* e *Pinus elliottii* var. *elliotti* aos 31 anos.

		Mean squares							
Causes of variation	DF	AD ($g.cm^{-3}$)	BD ($g.cm^{-3}$)	TL (mm)	TWT (µm)	f_{c0} (MPa)	f_{v0} (MPa)	MOR (MPa)	MOE (MPa)
Block	4	0.0061	0.0053	0.0448	2.2306	21.18	2.5113·	21015	3025225
Species	4	0.0086*	0.0063*	0.5432*	0.6143$^{n.s.}$	23.28$^{n.s.}$	3.0550$^{n.s.}$	330.18*	8793683$^{n.s.}$
Residual	16	0.0018	0.0008	0.1146	1.0014	13.00	2.9723	80.77	4528705
CV_e (%)		7.76	5.02	8.51	11.47	10.59	12.64	11.45	22.41
Pinus patula	mean	0.53	0.49	4.26	8.34	34.23	13.46	77.83	9941
Pinus elliottii	mean	0.61	0.57	3.50	9.26	33.17	14.36	81.03	7709

Apparent density (AD), basic density (BD), tracheid length (TL), tracheid wall thickness (TWT), compression strength parallel to the grain (f_{c0}), shear strength parallel to the grain (f_{v0}), modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending. *Significant at 5% level of significance; n.s. = not significant and CV_e= coefficient of experimental variation. DF= degrees of freedom.
Densidade aparente (AD), densidade básica (BD), comprimento da traqueíde (TL), espessura da parede da traqueíde (TWT), compressão paralela à grã (fc0), cisalhamento paralelo à grã (fv0), módulo de ruptura (MOR) e módulo de elasticidade (MOE) na flexão estática. *Significativo ao nível de 5% de significância; n.s. = não significativo e CVe= coeficiente de variação experimental. DF = graus de liberdade.

The basic density of Provenance 2 showed less variation in the pith-bark direction than other materials under study (Figure 2A).

Compression parallel to the grain and modulus of elasticity (MOE) in static bending were greater for *P. patula*, but shear strength in parallel to the grain and modulus of rupture (MOR) were greater for *P. elliottii* (Table 2).

For mechanical properties, only MOR differed significantly among provenances. Provenance 4, had the highest value and Provenance 3 the lowest (Table 3). In general, Provenance 4 had the highest mechanical strength, but it did not differ significantly from other provenances for all mechanical properties (Table 3).

Pearson's correlation analyses were performed (Table 4). All properties show a significant relationship with radial position (Table 4).

Tracheid length and tracheid wall thickness also increased significantly towards the bark (Figure 2B and 2C). For tracheid wall thickness, none of the species presented typical radial variation behavior (Figure 2C). Only PPLV tended to increase towards the bark, stabilizing close to 50% of the log radius (Figure 2C).

For radial variation of apparent density, an increase from the pith to the bark was found for all species (Figure 3A). Only for Provenance 3 did a higher density value occur in the central position in relation to pith. For all other species, the radial variation pattern was the same (Figure 3A).

The values of radial variation for compression parallel to the grain increased from the pith-bark for all species (Figure 3B). The behavior was the same for almost all species with the exception of Provenance 4 of *P. patula*, which showed a proportional increase towards the bark, while in the other species, the increase was not in the same proportion (Figure 3B).

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Pinus elliottii showed a more homogeneous behavior, from pith-bark, for tracheid length (Figure 2b). Provenance 1 showed a greater variation toward the bark (Figure 2B). Tracheid length of *P. elliotti* and Provenance 4, *P. patula* tended to stabilize close to 75% of the log radius (Figure 2B).

