

Mechanical and physical properties of three *Eucalyptus* spp. clones planted in Thailand

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Abstract: Eucalyptus plantations are an important source of raw materials for the Thai forest products industry. Despite its economic value, only a few noncomprehensive papers have been published about the wood properties and fungal susceptibility of eucalyptus. Our study covered the most commonly used commercial eucalyptus clones with a wide variety of sizes from eastern Thailand. We assumed that the properties of the clones would differ based on the tree sizes. The objectives of this study were to determine the effects of diameter at breast height (*DBH*), size, and clone type on wood properties and mould susceptibility. The optimal usage of each log characteristic based on the log quality and properties could be used to determine the maximum payoff. The wood properties and log characteristics of five eucalyptus log classes with three clones were investigated. In general, the levels of means and standard deviations were as follows: the modulus of rupture (*MOR*) was between 39 ± 4.9 MPa and 66 ± 5.4 MPa, and the modulus of elasticity (*MOE*) was between 14.5 ± 9.7 GPa and 24.0 ± 2.7 GPa. In addition, the compression parallel to the grain was between 28 ± 3.2 MPa and 43 ± 2.4 MPa, and the compression perpendicular to the grain was between 13 ± 0.7 MPa and 19 ± 1.1 MPa. The shear strength parallel to the grain was between 10 ± 0.3 MPa and 14 ± 0.6 MPa. The cleavage and hardness were from 4.7 ± 1.6 N to 7.4 ± 0.9 N and from 3.6 ± 0.3 kN to 6.2 ± 0.6 kN, respectively. The toughness and nail withdrawal were from 27.3 ± 3.5 kN·mm⁻¹ to 50.5 ± 1.0 kN·mm⁻¹ and from 28.56 ± 4.1 N·mm⁻¹ to 34.52 ± 2.8 N·mm⁻¹, respectively. Eucalyptus clone K7 had lower *MOR* and other mechanical properties than clones K58 and K62 except *MOE*. When *DBH* increased, the mechanical and physical property values increased as well. This happened for all clones, and especially when *DBH* was over 200 mm. The results of this study showed that log characteristics, such as taper, slenderness, and crookedness, should be used for log grading standards and that each fast-growing eucalyptus clone could be applied to different product classes.

Keywords: clone K7; clone K58; clone K62; eucalyptus wood; modulus of elasticity (*MOE*); modulus of rupture (*MOR*)

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The total *Eucalyptus* spp. plantation area in the world is approximately 25 million ha, and the area in Thailand is approximately 1.8 million ha (Haruthaithanasan 2016; Martins 2022). This property suggests that approximately 7% of eucalyptus plantations in the world are located in Thailand, where eucalyptus plantations are mainly used for pulp industry resources due to their fast growth, short rotation time, and pulp fibre properties. Hence, Thailand is a significant eucalyptus pulp and paper producer in Southeast Asia (Woods et al. 2011). In addition, fibre, particleboards, wood pallets, wood chips, and wood pellets are commonly produced wood products in Thailand. Thai export has instead focused on sawn timber from rubber tree (*Hevea brasiliensis*) and padauk (*Pterocarpus macrocarpus*) (Royal Forest Department 2021). Eucalyptus plantation forestry has managed a wide range of different growing conditions, from tropical to temperate regions (Larcombe et al. 2013; Elaieb et al. 2019; Kaakkurivaara, Kaakkurivaara 2021; Tomé et al. 2021; Zhang, Wang 2021; Florêncio et al. 2022). To maximise the growth potential of habitats, different hybrids and clones have been developed in Southwest Europe, Southeast Asia and South America (da Silva et al. 2018; Tomé et al. 2021; Van Duong, Schimleck 2022). In Thailand, similar development work has been carried out in which local characteristics, such as soil type, annual precipitation, resistance against diseases and insects and tolerance to drought and nutrient deficiency, have been considered (Clinton 2008; Hanvongjirawat 2016). The most prominent clones have been widely commercialised and utilised in Thai forestry to support the pulp industry. Properties between clones vary substantially to maximise yield (tons per ha), and the full potential of growing conditions is utilised. The yield varies between 75 and 187.5 tons per ha (12 to 30 tons per rai) (Kulkarni 2013; Hanvongjirawat 2016).

Mechanical and physical properties have been studied globally to investigate differences between locally developed eucalyptus clones (Ferreira et al. 2020). In the literature, the commonly used physical properties are between 575.8 kg·m⁻³ and 613.9 kg·m⁻³ in density (Kulkarni 2013), and the mechanical properties are 91.3 MPa in the modulus of rupture (*MOR*), 11.4 GPa in the modulus of elasticity (*MOE*), 61.9 MPa in compression parallel to the grain, and 15.6 MPa in compression perpendicular to the grain (Sharma et al. 2005). These characteristics affect lumber quality and, ultimately, prod-

uct quality, which drives the selection of the most suitable clone to fulfil the technical requirements of woody products. As the main use of eucalyptus has been in pulp and board manufacturing in Thailand, there have been a limited number of published studies about the mechanical properties of the clones used in Thailand. Ishiguri et al. (2013) studied the modulus of elasticity and stress wave characteristics of *Eucalyptus camaldulensis*, but the two investigated clone trademarks were not mentioned. Hanvongjirawat studied clones K58 (2016) and K7 (2022). The main finding was that K7 is not suitable for construction compared with K58 and K62 due to its relatively weak properties. Therefore, K7 is recommended for use in furniture, flooring, pallet, and pulp chips. Furthermore, Hanvongjirawat (2023) studied K62 and confirmed that this clone is suitable for construction due to its excellent mechanical properties. In summary, none of these scholars carried out comparison studies in which physical and mechanical properties were systematically and statistically investigated and compared.

In our study, we selected three eucalyptus clones, K7, K58, and K62, which are normally used in commercial plantations in Thailand. The clones are commonly used all over the country, and they are currently the most important clones in the Thai forestry sector due to their good survival rate and high main annual increment. The clones were developed from *Eucalyptus* spp. hybrids (*Eucalyptus camaldulensis*, *Eucalyptus urophylla*, and *Eucalyptus deglupta*) by Suankitti Company. Detailed information on the clones is not available for public use. To improve the sustainability of Thai forestry, there is a need to allocate the eucalyptus timber supply chain to serve a wide group of wood product industries. Therefore, knowledge of the mechanical properties of eucalyptus clones is necessary. This knowledge provides the opportunity to decrease the variation in the quality of timber used for wood products when the most suitable clone is selected as the timber source for certain wood products. Thus, added value could be created by manufacturing high-price wood products for markets.

