Journal of Tropical Forest Science 36(4): 424–433 (2024)
https://doi.org/10.26525/jtfs2024.36.4.424
ISSN: 0128-1283, eISSN: 2521-9847

GENETIC CONTROL OF TRAITS RELEVANT TO SOLID-WOOD USE IN *EUCALYPTUS PELLITA*

Kien ND[1,*] & Bien TH[2]

[1]*Institute of Forest Tree Improvement and Biotechnology, Vietnamese Academy of Forest Sciences*
[2] *Forest Science Institute of South Vietnam, Vietnamese Academy of Forest Sciences*

**nguyen.duc.kien@vafs.gov.vn*

Submitted March 2024; accepted July 2024

Genetic control of wood properties relevant to solid-wood utilisation was evaluated in an 11-year-old progeny trial of *Eucalyptus pellita* at Pleiku, central Vietnam. Wood samples taken from total of 160 trees from 40 open-pollinated families chosen randomly from five seed sources were evaluated for wood basic density (BD), dimensional shrinkage, modulus of elasticity (MoE) and modulus of rupture (MoR). Differences among the seed sources were not significant for these wood traits. Narrow-sense heritabilities were moderate to high, ranging from 0.33 to 0.54, with coefficients of additive genetic variation ranging from 4.5–11.8%, except for longitudinal shrinkage, for which heritability was non-significant. Genetic correlations between BD and the other wood properties were not significant, excepting a positive relationship between BD and MoR. The genetic correlations between diameter at breast height and wood properties, and between shrinkage traits and MoE/MoR were non-significant. Breeding to improve these wood properties should be feasible and compatible with improving growth

Keywords: Genetic correlation, heritability, wood basic density, modulus of elasticity, modulus of rupture, dimensional shrinkage

INTRODUCTION

Eucalyptus is a major planting genus in Vietnam with total plantation area in 2020 estimated at about 300,000 ha (Arnold et al. 2022). Major eucalypt taxa are *Eucalyptus urophylla* and selected clones of its interspecific hybrid combinations (*E. urophylla* × *grandis*, *E. urophylla* × *pellita* and *E. urophylla* × *tereticornis*).

Eucalyptus pellita F. Muell. is naturally distributed in the lowland tropic of Northern Queensland, Australia, the south-west of Papua New Guinea and adjacent regions of Papua Province, Indonesia. It is fast growing and has good resistance to pests and diseases (Harwood 1998). Timber from natural stands is rated as easily sawn and processed and suitable for construction, panelling and flooring (Bootle 1983). Due to its high productivity, good adaptability to humid tropical climates and good resistance to pests and diseases, including foliar leaf blights, *E. pellita* and its interspecific hybrids have replaced large areas of *A. mangium* plantations in Malaysia and Indonesia (Brune 2023, Zaiton et al. 2018).

Eucalyptus pellita was first introduced to Vietnam in the 1990s. Species and provenance trials confirmed that this species grew best in tropical climates on deep, well drained soils in the Southeast, Central Coastal and Central Highlands regions of Vietnam at altitudes below 800 m (Kha 2003). The interspecific hybrid between *E. pellita* and *E. urophylla* shows promising growth in cooler areas in the North of Vietnam (Thinh 2011, Kien 2015, Son 2023). *Eucalyptus pellita* is not yet planted commercially in Vietnam as a pure species but could become so in the future due to its good adaptability in high-rainfall regions in the south of the country.

Vietnam's wood-based furniture industries exported products valued at $US10.84 billion in 2022 (Cam et al. 2023) and about 75% of wood materials for the industry are supplied from Vietnamese plantations (Hung et al. 2020). However, eucalypt wood grown in Vietnam on short rotations has poor dimensional stability,

©Forest Research Institute Malaysia

creating challenges for its use in solid wood applications (Trung 2015). Eucalypt logs and flitches mainly from Uruguay, South Africa, Papua New Guinea and Brazil are currently imported into Vietnam (Vietnam Association of Wood and Forest Products 2021).

Evaluation of the wood properties of plantation-grown *E. pellita* in Malaysia has focused on the potential for veneer and solid wood applications. Processing of 7–9-year-old logs from Sarawak revealed that log end-splitting and knot-related defects were problematical for both veneer and sawn timber production, while density, strength, stiffness and hardness of sawn boards were considered sufficient for flooring and furniture applications (Hii et al. 2017). Log end-splitting (Espey et al. 2021) and dynamic Modulus of Elasticity (MoE) of young standing trees (Japarudin et al. 2022) were both shown to be under heritable genetic control when evaluated in *E. pellita* progeny trials in Sabah.