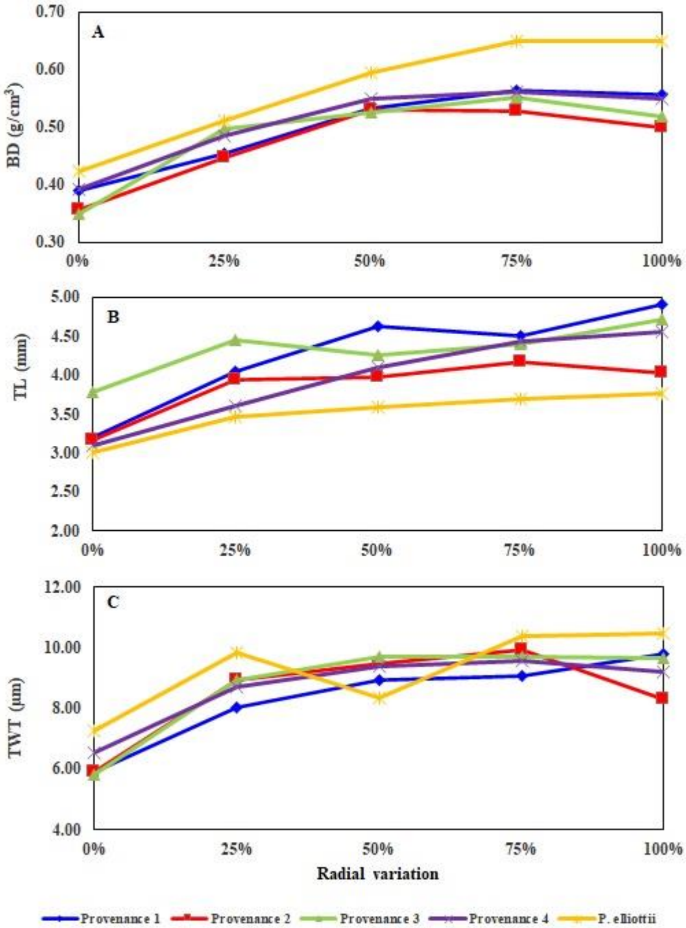

Figure 2 - BD = basic density (A), TL = tracheid length (B), TWT = tracheid wall thickness (C) according to wood radial position *Pinus patula* and *Pinus elliottii* var. *elliotti* at 31-year-old.

Figura 2 - BD = densidade básica (A), TL = comprimento da traqueíde (B), TWT = espessura da parede da traqueíde (C) de acordo com a posição radial da madeira de *Pinus patula* e *Pinus elliottii* var. *elliotti* aos 31 anos.

Table 3 - Average of physical and mechanical properties, and tracheid features of 31-year-old *Pinus patula* and *Pinus elliottii* var. *elliotti*.

Tabela 3 - Média das propriedades físicas e mecânicas, e características das traqueídes de *Pinus patula* e *Pinus elliottii* var. *elliotti* aos 31 anos.

Treatment	AD ($g.cm^{-3}$)	BD ($g.cm^{-3}$)	TL (mm)	TWT (µm)	f_{c0} (MPa)	f_{v0} (MPa)	MOR (MPa)	MOE (MPa)
Provenance 1	0.52 b	0.50 b	4.26 a	8.34 a	32.57 a	12.69 a	77.07 ab	9450 a
Provenance 2	0.50 b	0.47 b	3.86 ab	8.51 a	33.17 a	13.23 a	75.53 ab	10472 a
Provenance 3	0.54 ab	0.49 b	4.32 a	8.76 a	33.39 a	13.38 a	68.29 b	8797 a
Provenance 4	0.57 ab	0.51 b	3.96 ab	8.68 a	37.84 a	14.53 a	90.44 a	11044 a
Control	0.61 a	0.57 a	3.50 b	9.26 a	33.17 a	14.36 a	81.03 ab	7709 a

Apparent density (AD), basic density (BD), tracheid length (TL), tracheid wall thickness (TWT), compression strength parallel to the grain (f_{c0}), shear strength parallel to grain (f_{v0}), modulus of rupture (MOR) and modulus of elasticity (MOE). Means followed by different letters in the same column differ among themselves (at 5% level of significance). Densidade aparente (AD), densidade básica (BD), comprimento da traqueide (TL), espessura da parede da traqueíde (TWT), compressão paralela à grã (fc0), cisalhamento paralelo à grão (fv0), módulo de ruptura (MOR) e módulo de elasticidade (MOE). As médias seguidas de letras diferentes na mesma coluna diferem entre si (ao nível de 5% de significância).