The aim of this study was to determine the effect of diameter at breast height (*DBH*) and eucalyptus clone type on wood properties and fungal susceptibility by investigating the *MOR*, *MOE*, surface moisture content (*MC*), water activity and prong test results to statistically determine the best clones for supporting the development of the Thai wood product industry.

MATERIAL AND METHODS

Sample selection and specimen preparation.

The eucalyptus clones K7, K58, and K62 were selected due to their generality in eastern Thailand, which is one of the major eucalyptus cultivation regions in the country. The sampling process began with the selection of 60 stands with a wide range of *DBH* values located in two plantation areas. The plantations were located in Chachoengsao Province (13°43'48"N, 101°37'12"E). The province is typically characterised by northeast and southwest monsoons and tropical humidity (TMD 2023). The annual precipitation is 1 921 mm according to data collected by the nearest meteorological station in the study area (Nounmusig 2018). Both plantations had 3 m × 1.5 m of tree spacing and were approximately five years old, which is a common rotation time in Thailand. Random sampling was used for stand selection, but an adequate number of trees were chosen to cover the entire range of *DBH*s for each clone. This study aimed to represent different log sizes and characteristics for various clones of the same age. This study considered the effect of tree size and clone type on log quality and properties, resulting in the formation of five *DBH* classes: < 50 mm, 50–99 mm, 100–149 mm, 150–199 mm, and > 199 mm. The size classification was a consequence of the Thai timber market, where logs are sorted for different purposes based on the imperial system (Kaakkurivaara et al. 2024). The sample logs

were defined and classified as shown in Table 1. This study used a code system to correspond to the situation in practice. Every code included four butt logs for physical and mechanical tests and seven logs for log characteristics, prong, surface *MC*, and a water activity test with four replicates. A schematic diagram for sample selection, specimen preparation, and property testing is shown in Figure 1.

Determination of log characteristics. The log characteristics, such as taper, slenderness, and crookedness, were tested. The log characteristics were evaluated following Muñoz's method (Muñoz et al. 2013). Taper, crookedness, and slenderness ratio parameters were measured for each log. Every code included four stems and each stem included seven logs, including butt log. The method is shown in Figure 2, and the Equations (1–3) are shown below.

$$\text{Taper (\%)} = \frac{100 \times (D - d)}{d} \quad (1)$$

$$\text{Slenderness} = \frac{L}{D} \quad (2)$$

$$\text{Crookedness} = \frac{f}{d} \times 100 \quad (3)$$

where:

D – large end diameter (m);

d – small end diameter (m);

L – log length (m);

f – maximum deflection (cm).

Table 1. Experimental design of the study

Class code	Inch class	Clone	<i>DBH</i> classes (mm)	Amount of specimen
A	< 2.00	K7	< 50	NA
B	2.00–3.99		50–99	4
C	4.00–5.99		100–149	4
D	6.00–7.99		150–199	4
E	> 8.00		> 200	4
A	< 2.00	K58	< 50	4
B	2.00–3.99		50–99	4
C	4.00–5.99		100–149	4
D	6.00–7.99		150–199	4
E	> 8.00		> 200	4
A	< 2.00	K62	< 50	NA
B	2.00–3.99		50–99	4
C	4.00–5.99		100–149	4
D	6.00–7.99		150–199	4
E	> 8.00		> 200	NA

DBH – diameter at breast height; NA – no samples available

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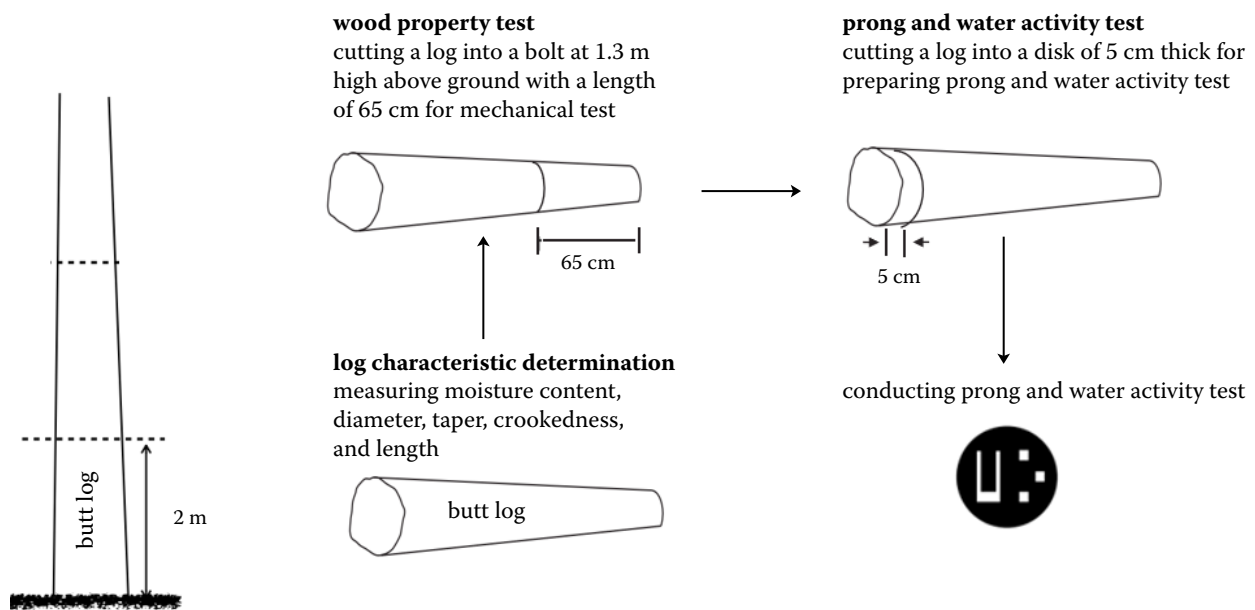


Figure 1. Schematic diagram of sample selection and specimen preparation

Mechanical and physical property tests. The specimens were prepared from butt logs at heights between 1.3 m and 2 m (Figure 1). The ASTM, ISO, and BS standards were used in this study; these are usually used in national Thai standards as well. The investigated wood properties were bending strength (ASTM D143-19), bending stiffness (ASTM D143-19), compression parallel to the grain (ISO 3787:1976), compression perpendicular to the grain (ASTM D143-19), shearing parallel to the grain (ISO 3346:1975), tension perpendicular to the grain (BS 373:1957), hardness (ISO 3348:1975), cleavage (BS 373:1957), tough-

ness (ISO 3350:1975), and nail withdrawal ability (ISO 9087:1998). Every test was carried out for four replicates from each butt log. The prepared specimens were conditioned in a room at the temperature of 20 ± 3 °C and $65 \pm 5\%$ relative humidity until the specimens reached equilibrium moisture content of about 12%. A schematic diagram of the specimen preparation process is shown in Figure 3.