A study of two *E. pellita* progeny trials in Vietnam (Hung et al. 2015) examined traits relevant to pulp quality and wood stiffness. These authors reported moderate to high heritabilities and non-signficant genetic correlations between tree diameter at breast height (Dbh) and NIR-estimated basic density (BD), kraft pulp yield (KPY), MoE and microfibril angle (MFA), suggesting that simultaneous genetic improvement of these traits could be achieved through family and within-family selection. Although small-scale studies in Malaysia (Hii et al. 2017) and Indonesia (Prasetyo et al. 2017) have evaluated wood shrinkage of plantation-grown *E. pellita*, the genetic control of transverse and radial shrinkage and the coefficient of anisotropy, traits which are important for the dimensional stability of furniture and other solid-wood products (Skaar 1988) has not been reported to date.

The aim of our study was to determine whether wood properties of *E. pellita* relevant to solid-wood product quality are under genetic control, and to obtain information that would assist in developing a genetic improvement strategy. We estimated genetic parameters for these wood properties in one of the two *E. pellita* progeny trials previously studied by Hung et al. (2015).

MATERIALS AND METHODS

Materials and sampling strategy

A progeny trial of *E. pellita* was established in 2002 at Pleiku, Gia Lai province, Vietnam (13.95°N, 108.01°E, altitude 780 m, mean annual rainfall 1800 mm and mean annual temperature 23°C) on an eroded, basalt-derived soil. The trial tested 104 open-pollinated families of *E. pellita* from nine seed sources: the Bupul Muting provenance in Irian Jaya, Indonesia; the Goe, Kiriwo, South of Kiriwo and Serisa provenances in Papua New Guinea; three seedling seed orchards in north Queensland, the first at Atherton based on the Bupul Muting provenance, the second at Cardwell and the third at Melville Island based on Bupul Muting and Papua New Guinea provenances; and one Vietnamese plantation seed source of unknown provenance origin established at Bau Bang in southern Vietnam in the early 1990s. A a row-column incomplete block design with eight replicates and four trees per family row plot was employed, with initial spacing of 4 m between planting rows and 1.5 m between trees along the rows. The trial was thinned phenotypically at the age of five years, retaining the best two trees per plot, and at eight years to retain the best tree per plot, with trees selected for superior growth and stem/branch form.

At age eleven years, prior to sampling for wood properties assessment, diameter at breast height (Dbh) of all surviving trees was measured. A total of 40 families were chosen at random from five of the seed sources (Table 1), and four trees per family (one from each of four of the replicates) were randomly selected for measurement of wood properties.

The selected trees were felled by chainsaw with a cut at 0.3 m tree height. One disc 50 mm in thickness was cut from the felled stem at a position corresponding to 1.3 to 1.35 m tree height to determine basic density, and samples from the 1.0 m billet from 0.3 m tree height to 1.3 m tree height were prepared for measurement of the other wood traits.

A defect-free board, 20 mm in width, was cut from each 1.0 m billet along the east-west axis from pith to bark. Samples midway between the cambium and the pith sized at 20 mm (tangential) × 20 mm (radial) ×

Table 1 Overall mean, seed source mean and statistical significance between and within seed sources of Dbh and wood properties of *Eucalyptus pellita* at 11 years

Provenance	Lat	Long (E)	Alt (m)	Dbh (cm)	BD (g cm^{-3})	S_T (%)	S_R (%)	S_L (%)	T/R	MoE (GPa)	MoR (MPa)
Atherton SSO (6 families)	17°15'S	145°50'	760	19.5 (17.7–21.7)	0.57 (0.55–0.60)	4.8 (4.2–5.3)	3.3 (2.8–3.9)	0.14 (0.10–0.17)	1.5 (1.4–1.7)	20.3 (19.6–21.1)	195.2 (178.6–212.3)
Bau Bang (7 families)	11°16'N	106°37'	35	18.2 (16.2–19.6)	0.59 (0.56–0.64)	5.3 (4.3–6.4)	3.5 (2.9–4.0)	0.12 (0.09–0.15)	1.5 (1.4–1.8)	21.3 (20.2–22.3)	195.4 (185.8–204.8)
Bupul Muting (7 families)	07°15'S	140°36'	40	18.3 (16.2–19.4)	0.59 (0.56–0.62)	5.1 (4.6–5.6)	3.4 (3.0–3.9)	0.14 (0.10–0.17)	1.5 (1.4–1.8)	21.3 (20.2–22.5)	200.6 (185.1–216.0)
Melville SSO (8 families)	11°34'S	130°34'	50	18.0 (16.1–19.6)	0.59 (0.56–0.61)	5.2 (4.3–6.0)	3.1 (2.6–3.7)	0.15 (0.11–0.18)	1.6 (1.4–2.0)	21.3 (20.1–22.4)	194.3 (178.2–210.7)
Serisa (12 families)	08°36'S	141°26'	45	17.8 (15.7–20.1)	0.58 (0.54–0.63)	4.8 (4.1–5.6)	3.1 (2.5–3.6)	0.14 (0.09–0.18)	1.6 (1.4–2.0)	20.3 (18.5–22.0)	185.8 (151.8–220.1)
Mean				18.3	0.58	5.0	3.3	0.14	1.6	20.9	194.3
Fpr (between seed sources)				0.158	0.478	0.055	0.184	0.914	0.196	0.01	0.089
Fpr (within seed sources)				0.657	0.021	0.019	0.050	0.736	0.016	0.355	0.011