Table 4 - Pearson's correlation coefficient obtained for the relation among the variables studied and the radial position.
Tabela 4 - Coeficiente de correlação de Person obtido entre as propriedades da madeira e suas posições radiais.

	Pearson's correlation coefficient							
	AD	BD	TL	TWT	f_{c0}	f_{v0}	MOR	MOE
Radial position (%)	0.71	0.67	0.72	0.47	0.85	0.65	0.84	0.79

Apparent density (AD), basic density (BD), tracheid length (TL), tracheid wall thickness (TWT), compression strength parallel to the grain (f_{c0}), shear strength parallel to grain (f_{v0}), modulus of rupture (MOR) and modulus of elasticity (MOE).** significant at level 1% of significance.
Densidade aparente (AD), densidade básica (BD), comprimento da traqueíde (TL), espessura da parede da traqueíde (TWT), compressão paralela à grã (fc0), cisalhamento paralelo à grão (fv0), módulo de ruptura (MOR) e módulo de elasticidade (MOE).** significativo ao nível de 1%.

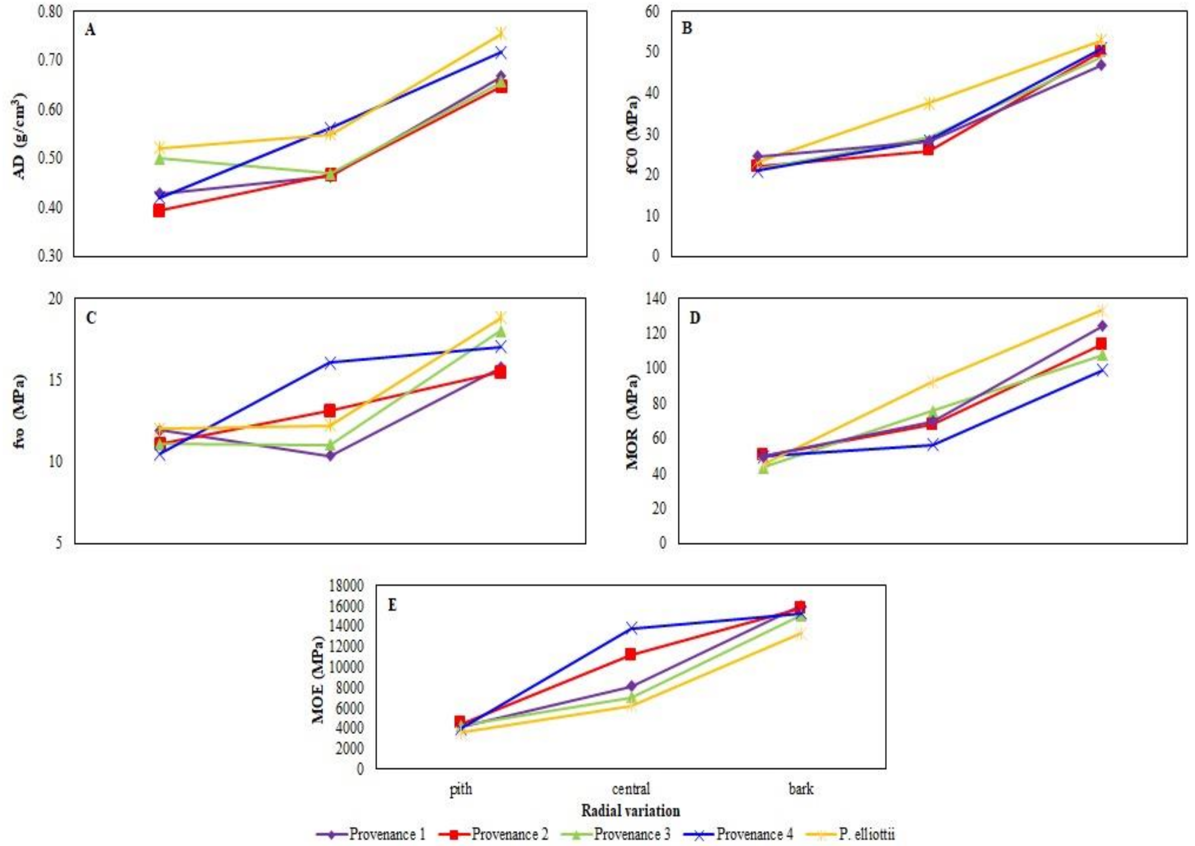

Figure 3 - AD = Apparent density (A), f_{c0} = compression strength parallel to the grain (B), f_{v0} = shear strength parallel to grain (C), MOR (D) and MOE (E) according to wood radial position *Pinus patula* and *Pinus elliottii* var. *elliotti* at 31-year-old.
Figura 3 - AD = Densidade aparente (A), fc0 = compressão paralelo à grã (B), fv0 = cisalhamento paralelo à grã (C), MOR (D) e MOE (E) conforme a posição radial da madeira de *Pinus patula* e *Pinus elliottii* var. *elliotti* aos 31 anos.

DISCUSSIONS

Variation between species

In general, *P. elliottii var. elliottii* wood is denser than that of *P. patula*. This result was confirmed for both apparent and basic density (Table 3). For apparent density and basic density, *P. elliottii* species presented the highest values among all the analyzed species and Provenance 2 the lowest values among all the analyzed species, indicating variation between these two species under study (Table 3). The thickness of the tracheid wall did not show significant variation between the provenances (Table 3).

The results obtained for density of *P. patula* wood are important because many studies have shown that higher values of wood density are strongly associated with favorable properties of strength, stiffness, hardness and easier to saw wood (KAMALA *et al*., 2014).

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P. patula reached 0.53 g.cm^{-3} of medium apparent density and 0.61 g.cm^{-3} for *P. elliottii* (Table 2). The average basic density values of *P. patula* were 0.49 g.cm^{-3} and 0.57 g.cm^{-3} for *P. elliottii* (Table 2).