Prong, surface MC and water activity tests. The internal stress of wood during the drying process is one of the major causes of wood defects. Due to the complexity of the drying mechanism, the internal stress of wood could be roughly determined

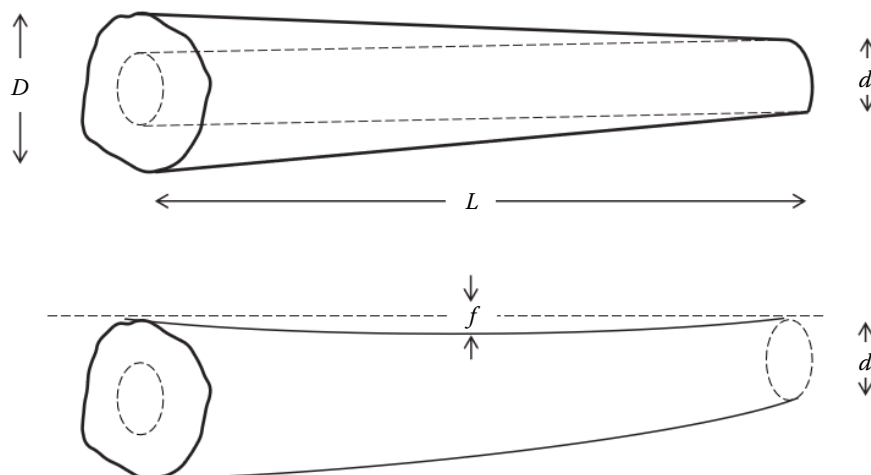


Figure 2. Schematic diagram of log taper, slenderness, and crookedness

D – large end diameter (m); d – small end diameter (m); L – log length (m); f – maximum deflection (cm)

wood property test

cutting a log into a bolt at 1.3 m high above ground with a length of 65 cm for mechanical test

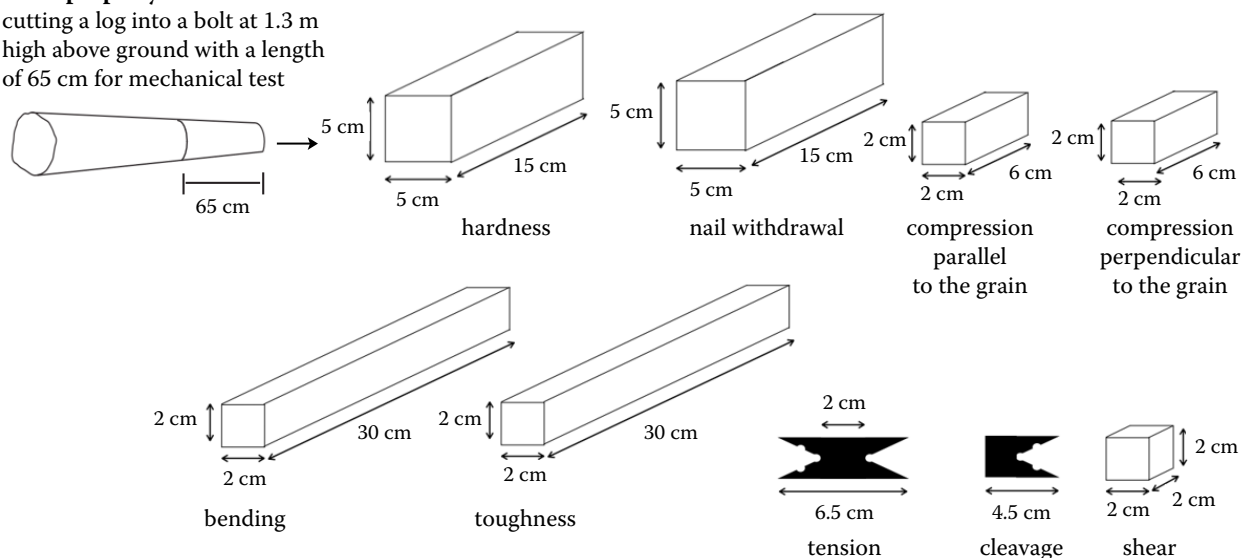


Figure 3. Schematic diagram of specimen preparation and physical and mechanical property tests

by using the prong test, which is one of two typical testing methods, with the other being a slicing test (Yin, Liu 2021). For the prong test, case-hardening (case hardened, not case hardened, and reverse case hardened) was determined for each log (from 4 stems and each stem had 7 logs including butt log), as shown in Figure 4 (McMillen 1955; Zhan, Avramidis 2017). For surface MC, each log was measured by a LANDTEK moisture meter model MC-7806 (Guangzhou Landtek Instruments Co., Ltd., China) at both log ends of each log the day after the tree had been felled and crosscut into 2 m long segments. The ability of fungi to grow in wood could be determined by the environment within

the wood and its surroundings, which are intrinsic and extrinsic factors. The use of only nonequilibrium conditions, such as the bulk moisture content, could not accurately imply fungal growth ability. The availability of water for fungal growth was introduced as water activity (Ye et al. 2014). Water activity is one parameter for determining the resistance of rotten plants. Therefore, for water activity determination, wood disk samples, which were cut from the large end of each log from 4 stems, were placed in the chamber and sealed in a LANDTEK water activity meter model WA-60A (Guangzhou Landtek Instruments Co., Ltd., China) the day after sampling. The free water was allowed to escape into the

prong and water activity test

cutting a log into a disk of 5 cm thick for preparing prong and water activity test