Dbh = diameter at breast height, BD = wood basic density, S_T = tangential shrinkage, S_R = radial shrinkage, S_L = longitudinal shrinkage, T/R = coefficient of anisotropy, MoE = modulus of elasticity, MoR = modulus of rupture; family mean range within seed sources in brackets, Fpr = p-values for F statistics

30 mm (longitudinal), for measurement of dimensional shrinkage traits, were cut from each board using an adjustable table saw. To determine mechanical wood properties, a clear-wood standard specimen with dimensions 20 mm (tangential) × 20 mm (radial) × 320 mm (longitudinal) also positioned midway between the cambium and the pith, was cut from each board in the same way.

Wood basic density assessment

The wood discs were debarked and immediately stored in plastic zip-lock bags, and kept in cool conditions in sealed, ice-cooled boxes prior to density measurement. Basic density was determined using the water displacement method (Olesen 1971), from the fresh volume of the sample (v), estimated by the mass of water displaced on immersion; and oven dry mass (m). Basic density was calculated as BD = v/m.

Wood shrinkage

Sample preparation and measurement of shrinkage in different dimensions followed ISO standard 4469–1981. Samples were soaked in distilled water for 72 hours to ensure moisture content above the fiber saturation point. The dimensions were measured with a digital caliper to the nearest 0.01 mm at the mid-point on each axis of all three principal directions, which were marked for re-measurement. The specimens were subsequently placed in a conditioning chamber at 20 ± 2 °C and 65 ± 5% relative humidity (RH) for 60 days until they reached the equilibrium moisture content (EMC) at air-dry condition (EMC average = 12.4% ± 0.2%). Dimensional differences were used to estimate partial shrinkage (from green to 12% humidity) in the tangential (Tn), radial (Rn), and longitudinal (Ln) dimensions and these values were used to calculate the partial coefficient of anisotropy (Tn/Rn).

Mechanical wood properties

Sample preparation and measurements of MoE and Modulus of Rupture (MoR) followed the International Standards ISO 3133 and ISO 3349. The specimens were placed in a conditioning chamber at 20 ± 2°C and 65 ± 5% relative humidity (RH) for 60 days until they reached approximately 12% equilibrium moisture content (percent of oven-dry weight). Finally, the mechanical properties were tested by three-point bending in the tangential direction, using an INSTRON 5569 universal testing machine. The MoE was calculated using following formula (ISO 3349):

$$\text{MoE} = \frac{P.l^3}{36.b.h^3.f}$$

where P is the load equal to difference between the arithmetic means of the upper (80 kgf - kilogram-force) and lower (20 kgf) limits of loading, in kgf; l is the distance between the supports, 240 mm; b and h are the cross-sectional dimensions in the radial and tangential directions respectively of the test specimen, in mm; and f is the deflection in the net bending equal to the difference between the arithmetic means of the results obtained in measuring the deflection at the upper and lower limits of loading, in mm. The MoR was calculated using following formulae (ISO 3133):

$$\text{MoR} = \frac{3P_{max}.l}{2b.h^2}$$

where Pmax is the breaking load, in kg f; l is the distance between the supports, 240 mm; b and h are the cross-sectional dimensions in the radial and tangential directions respectively of the test specimen, in mm.

Statistical analysis

The statistical analysis was conducted in two steps: (i) univariate analysis, where variance components for each trait were estimated; and (ii) multivariate analysis to estimate variances and covariances between traits. Row and column incomplete block effects within replicates were not modeled because the wood traits under consideration in this study were evaluated using a sub-sample of less than one quarter of the trees in the trial. In the case of Dbh, values of all surviving trees in the trial were used for analysis. The linear mixed-effects model equation for univariate analysis shown as:

$$y = X_B b + X_M m + Z_F f + e$$

where y is the vector of observations of Dbh, Tn, Rn, Ln, MoE and MoR, b is the vector of fixed replicate effects, m is the vector of fixed seed source effect, f is the vector of random family effects, and e is the vector of random residuals. X_B, X_M and Z_F are incidence matrix relating b, m, f and e to y.