According to these values, *P. elliottii* belongs to resistance class C30, and *P. patula* belongs to class C25, of the wood strength standard of NBR 7190 (ABNT, 1997). *P. patula* showed a higher basic density value of 0.49 g.cm^{-3}, when compared to 0.37 g.cm^{-3} obtained by (MODES *et al*., 2019) but less than the 0.51 g.cm^{-3} value obtained by (GETAHUN *et al*., 2014).

P. patula wood showed a lower value for compression parallel to the grain and a higher MOE than the 28-year-old *P. patula* wood reported by (GETAHUN *et al*., 2014). However, the average value of MOE (9941 MPa) is higher than the one obtained by (WESSELS *et al*., 2014) for 20-year-old *P. patula* (6423 MPa), a value deemed to be much lower than that required for use of structural wood in South Africa in these authors' opinion.

Physical and mechanical properties presented by *P. patula* confirm that its wood can be included in Class C25 (conifers), according to NBR 7190, and thus suitable for use in civil construction in accordance with these conditions (ABNT, 1997). The mechanical strength of *P. patula* wood was greater than what some authors found in their studies; however, this is from the influence of age on wood strength, mainly from the age of 20 years on (MUSTEFAGA *et al*., 2019).

For comparative purposes, we have results from the literature on the mechanical properties of *Pinus* spp. (Table 5).

Table 5. Average results of mechanical properties of wood from tropical *Pinus* spp. for comparative purposes (data obtained from the literature).

Tabela 5. Resultados médios de propriedades mecânicas de madeira de espécies de *Pinus* tropicais para efeito comparativo (dados obtidos na literatura).

Species	Age (years)	f_{c0} (MPa)	f_{v0} (MPa)	MOR (MPa)	MOE (MPa)	Reference
Pinus patula	12	31	6.79	45.3	9003	MUSTEFAGA *et al*., 2019
P. caribaea var. *caribaea*	17	28	9.10	58	6060	TRIANOSKI *et al*., 2014
P. caribaea var. *hondurensis*	17	34	10.49	62	7106	TRIANOSKI *et al*., 2014
P. chiapensis	17	33	8.72	59	7293	TRIANOSKI *et al*., 2014
Pinus maximinoi	17	37	11.37	70	8943	TRIANOSKI *et al*., 2014
Pinus oocarpa	17	39	11.95	70	7943	TRIANOSKI *et al*., 2014
Pinus tecunumanii	17	39	11.42	71	8943	TRIANOSKI *et al*., 2014
Pinus caribaea var. bahamensis	17	30	10.64	65	7187	TRIANOSKI *et al*., 2014

Compression strength parallel to the grain (f_{c0}), shear strength parallel to grain (f_{v0}), modulus of rupture (MOR) and modulus of elasticity (MOE). Compressão paralela à grã (fc0), cisalhamento paralelo à grão (fv0), módulo de ruptura (MOR) e módulo de elasticidade (MOE).