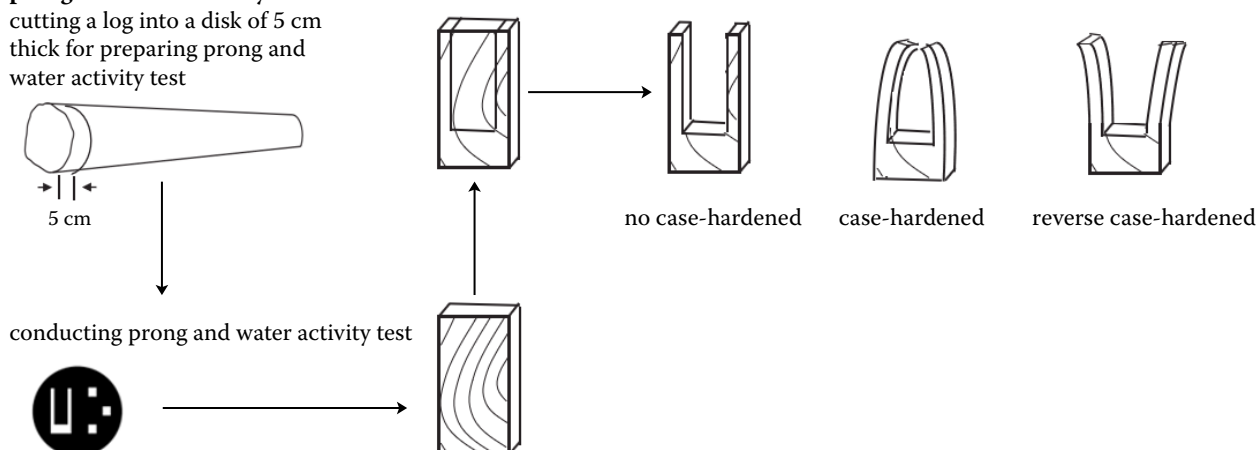


Figure 4. Determination of drying stress in eucalyptus logs via the prong test

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air in the chamber, where it remained until all the free water left the sample. After the equilibrium state was reached, the relative humidity of the air in the chamber was measured. The relation of this reading to pure water is the water activity measurement expressed as the term *aw*. The range of water activity was from zero to 1.0 *aw*. Mould susceptibility (water activity) was tested following Adams's method (Adams et al. 2019).

Statistical analysis. Statistical analysis was performed using R Studio statistical software (RStudio Team 2016). The mean and standard deviation were calculated for each log variable. Post hoc Tukey tests were conducted to compare wood properties among different log sizes and clone types (significance level 0.05). One-way analysis of variance (ANOVA) for linear mixed models was used to evaluate the effects of log size and clone type on wood properties, with tree type serving as a random factor to account for the nonindependence of logs.

RESULTS AND DISCUSSION

Log characteristics. The mean log diameters were 11.2 cm, 9.49 cm, and 9.13 cm for clones K7, K58, and K62, respectively. Balasso et al. (2022) reported

that logs largely differed in their characteristics, depending on their position within the tree and log size. Table 2 presents the taper, slenderness, and crookedness values for all eucalyptus clones. The clone K7 logs had taper values of 0.48–0.65%, the clone K58 logs had taper values of 0.55–0.75%, and the diameter was 2.00–7.99 inches (50–199 mm). Additionally, the clone K62 logs had taper values of 0.57–0.81%. When averaging the taper values of logs with diameters of 2.00–7.99 inches (50–199 mm), the average tapers were determined to be 0.58%, 0.62%, and 0.71% for clones K7, K58, and K62, respectively. The logs from clones K62 and K58 thinned faster than those from clone K7. The highest mean values of log tapers were 0.81%, 0.78%, and 0.78% for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter, and clones K58 and K7, which were greater than 8.00 inches (200 mm) in diameter, respectively. The butt log was expected to be thinner (low taper value) than the uppermost log. Balasso et al. (2022) reported high variation in the taper among the butt log, second log, and other positions of the logs, probably due to the adaptation of the taper to the tree crown. In this study, the comparison of average values between the *DBH* classes could be an issue due to their high standard deviations.

Table 2. Log characteristics of eucalyptus clones K7, K58, and K62 planted in eastern Thailand

Clone	Inch class	Diameter (cm)	Taper (%)	Slenderness (–)	Crookedness (%)
K7	< 2.00	NA	NA	NA	NA
	2.00–3.99	5.93 ± 2.07	0.48 ± 0.30 ^a	38.15 ± 17.48 ^b	0.26 ± 0.15 ^b
	4.00–5.99	9.49 ± 3.61	0.62 ± 0.21 ^a	23.75 ± 11.19 ^c	0.19 ± 0.14 ^{bc}
	6.00–7.99	11.59 ± 4.39	0.65 ± 0.31 ^a	16.40 ± 6.00 ^c	0.16 ± 0.13 ^{cd}
	> 8.00	13.69 ± 6.26	0.78 ± 0.26 ^a	15.23 ± 4.56 ^c	0.13 ± 0.13 ^{cd}
	mean	11.18 ± 4.47	0.74 ± 0.44	20.76 ± 15.34	0.18 ± 0.13
K58	< 2.00	3.58 ± 1.15	0.26 ± 0.26 ^a	52.41 ± 15.53 ^a	0.36 ± 0.35 ^d
	2.00–3.99	5.47 ± 2.35	0.55 ± 0.38 ^a	38.03 ± 17.94 ^b	0.31 ± 0.14 ^d
	4.00–5.99	9.14 ± 3.20	0.56 ± 0.33 ^a	23.05 ± 9.14 ^c	0.26 ± 0.18 ^d
	6.00–7.99	12.28 ± 5.17	0.75 ± 0.61 ^a	18.11 ± 8.69 ^c	0.21 ± 0.15 ^d
	> 8.00	13.41 ± 5.11	0.78 ± 0.42 ^a	16.19 ± 7.08 ^c	0.19 ± 0.12 ^d
	mean	9.49 ± 5.17	0.65 ± 0.44	26.39 ± 16.32	0.22 ± 0.12
K62	< 2.00	NA	NA	NA	NA
	2.00–3.99	6.47 ± 2.26	0.57 ± 0.34 ^a	31.32 ± 11.62 ^b	0.18 ± 0.17 ^c
	4.00–5.99	10.19 ± 3.34	0.76 ± 0.45 ^a	20.19 ± 7.86 ^c	0.22 ± 0.22 ^{cd}
	6.00–7.99	12.07 ± 4.14	0.81 ± 0.55 ^a	17.35 ± 6.73 ^c	0.16 ± 0.14 ^{cd}
	> 8.00	NA	NA	NA	NA
	mean	9.13 ± 4.32	0.72 ± 0.47	22.39 ± 10.45	0.19 ± 0.18

^{a–d} Post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$); data are expressed as the means ± SD (standard deviation); NA – not enough samples

The clone K7 logs had slenderness values between 16.40 and 38.15. In addition, the clone K58 logs had slenderness values of 18.11–38.03, and the clone K62 logs had slenderness values of 17.35–31.32. These values were valid for logs with diameters of 2.00–7.99 inches (50–199 mm). According to our results, the log slenderness had the same trend as the log taper across all the clones. The highest mean slenderness values were 52.41, 38.15, 38.03, and 31.32 for clone K58, which was less than 2.00 inches (50 mm) in diameter, and K7, K58, and K62, which were 2.00–3.99 inches (50–99 mm) in diameter, respectively. However, when averaging the slenderness values in the *DBH* logs with diameters of 2.00–7.99 inches (50–199 mm), the average slenderness was determined to be 26.10%, 26.40%, and 22.95% for clones K7, K58, and K62, respectively. From the results, clone K62 was less slender than the other clones, which could be valuable for designing a column in a wood-construction building.