Following Hung et al. (2015), the coefficient of genetic relationship (r) was assumed to be 0.33 for open pollinated families on the assumption that there was a proportion of inbreeding and correlated paternity in both seed orchards and natural stands (House & Bell 1996). Additive genetic variance (σ_A^2), phenotypic variance (σ_p^2), within provenance heritability ($\hat{h}^2$), coefficient of additive variation (CV_A) and genetic correlation ($\hat{r}_g$) between traits were estimated as:

$$\sigma_A^2 = \frac{\sigma_f^2}{r} = 3\sigma_f^2$$

$$\sigma_p^2 = \sigma_f^2 + \sigma_e^2$$

$$\hat{h}^2 = \frac{\sigma_A^2}{\sigma_p^2}$$

$$CV_A = \frac{100\sigma A}{\overline{X}}$$, where $\overline{X}$ is mean value of the trait

$$\hat{r}_g = \frac{\sigma A_1 A_2}{\sigma A_1 \sigma A_2}$$

where σ_f^2 is family within provenance variance and σ_e^2 is the residual variance. Standard errors of the estimates of heritabilities and genetic correlations were calculated using a standard Taylor series approximation in the ASREML software (Gilmour et al. 2015).

RESULTS

Variation among and within seed sources

Differences among the five seed sources (two natural provenances, two Australian seedling seed orchards and one local plantation) were not statistically significant for the studied traits, with the exception of MoE ($P < 0.05$), for which seedlot means ranged from 20.3 to 21.3 GPa (Table 1). Family within seed source differed statistically in most of wood properties, except for longitudinal shrinkage and modulus of elasticity (Table 1). Dbh of sampled families within seed source did not differ statistically (Table 1) but significant ($P < 0.001$) when analysis of Dbh included all trees in the trial.

Additive genetic variation

Within-source heritabilities for the studied wood properties were moderate to high, ranging from 0.33 to 0.54, except for longitudinal shrinkage (S_L) which had a heritability of zero (Table 2). The standard errors of the heritability estimates for these wood traits were large, due at least in part to the small sample size. The heritability of Dbh, estimated from all families in the trial, was moderate (0.28 ± 0.12). Coefficients of additive genetic variation were low to moderate (4.5–11.8%).

The genetic correlations between Dbh and wood properties were not significant, except in the case of radial shrinkage where there was a positive, unfavourable genetic correlation of 0.76 ± 0.34, suggesting that selecting for growth would increase radial shrinkage. Genetic correlations between wood basic density and other traits were not significant except for

Table 2 Heritability and coefficient of additive genetic variation of wood properties of *Eucalyptus pellita* at 11 years

Trait	Mean	h^2	CV_A(%)
Wood basic density (g cm^{-3})	0.58	0.46 ± 0.27	5.0
Tangential shrinkage (%)	5.0	0.39 ± 0.28	8.8
Radial shrinkage (%)	3.3	0.37 ± 0.27	11.8
Longitudinal shrinkage (%)	0.14	0.00 ± 0.00	0.0
Coefficient of anisotropy	1.6	0.54 ± 0.28	10.8
Modulus of elasticity (GPa)	20.9	0.33 ± 0.27	4.5
Modulus of rupture (MPa)	194.3	0.52 ± 0.27	8.6
Dbh (cm) (all trees measured)	16.9	0.28 ± 0.12	4.6

that with modulus of rupture (0.58 ± 0.29). Correlations among dimensional stability (S_T, S_R and T/R) and mechanical properties (MoE and MoR) were also non-significant. The genetic correlation between MoE and MoR was strongly positive and favourable, and statistically significant (0.83 ± 0.25).

DISCUSSION

This study focused primarily on the genetic control of dimensional stability, stiffness and bending strength, traits relevant for potential solid-wood products from plantation-grown *E. pellita*. In the eleven-year-old progeny trial that was evaluated, there was substantial additive genetic variation in growth, wood basic density, dimensional stability, stiffness and strength, demonstrating significant potential for breeding to deliver genetic improvement.

Wood properties of *Eucalyptus pellita*

Basic density at age eleven years observed in our study, averaging 0.58 g cm^{-3}, was very similar to that reported at age ten years in a small-scale study of four provenances of *E. pellita* in Indonesia (Yuniarti & Nirsatmanto 2018). The NIR-predicted basic density in our trial at age ten years, reported by Hung et al. (2015), was somewhat higher, averaging 0.66 g cm^{-3}. This may reflect the slightly different sampling method used by these authors, who predicted basic density from outer-wood drill swarf collected at breast height, and applied an NIR calibration which was developed from a range of eucalyt species.