In general, it can be verified that average values of mechanical properties obtained from *P. patula* and *P. elliotti* provenances are greater than most of the various species compared, however the trees in the present study are older than the studies referenced in the tables (Tables 2 and 5).

The modulus of elasticity evaluated in the compression tests parallel to the fibers and static bending, although it does not provide real information on the behavior of the wood material, in general it is verified that: 1) the higher the modulus of elasticity, the higher the resistance of the wood; 2) the higher the modulus of elasticity, the lower the deformity of the wood; 3) the lower it is, the worse the qualities of the wood for civil construction purposes. It is verified that the age of the wood and the species directly influence the modulus of elasticity for the species of *Pinus*.

Concerning anatomical features, the axial tracheids of *Pinus* spp., length (mm), width (µm), diameter (µm), wall thickness (µm), respectively: *Pinus caribaea* var. *hondurensis* (4, 8 and 11 years): 3.2, 4.5 and 4.8; 60, 64.8 and 65; 40, 25 and 26; 8.9, 12.9 and 11.3 (CORRÊA; BELLOTE, 2011); *Pinus patula* (14 years): 2.3; 40.3; 29.9; 5.4 (MODES *et al*., 2019); *Pinus elliottii* (19 years): 3.3; 57.3; 25.6; 11.81 (AMARAL, 2014); *Pinus taeda* (21 years): 3.5; 40.5; 27.7; 6.4 (VIVIAN *et al*., 2015).

Despite tracheids dimensions of *P. patula* in the present study (tracheid length of 4.26 mm and tracheid wall thickness of 8.34 µm, Table 2), being higher than those presented by (MODES *et al*., 2019) *e.g.*, 2.37 mm and 5.49 µm, respectively. In MODES *et al*. (2019) the wood came from 14-year-old trees and the wood in the present study came from 31-year-old trees. According to MODES *et al.* (2019), *P. patula* wood showed good potential of quality indicators for paper production, which is within the values found for the *P. taeda* species traditionally used in this segment.

Differences in cell dimensions may explain why wood density of *P. elliottii* is higher than that of *P. patula* (Table 2). From wood density value, KAMALA *et al.* (2014) suggests that wood of *P. patula* provides a good material for pulp and paper. This result, in addition to tracheid data, reinforces the potential application of *P. patula* wood in the paper and cellulose industry, however, obviously practical tests need to be applied to certify the wood quality on an industrial scale.

Radial variation

For basic density, variations toward the bark from *P. patula* provenances are more homogeneous than those of *P. elliottii* (Figure 2A). Most basic density of the species tended to stabilize close to the 75% position of log radius, indicating a higher proportion of adult wood in relation to juvenile wood, starting from point of transition (Figure 2A). This can be explained by the presence of tracheid with a larger diameter and with thinner walls produced during cambial activity, resulting in low wood density. However, this trend is reversed as cambium rate matures, generating cells with thicker cell walls, increasing density (TAVARES *et al*., 2020). *P. patula* shows radial variation in basic density, humidity, and wood shrinkage, and these properties tend to decrease close to the pith, except for moisture content, which increases in the bark-to-pith direction (JUIZO *et al*., 2015).

However, the tracheid length was longer for Provenance 1 and shorter for *P. elliottii*. Tracheid wall thickness plays a key role in wood quality due to its strength, as it varies between species and locations and between and within trees. It is also highly correlated with wood density (NAZARI *et al*., 2020). *P. elliottii* presented the highest values of tracheid wall thickness, but they were not enough to differentiate it from the other provenances (Table 3).