The clone K7 logs had crookedness values of 0.16–0.26%, and the K58 logs had crookedness values of 0.21–0.31% for those 2.00–7.99 inches (50–199 mm) in diameter. Additionally, the clone K62 logs had crookedness values of 0.16–0.22%. According to the results, the clone K58 logs were more crooked than the K7 and K62 logs. The highest mean crookedness values were 0.36% and 0.31% for the eucalyptus clone K58 logs, which were less than 2.00 inches (50 mm) and 2.00–3.99 inches (50–99 mm) in diameter, respectively. However, when averaging the crookedness values of logs with diameters of 2.00–7.99 inches (50–199 mm), the average crookedness values were 0.20%, 0.26%, and 0.56% for clones K7, K58, and K62, respectively. According to the results, clone K62 was more crooked than the other clones, in which case log crookedness and taper could decrease the lumbering and veneering yield in sawing and veneering mills.

Table 3 presents the ANOVA results, the taper did not have any statistical significance observed

with clone or *DBH* size, likely due to the similar average position of each log within the tree. In contrast, slenderness and crookedness have high significance, except for the case of the combined effect of clone and *DBH* size at slenderness. The slenderness values of the K7, K58, and K62 logs were not significantly different from those of trees of the same size. When comparing samples from the same position in the tree, there were no significant differences in slenderness for large logs, but there were significant differences for small logs. The level of crookedness was not significantly different between clone types, but there was a significant difference between the *DBH* classes of both K7 and K62. However, no significant trend in crookedness was detected for the clone K58 log. However, the crookedness noticeably decreased as the diameter increased. The slenderness, taper, and crookedness of eucalyptus logs slightly affected wood chip production for pulping and energy application as raw materials, but they critically affected lumber and veneer yield.

In this study, the log characteristics were log taper, slenderness, and crookedness. These characteristics were considered important factors for determining the sawing yield of sawn lumber. The high values of their log characteristics presumably reduced the volume of sawn lumber, although Muñoz et al. (2013) reported no significant correlations between log characteristics or log quality and sawing yield. However, the variation in log characteristics was very high, which could affect wood veneer yield in the plywood industry.

Physical and mechanical properties. Figures 5–10 show the mean values of the mechanical properties, such as density, *MOE*, *MOR*, compression, tension, shear, cleavage, toughness and nail withdrawal capability, across the clone types and *DBH* classes. The specimens were conditioned until they reached the equilibrium moisture content. The average mois-

Table 3. Significance of clone and class on log characteristics (ANOVA)

Attribute	Fixed terms: <i>F</i> -value		
	taper	slenderness	crookedness
Clone	0.64 ^{NS}	20.15***	61.97***
<i>DBH</i>	1.81 ^{NS}	105.41***	19.18***
Clone × <i>DBH</i>	0.50 ^{NS}	0.47 ^{NS}	21.61***

****P* < 0.001; ^{NS} not significant; ANOVA – analysis of variance; *DBH* – diameter at breast height

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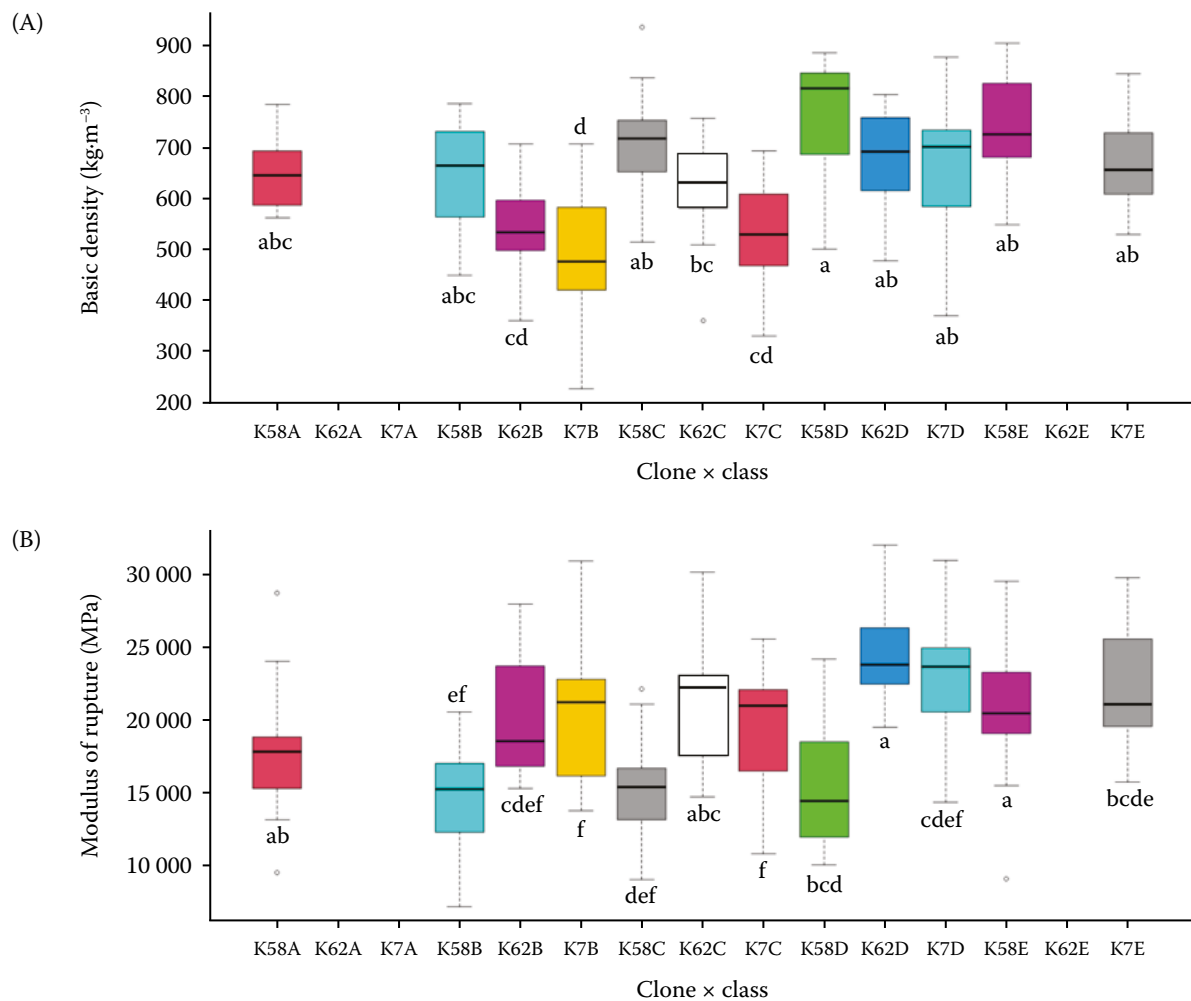