Static MoE determined from clear-wood samples in our study (mean of 20.9 GPa) was about 10% higher than the NIR-predicted MoE (mean of 19.0 GPa) reported by Hung et al. (2015) at age ten years in the same trial. It was likewise about 20–25% higher on average than values measured on air-dried sawn boards prepared from seven- and nine-year old plantatation-grown *E. pellita* trees in Sarawak (Hii et al. 2017). These boards were 2 m in length and 25 × 100 mm in cross section, and defects such as knot traces and cracks may have lowered their stiffness and strength relative to the smaller and defect-free samples used in our study. Our values of MoR, averaging 194 MPa, were similarly some 30–40% higher than those reported by Hii et al. (2017), again, use of boards versus small-clear samples may explain some of this difference.

There were significant differences in MoE among the five seed sources in our study, and significant differences for NIR-predicted basic density and MoE among the nine seed sources in the entire Pleiku trial and for a second trial of the same seed sources in the lowlands of southern Vietnam at Bau Bang reported by Hung et al. (2015). However, the range in seed source means was small (in most cases less than 5% of the site mean) even where differences were significant in either study.

Wood shrinkage from green to air-dry (12.4% moisture content) condition in tangential and radial directions in this study averaged at 5.0% and 3.1%, respectively. These values are similar to those for ten-year-old *E. urophylla* grown at Ba Vi, in northern Vietnam, with corresponding mean tangential and radial shrinkages of 5.8% and 3.7% (Thomas et al. 2009). The coefficient of anisotropy obtained in our study was low (1.6), and slighty less than that obtained for *E. pellita* at age nine years (Prasetyo et al. 2017) or ten years (Yuniarti & Nirsatmanto 2018) in two small-scale studies in Indonesia, these authors obtained mean coefficients of anisotropy of 1.8 and 1.7, respectively. The much smaller magnitude of longitudinal shrinkage, relative to tangential and radial shrinkage (Table 1), made it harder to assess accurately and detect genetic differences.

Overall, our findings, taken with those of previous studies indicate that the basic density, stiffness and strength of *E. pellita* grown on rotations of ten or more years should be adequate for solid-wood products. However, it should be noted that most published studies evaluating variation in *E. pellita* seed sources, including ours, have not tested natural provenances from Queensland, Australia, instead focussing on provenances from Papua New Guinea and adjacent Papua Province in Indonesia. The knowledge of provenance variation in wood properties for *E. pellita* is therefore not yet complete.

With the exception of MoE, differences in wood properties between the five seed sources were not statistically significant. The two seed orchards were derived from one or more of the three natural provenances under study, reducing the chance of any seed source differences being present. Only 6 to 12 families per seed source and 4 trees per family were sampled, making detection of differences difficult. Similarly, to our study, Japarudin et al. (2022) reported significant difference in dynamic MoE between four seed sources of *E. pellita* (natural provenances from Queensland, natural provenances from Papua New Guinea and different seedling seed orchards) at age 3 years.

Additive genetic variation

Narrow-sense heritabilities of wood traits, excepting longitudinal shrinkage, were higher than that of Dbh, a finding consistent with earlier studies on other *Eucalyptus* species (Raymond 2002). The coefficient of additive genetic variation was low, 5% or less, for BD, Dbh and MoE while it was moderate to high (8–12%) for radial and tangential shrinkage and MoR.

High heritability and low coefficients of additive genetic variation for wood density have been globally reported in eucalypt and other forest tree species (Cornelius 1994). Heritabilities for wood density estimated in this study are similar to those in other eucalypt species (Kien et al. 2008, Hamilton & Potts 2008, Henson et al. 2004, Wei & Borralho 1997). Our estimate was double that obtained by Hung et al. (2015) for the entire Pleiku trial using NIR-predicted density ($h^2 = 0.23 \pm 0.13$).

Moderate heritabilities for MoE and MoR obtained in the study agreed well with those reported for other eucalypt species, such as *E. dunnii* (Henson et al. 2004) and *E. urophylla* (Thomas et al. 2009). A very similar estimate for heritability of NIR-predicted MoE of *E. pellita* at age ten years, based on all families in the Pleiku trial, was obtained by Hung et al. (2015).

Heritabilities for tangential and radial shrinkage were moderate and in good agreement with those for other eucalypt species such as *E. grandis* (Bandara 2006), *E. dunnii* (Henson et al. 2004), *E. nitens* (Hamilton et al. 2009), *E. pilularis* (Pelletier et al. 2008) and *E. urophylla* (Thomas et al. 2009). Heritability for longitudinal shrinkage was zero in our study, reflecting minimal genetic variation detected among families. In *Pinus radiata*, Gapare et al. (2008) reported complex patterns of longitudinal shrinkage, with the inner juvenile wood core displaying greater levels shrinkage and some genetic control, but zero heritability in the outerwood of 8–9-year-old trees.