MOR presented a similar behavior in compression strength parallel to the grain for all species, increasing in the pith-bark direction where treatment 4 also had the same behavior (Figure 3D). MOE increased toward the bark for all species, but the behavior was not the same for all provenances in that treatment 2 and Provenance 4 presented an increase from the pith to the bark, which was more abrupt at the center, but less so from that point onward (Figure 3E).

Shear strength parallel to grain also increased towards the bark for all species, but the variation was not the same for all provenances since the increase in Provenance 2 and Provenance 4 was more pronounced in the central position than that from central position to the bark (Figure 3C).

In 36-year-old *P. taeda* wood, the transition from juvenile to mature wood occurred gradually, showing a transition zone from the 10th to 15th growth ring, with mature wood beginning to form from the 16th growth ring onward (TOPANOTTI *et al*., 2021).

Variations in growth ring, wood density, and increase of basal area in pine species may be influenced by climatic changes (precipitation and temperature), mainly in times of wide swings in variations, but they could also be affected by age of cambium (YU *et al*., 2014). Therefore, knowledge of radial variation of the properties is essential for determining the use of wood of any species, in our case, *Pinus* wood.

As expected, almost all properties increased from the pith to the bark. This resulted from a higher percentage of adult wood in relation to juvenile wood, as also observed by (WESSELS *et al*., 2014). Therefore, in order to obtain trees with higher proportions of adult wood, a longer cutting cycle should be used for wood from older trees for structural purposes. Wood samples that show good mechanical strength, at an earlier transition age, are indicative that this species can produce good quality wood, even in young trees (LOURENÇON *et al*., 2014).

Based on the results obtained in this research, different provenances of *P. patula* have potential for industrial use of wood, mainly trees of Provenance 4 from Tianquistenango Hidalgo, which presented the best results of mechanical strength, as a good indicator for use in construction. Similar results were obtained for *P. patula* wood, in South Africa, and it was considered ideal for civil construction use (KAMALA *et al*., 2014).

However, the lack of significant variation in strength among the four provenances of *P. patula* may be important for its use in civil construction to meet the demand for uniform wood products from a sustainable provenance. Well, there are cases where it is necessary to use wood with the most uniform characteristics possible to produce quality products in a sustainable way. Additionally, according to results in Africa by TADESSE & FONSECA (2022), *P. patula* presents very fast-growing in many countries, then wood is mainly used for timber and firewood. However, the increase in forest area and its maintenance in good conditions contribute to the Sustainable Development Goals (SDG) of United Nations Agenda 2030 with positive impacts in SDG 1 (income to fight poverty), SDG 6 (freshwater), and SDG 13 (carbon capture). In this context, the planting in Brazil of reforestation or native species also meets the agenda of United Nations mentioned above and can give a gain to the Brazilian forestry sector.

REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

CONCLUSIONS

- We found no difference between studied materials for tracheid wall thickness, compression strength parallel to the grain, shear strength parallel to grain and modulus of elasticity. *Pinus elliottii* showed shorter tracheid length compared to *Pinus patula* provenances.
- The interaction between the properties of the wood from the provenances x radial position was significant, demonstrating to have dependence among these variables.
- All properties evaluated showed an increase towards the bark, and from position 75%, the values of properties tended to stabilize, as an indication of the greater presence of adult wood. Based on the results of this research, it is possible to conclude that *Pinus patula* may be best suited for construction.
- The little significant variation between the properties of the wood from the *Pinus patula* provenances can be beneficial for the use of wood that requires greater homogeneity of its properties.
- In general, the provenances of *Pinus patula* present lower values of density, mechanical strength and cellular dimensions than *Pinus elliottii*, which may be an indication for industrial use that requires less physical and mechanical strength.

ACKNOWLEDGMENTS

The authors thank Sonia Regina Godoi Campião and Juraci Barbosa (Instituto de Pesquisas Ambientais - IPA), and Luis Eduardo Facco (Esalq – USP) for laboratory assistance. We are grateful to the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (National Council for Scientific and Technological Development for the grants to Karen Rizzato Bermúdez, Patricia Gurgel Vicentin and Rafaela Bergamo.

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