Figure 5. Properties of clones K7, K58, and K62: (A) basic density and (B) modulus of rupture

a–f – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

ture content was 11.3%. The mean values of basic density (Figure 5) were 492–670 kg·m⁻³, 642–754 kg·m⁻³, and 539–681 kg·m⁻³ for clones K7, K58, and K62, respectively. The highest mean basic density was 755 kg·m⁻³ for clone K58, which was 6.00–7.99 inches (150–199 mm) in diameter. The lowest mean basic density was 492 kg·m⁻³ for clone K7, which was 2.00–3.99 inches (50–99 mm) in diameter. However, compared with the mean values of all DBH classes, clone K58 had the highest mean basic density (705 kg·m⁻³), while clones K62 and K7 had mean values of 614 kg·m⁻³ and 588 kg·m⁻³, respectively. Furthermore, the results of the statistical analysis implied that there were significant differences in the wood densities among the samples of different clone types and log sizes (DBH classes). The densities could be sorted in descending order for K58, K62, and K7. Our study

results showed that all densities could be classified as intermediate (500–750 kg·m⁻³) according to Ferreira et al. (2020). Previous studies reported that the nominal densities of 7-year-old K7 (*E. camaldulensis* × *E. deglupta* hybrid) and K58 (*E. urophylla* hybrid) and 4-year-old K62 (*E. urophylla* hybrid) clones were estimated to be 520 kg·m⁻³, 720 kg·m⁻³, and 630 kg·m⁻³, respectively, with limited sample sizes in Prachinburi Province, Thailand (Hanvongjirawat 2016, 2022, 2023). Ferreira et al. (2020) reported that the basic density of 7-year-old *E. urograndis* (the H13 clone of *Eucalyptus urophylla* × *Eucalyptus grandis* hybrid in Brazil) was 546–586 kg·m⁻³, and it has been reported that 4-year-old *E. pellita* planted in East Kalimantan had a basic density of 450–565 kg·m⁻³ (Ramadan et al. 2018). Prasetyo et al. (2017) reported that the basic density of 9-year-old *E. pellita* planted

in North Sumatra, Indonesia, was 400–450 kg·m⁻³. The basic density in the present study was close to that reported by Hanvongjirawat (2016, 2022, 2023). However, the results were greater than those of Ramadan et al. (2018) and Prasetyo et al. (2017). Instead, Spanish *E. globulus* were detected to have 847 kg·m⁻³ (Crespo et al. 2020). The differences in the basic density at various clonal and planted sites could be explained by differences in genetic material, site quality, age, growing space, fertilisation, and other environmental factors (Downes et al. 1997; Ferreira et al. 2020).

As shown in Figure 5, the mean MOR values were 39–53 MPa, 54–64 MPa, and 48–66 MPa for clones K7, K58, and K62, respectively. The highest mean MOR was 66 MPa for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter, while the lowest mean MOR was 39 MPa for clone K7,

which was 4.00–5.99 inches (100–149 mm) in diameter. However, compared with the mean values of all DBH classes, clone K62 had the highest mean value of MOR (57 MPa), while clones K58 and K7 had mean values of 54 MPa and 45 MPa, respectively. McKinley et al. (2002) reported that the MOR of 11-year-old *Eucalyptus maidenii* wood was two times lower than that reported in Nogueira et al. (2018), probably due to differences in age and density. In this study, the variation in MOR was very high.

The MOE values of clones K7, K58, and K62 were 19.20–22.50 GPa, 14.46–20.46 GPa, and 19.71–24.01 GPa, respectively (Figure 6). The highest mean value was 24.01 GPa for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter, while the lowest mean value was 14.46 GPa for clone K58, which was 2.00–3.99 inches (50–99 mm)