Few studies have reported heritabilities for the coefficient of anisotropy in eucalypts. Non-significant heritabilities of this trait in *E. pillularis*, as determined either from 12 mm increment cores (or wood blocks (zero) were reported by Pelletier et al. (2008). Thomas et al. (2009) similarly reported zero heritability for coefficient of anisotropy in *E. urophylla.* The genetic correlations between Dbh and wood properties were weak and not significant. This is not unexpected given the relatively small sample size of only 40 families employed in our study. White et al. (2007) note that large numbers of families should be sampled for reliable estimates of genetic correlations and that, as with heritabilities, estimates made from a single site are subject to upwards bias. The selective thinnings undertaken in developing the Pleiku trial would also impact the estimation of genetic parameters, particularly those for growth traits.

Our finding of weak and non-significant genetic correlations between wood density and shrinkage differ somewhat from the results of other studies in eucalypt species. Bandara (2006) reported a significant positive genetic correlation between basic density and tangential shrinkage in *E. grandis* (0.67 ± 0.22) but that between density and radial shrinkage was not significant. In contrast, Pelletier et al. (2008) reported significant negative genetic correlation between wood density and an increment core-based measurement of tangential shrinkage (-0.57 ± 0.19) in *E. pilularis.*

The genetic correlation between wood density and MoE was not significant, suggesting that density is not a very strong predictor of stiffness in *E. pellita.* In contrast, the genetic correlation between density and MoR was strong and significant, implying that genetically improving density, an easy-to-measure trait, would also increase wood strength.

Implications for breeding for solid wood production

The rotation age for *E. pellita* for sawn timber production in Vietnam is anticipated to be 10–15 years, depending on site productivity, in order to achieve in thinned stands an average Dbh at harvest in the range of 20–25 cm (Thuyet 2010). As noted above, improvement in wood density, MoE and MoR at this harvest age is probably not required and breeding should focus more on improving shrinkage and the coefficient of anisotropy which are more important for solid-wood products. Tree and log traits including stem straightness, knot-related defects and end-splitting of logs following harvest will also be important, as has been identified for *E. pellita* solid-wood production in Malaysia. Knot-related defects can be reduced through pruning rather than solely through breeding, while end-splitting can be managed by log handling during harvesting (Hii et al. 2017, Yang & Waugh 2001). Log-end-splitting has been shown to be a heritable trait in *E. pellita* (Espey et al. 2021) and other eucalypt species such as *E. grandis* (Bandara & Arnold 2017).

A breeding objective for solid-wood production must integrate improvement of volume and tree form with improvements in target wood traits. Therefore, a selection index that account for relative importance of different traits, level of additive genetic variance and genetic correlations between traits is recommended (Missanjo & Matsumura 2017). Such an index, including stem volume, stem straightness and wood stiffness as assessed by dynamic MoE of standing trees has been proposed for *E. pellita* breeding in Sabah (Japarudin et al. 2022), with the expectation that gain in all three traits would be achieved. The high heritabilities and high coefficients of additive genetic variation for shrinkages and the coefficient of anisotropy obtained in the current study study suggest effective improvement of drying stability could be achieved through a selection index that combined growth and shrinkage traits. Examination of family breeding values for Dbh and wood traits from our study (data not shown) has identifed such families.

Interspecific hybrids between *E. pellita* and other eucalypt species have shown superiority in growth rate and adaptability to various soil and climatic condition compared to parental species in Vietnam (Thinh 2011, Kien 2015, Kien et al. 2023). *Eucalyptus pellita* is typically used as a pollen parent in hybrid combinations with other tropical/subtropical eucalypts because of its larger flower size and hence greater pollen tube vigour result in better crossing success than achieved with the reciprocal combinations (Kien 2015). Pollen will be collected from the best individuals identified in our study, with outstanding breeding values for growth and wood traits, and used in hybrid breeding.

CONCLUSIONS

The present study shows that genetic variation in wood properties relevant to solid wood production is substantial within natural provenances of *E. pellita* originating from Papua New Guinea and Irian Jaya and seedling seed orchards developed from them. Except for longitudinal shrinkage, wood properties are under moderate to high levels of genetic control. The results suggest breeding to improve wood properties in *E. pellita* should be feasible and compatible with improving growth.

ACKNOWLEDGEMENTS

The authors would like to thank the researchers of the Institute of Forest Tree Improvement and Biotechnology, and the Institute of Forest Industry Research of the Vietnamese Academy of Forest Sciences for helping in field data collection, sampling and wood property

Table 3 Genetic correlations between traits of *Eucalyptus pellita* at 11 years

Trait	BD	S_T	S_R	T/R	MoR	MoE
Dbh	-0.18 ± 0.91	-0.20 ± 0.92	0.76 ± 0.34	0.20 ± 0.58	0.16 ± 0.80	0.15 ± 0.16
BD		0.01 ± 0.48	0.26 ± 0.46	-0.43 ± 0.42	0.58 ± 0.29	0.26 ± 0.38
S_T			0.77 ± 0.21	-0.43 ± 0.35	0.19 ± 0.11	0.01 ± 0.01
S_R				-0.21 ± 0.39	0.26 ± 0.16	0.01 ± 0.01
T/R					-0.61 ± 0.33	-0.35 ± 0.37
MoR						0.83 ± 0.25

Dbh = diameter at breast height, BD = wood basic density, S_T = tangential shrinkage, S_R = radial shrinkage; T/R = coefficient of anisotropy, MoE = modulus of elasticity, MoR = modulus of rupture

assessments. The authors would like to thank Dr. Chris Harwood for his detailed review of an earlier draft of the manuscript. We are grateful to the two anonymous reviewers for their revisions and suggestions to improve the quality of the manuscript.

REFERENCES

Arnold R, Midgley S, Stevens P, Phimmavong S, Kien ND & Chen S. 2022. Profitable partnerships: smallholders, industry, eucalypts and acacias in Asia. *Australian Forestry*. 85: 38–53. DOI: 10.1080/00049158.2022.2051261

Bandara K. 2006. Genetic improvement of solid wood product value of subtropical eucalyptus: a case study of *Eucalyptus grandis* and *E. dunni*. PhD thesis, The Australian National University, Canberra.

Bandara K & Arnold R. 2017. Genetic variation of growth and log end-splitting in second-generation *Eucalyptus grandis* in Sri Lanka. *Australian Forestry*. 80: 264–271.

Bootle KR. 1983. *Wood in Australia: Types, Properties and Uses*. McGraw-Hill, Sydney.

Brune A. 2023. Eucalypt alternatives to *Acacia mangium* in wet tropics. *Journal of Tropical Forest Science*. 35: 1–15. https://doi.org/10.26525/jtfs2023.35S.SI.

Cam CT, Anh LK, Phuc TX & Huy TL. 2023. Vietnam Wood and Wood Products Export and Import 2022 and Trend in 2023 (in Vietnamese). https://goviet.org.vn/upload/aceweb/content/BAO CAO VN XK GSPG 2022_FN.pdf

Cornelius J. 1994. Heritabilities and Additive Genetic Coefficients of Variation in Trees. *Canadian Journal of Forest Research*. 24: 372–379.

Espey M, Tahir P, Lee S, Roseley A & Meder R. 2021. Incidence and Severity of End-Splitting in Plantation-Grown *Eucalyptus pellita* F. Muell. in North Borneo. *Forests*. 12: 266. https://doi.org/10.3390/f12030266

Gapare WJ, Ivkovic M, Powell MB, McRae T & Wu HX. 2008. Genetics of Shrinkage in Juvenile Trees of *Pinus radiata* from two test sites in Australia. *Silvae Genetica*. 57: 145–151.

Gilmour AR, Gogel BJ, Cullis BR, Welham SJ & Thompson R. 2015. ASReml

User Guide Release 4.1 Functional Specification, VSN International Ltd, Hemel Hempstead, HP1 1ES, UK

Harwood C. 1998. *Eucalyptus pellita: an annotated bibliography*. CSIRO publishing, Clayton.

Hamilton M & Potts B. 2008. *Eucalyptus nitens* genetic parameters. *New Zealand Journal of Forestry Science*. 38: 102–119.

Hamilton M, Raymond C, Harwood C & Potts B. 2009. Genetic variation in *Eucalyptus nitens* pulpwood and wood shrinkage traits. *Tree Genetics and Genome* 5: 307–316

Henson M, Boyton S, Davies M et al. 2004. Genetic Parameters of Wood Properties in a 9-year-old *E. dunnii* Progeny TriaL in NSW, Australia. Pg 83 in Borralho N, Pereira J, Marques, C et al. (Eds.) *Eucalyptus* in a changing world. 11–15 October 2004, Aveiro.

Hii SY, Ha KS, Ngui ML, Penguang Jnr A, Duju XY & Meder R. 2017. Assessment of plantation-grown *Eucalyptus pellita* in Borneo, Malaysia for solid-wood utilization. *Australian Forestry*. 80: 26–33. DOI: 10.1080/00049158.2016.1272526

House APN & Bell JC 2016. Genetic diversity, mating system and systematic relationships in two red mahoganies, *Eucalyptus pellita* and *E. scias*. *Australian Journal of Botany* 44: 157–174.

Hung TD, Brawner J, Meder R, Lee D, Southerton S, Thinh HH & Dieters M. 2015. Estimates of genetic parameters for growth and wood properties in *Eucalyptus pellita* F. Muell. to support tree breeding in Vietnam. *Annals of Forest Science*. 72: 205–217.

Hung T, Thuy P & Chi D. 2020. Results of implementing the Vietnam Forestry Development Strategy for the period 2006–2020 and Proposed content of the Vietnam Forestry Development Strategy for the period 2021–2030, vision to 2050. Research Report 209. CIFOR, Bogor.