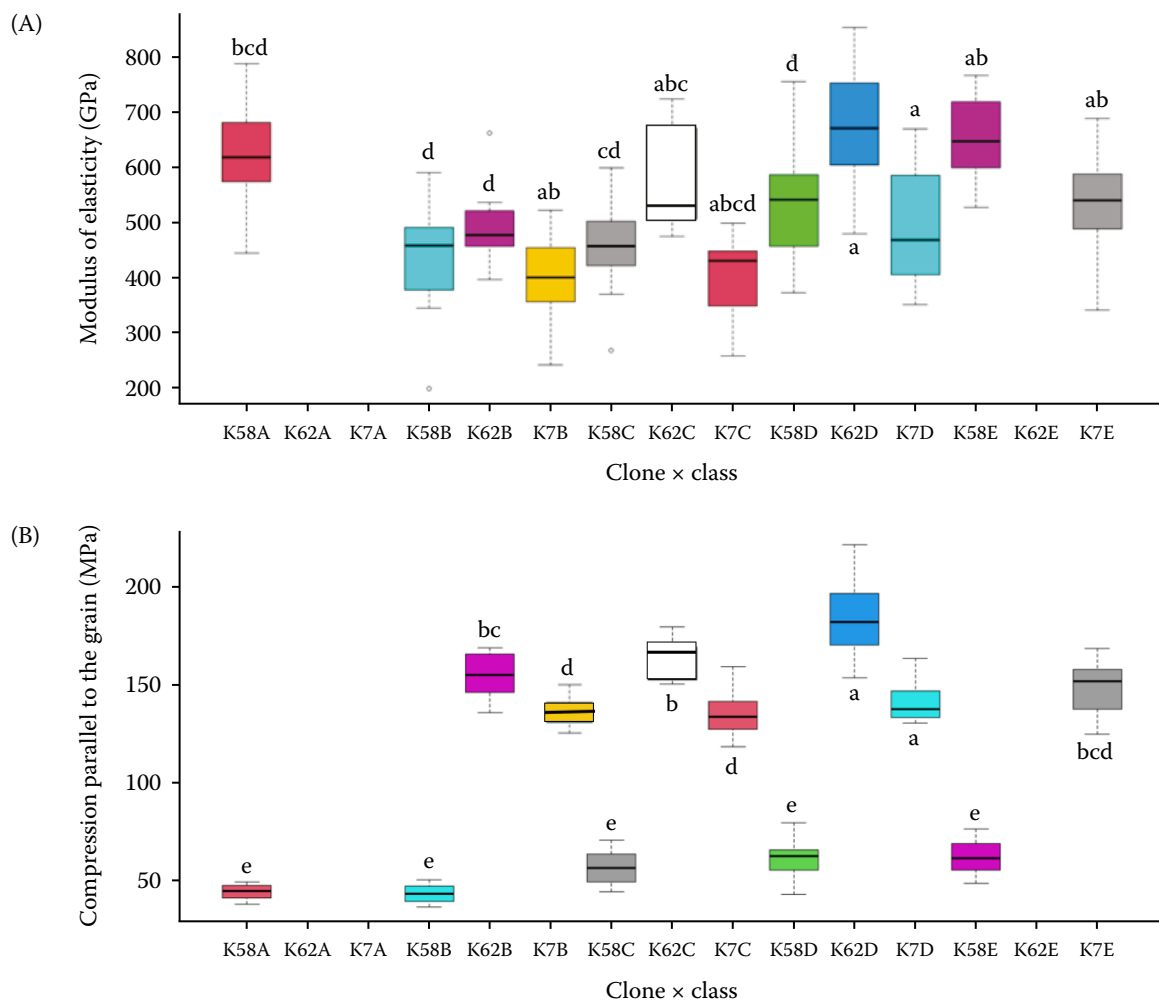


Figure 6. Properties of clones K7, K58, and K62: (A) modulus of elasticity and (B) compression parallel to the grain a–e – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

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in diameter. For the mean values of all *DBH* classes, the highest *MOE* was 21.22 GPa for clone K62, which was comparable to that of clone K7, which had a value of 21.01 GPa, whereas the mean value of clone K58 was 16.55 GPa. The results of the statistical analysis proved that there were significant differences between clone K58 and the other clones. The values of the *MOE* could be sorted in descending order for K62, K7, and K58. Thus, compared to Hanvongjirawat's study (2016) on 7-year-old eucalyptus K58, Hanvongjirawat's study (2022) on 7-year-old eucalyptus K7, and Hanvongjirawat's study (2023) on 4-year-old eucalyptus K62, our results were 1.5 times greater. *MOE* values were considered important for describing young wood properties, which were important for select-

ing suitable clones for structural use. McKinley et al. (2002) reported that for 11-year-old *Eucalyptus maidenii* wood, the *MOE* was one-fifth greater than that reported in Nogueira et al. (2018), likely due to differences in age and density.

The mean values of the compression parallel to the grain and perpendicular to the grain are shown in Figures 6 and 7. The highest value of compression parallel to the grain was 43 MPa for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter, while the highest value of compression perpendicular to the grain was 18.84 MPa for clone K58, which had a diameter greater than 8.00 inches (200 mm). However, compared with the mean values of all *DBH* classes, clone K62 had the highest mean value of compression parallel

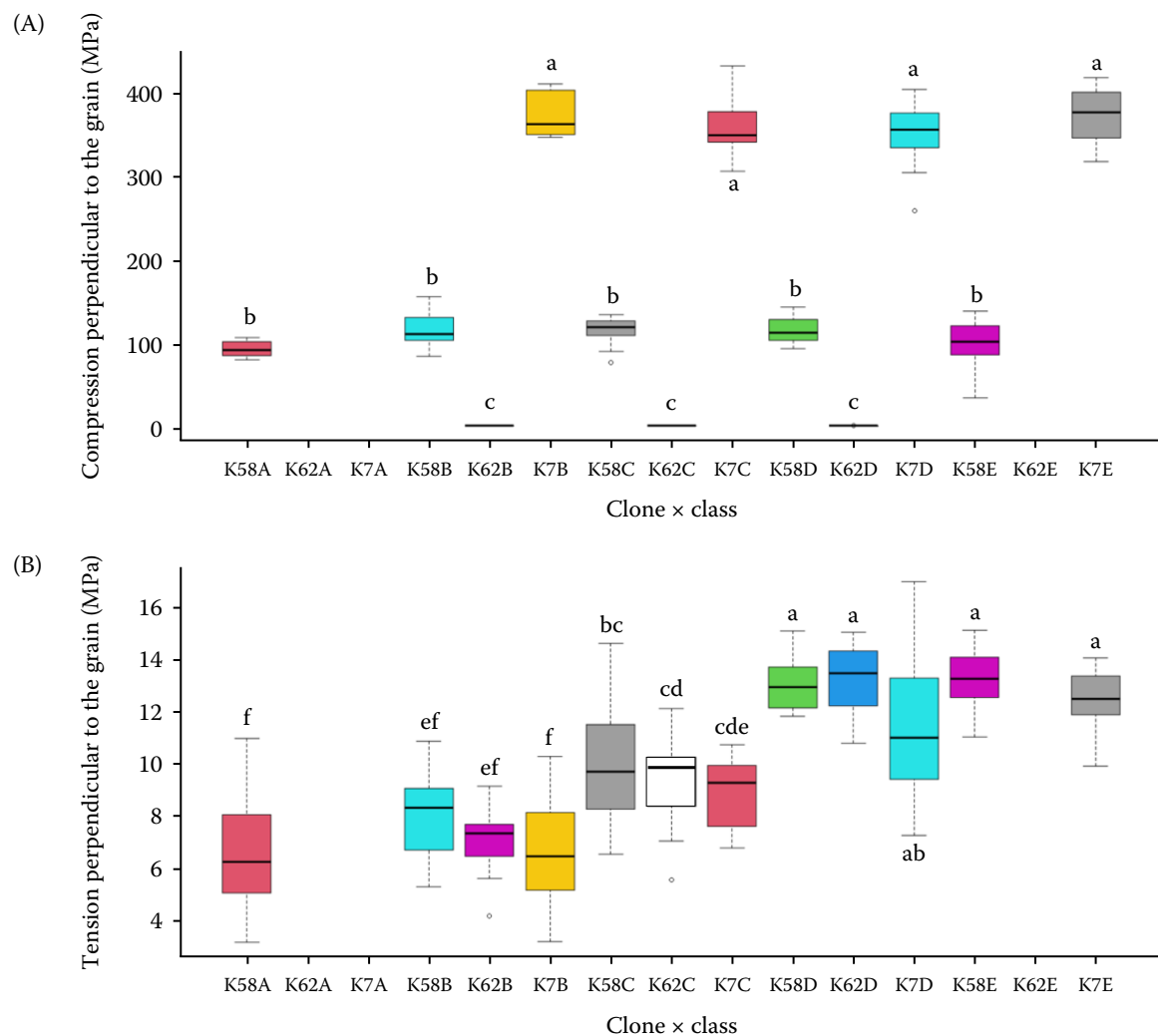


Figure 7. Properties of clones K7, K58, and K62: (A) compression perpendicular to the grain and (B) tension perpendicular to the grain