Japarudin Y, Meder R, Lapammu M, Waburton P, Paul-Macdonell P, Brown M & Brawner J. 2022. Developing *Eucalyptus pellita* breeding populations for the solid wood industry of eastern Malaysia. *Journal of Tropical Forest Science* 34: 347–358. https://doi.org/10.26525/jtfs2022.34.3.347

Kha LD. 2003. *Selection, breeding and propagation of some main plantation tree species in Viet Nam* (in Vietnamese). Agricultural Publishing House, Hanoi.

Kien, ND. 2015. *Research on hybridization between Eucalyptus pellita and other eucalypt species in Vietnam* (in Vietnamese). Scientific report, Vietnamese Academy of Forest Sciences, Hanoi.

Kien ND, Jansson G, Harwood C, Almqvist C & Thinh HH. 2008. Genetic variation in wood basic density and pilodyn penetration and their relationships with growth, stems straightness and branch size for *Eucalyptus urophylla* S.T. Blake in Northern Vietnam. *New Zealand Journal of Forestry Science*. 38: 160–175.

Kien ND, Cuong NV, Thinh HH et al. 2023. Research on hybrid breeding of *Eucalyptus*. In Kien ND, Thinh HH & Son L. (Eds.) *Scientific Results of Research on Breeding and Selection of Main Planting Species in the period 2012–2022*. (in Vietnamese). Agricultural Publishing House, Hanoi.

Missanjo E & Matsumura J. 2017. Multiple Trait Selection Index for Simultaneous Improvement of Wood Properties and Growth Traits in *Pinus kesiya* Royle ex Gordon in Malawi. *Forests* 8: 96. doi:10.3390/f8040096

Olesen P. 1971. The water displacement method. A fast and accurate method of determining the green volumn of wood samples. *Forest Tree Improvement*. 3: 1–23

Pelletier M, Henson M, Boyton S, Thomas D & Vanclay J. 2008. Genetic variation in shrinkage properties of *Eucalyptus pilularis* assessed using increment cores and test blocks. *New Zealand Journal of Forestry Science*. 38: 194–210.

Prasetyo A, Aiso H, Ishiguri F et al. 2017. Variations on growth characteristics and wood properties of three *Eucalyptus* species planted for pulpwood in Indonesia. *Tropics*. 26: 59–69.

Raymond C. 2002. Genetics of Eucalyptus wood properties. *Annal Forest Science* 59: 525–531.

Skaar C. 1988. *Wood water relations*. Springer-Verlag, New York.

Son DH. 2023. *Research on breeding and selection of fast growing and desired wood quality of eucalypts for planting for timber production in North West Vietnam* (in Vietnamese). Scientific report. Vietnamese Academy of Forest Sciences, Hanoi.

Thinh HH. 2011. Research on selection and breeding of main planting species in Vietnam (in Vietnamese). Scientific report, Vietnamese Academy of Forest Sciences, Hanoi.

Thomas D, Harding K, Henson M, Kien ND, Thinh HH & Trung NQ. 2009. Genetic variation in growth and wood quality of *Eucalyptus urophylla* in northern Vietnam. ACIAR Project FST/1999/95, ACIAR Canberra,

Thuyet DV. 2010. *Research on silviculture techniques for planting and management of acacia, eucalypt and Caribbean pine plantation for timber production* (in Vietnamese). Scientific Report. Forest Science Institute of Vietnam, Hanoi.

Trung NQ. 2015. *Producing E. urophylla sawn board for furniture making* (in Vietnamese). Scientific report, Vietnamese Academy of Forest Sciences, Hanoi.

Vietnam Association of Wood and Forest Products. 2021. https://goviet.org.vn/bai-viet/brazil-la-thi-truong-cung-cap-go-bach-dan-lon-nhat-cho-viet-nam-9349. (in Vietnamese).

Wei X & Borralho N. 1997. Genetic Control of Wood Basic Density and Bark Thickness and Their Relationships with Growth Traits of *Eucalyptus urophylla* in South East China. *Silvae Genetica*. 46: 245–250

White T, Adams W & Neale D. 2007. Forest Genetics. CABI Publishing, Wallingford.

Yang J & Waugh G. 2001. Growth stress, its measurement and effects. *Australian Forestry*. 64: 127–135.

Yuniarti K & Nirsatmanto A. 2018. Several physical properties of *Eucalyptus pellita* F. Muell from different provenances and sampling position on tree. *Jurnal Penelitian Kehutanan Wallacea*. 7: 151-163.

Zaiton S, Paridah M, Hazandy A & Azim R. 2018. Potential of eucalyptus plantation in Malaysia. *Malaysian Forester*. 81: 64–72.

©*Forest Research Institute Malaysia*