a–f – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

to the grain (40 MPa), while the highest mean value of compression perpendicular to the grain was 17 MPa for clone K58. Therefore, the compression parallel to the grain of the butt logs from K62 was superior to that of the logs from K58, and the compression perpendicular to the grain of the logs from K58 was superior. The values of compression parallel to the grain could be sorted in descending order for K62, K7, and K58. The compression perpendicular to the grain could be sorted in descending order for K62, K7, and K58. The results from Figures 6 and 7 indicate that the clone had a strong effect on the parallel-to-the-grain and perpendicular-to-the-grain compressive strengths.

The highest mean perpendicular-to-the-grain tensile strength was 1.30 MPa for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter (Figure 7). The highest mean shear strength was

14 MPa for clone K62, which was 6.00–7.99 inches (150–199 mm) in diameter (Figure 8). The highest mean cleavage strength was 7.37 N for clone K58, which had a diameter of 6.00–7.99 inches (150–199 mm) (Figure 8). The highest mean hardness was 6.17 kN for clone K58, which was greater than 8.00 inches (200 mm) in diameter (Figure 9). The highest mean toughness was 50.47 kN·mm for clone K58, which was 2.00–3.99 inches (50–99 mm) in diameter (Figure 9). The highest mean nail-holding capacity was 34.52 N·mm⁻¹ for clone K7, which was 6.00–7.99 inches (150–199 mm) in diameter (Figure 10). As shown in Figure 7, for the mean values of all DBH classes, the highest mean perpendicular-to-the-grain tensile strength was 1.00 MPa for clone K58; however, there were no significant differences among all the clones. The highest mean values of parallel-to-grain shear strength, cleav-

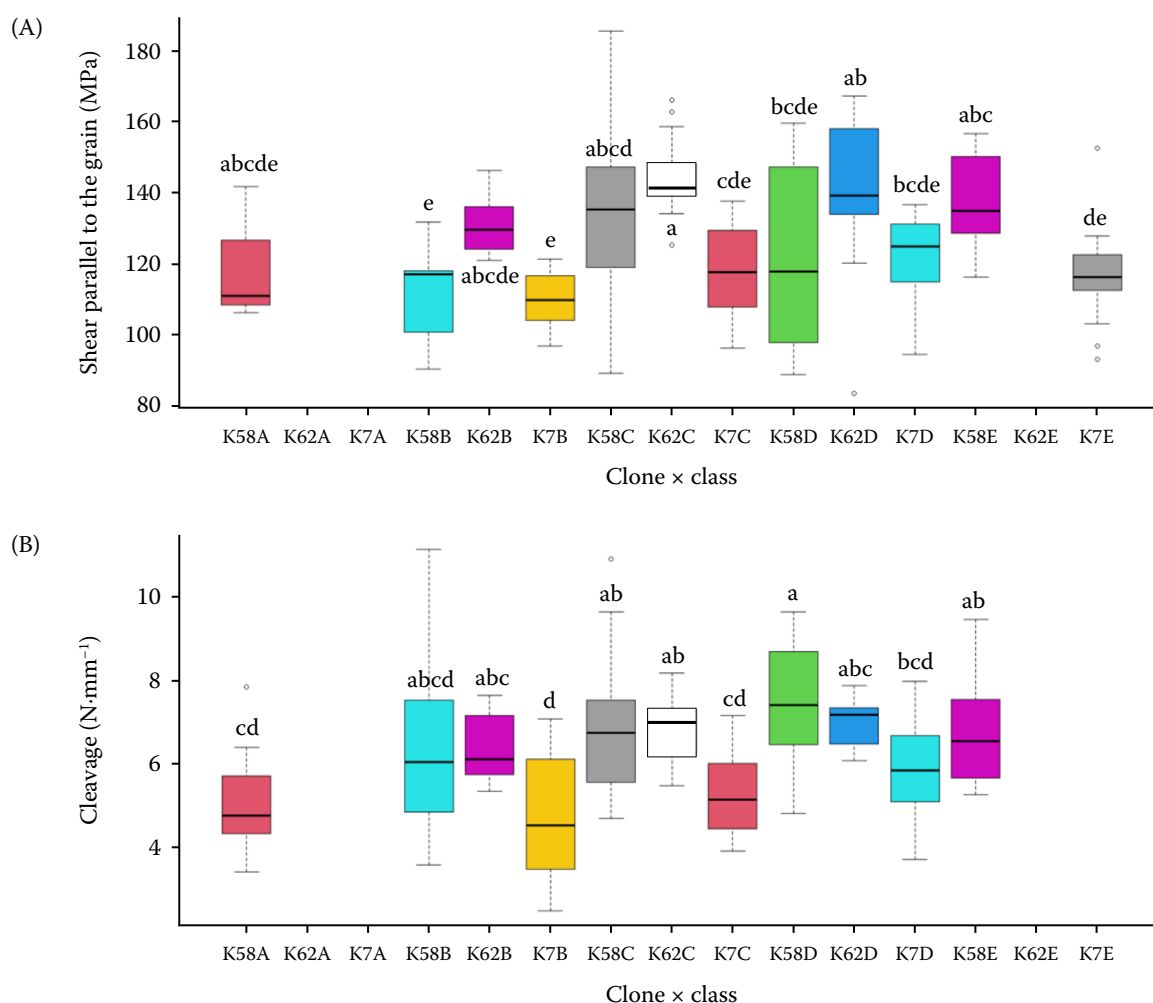


Figure 8. Properties of clones K7, K58, and K62: (A) shear parallel to the grain and (B) cleavage

a–e – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

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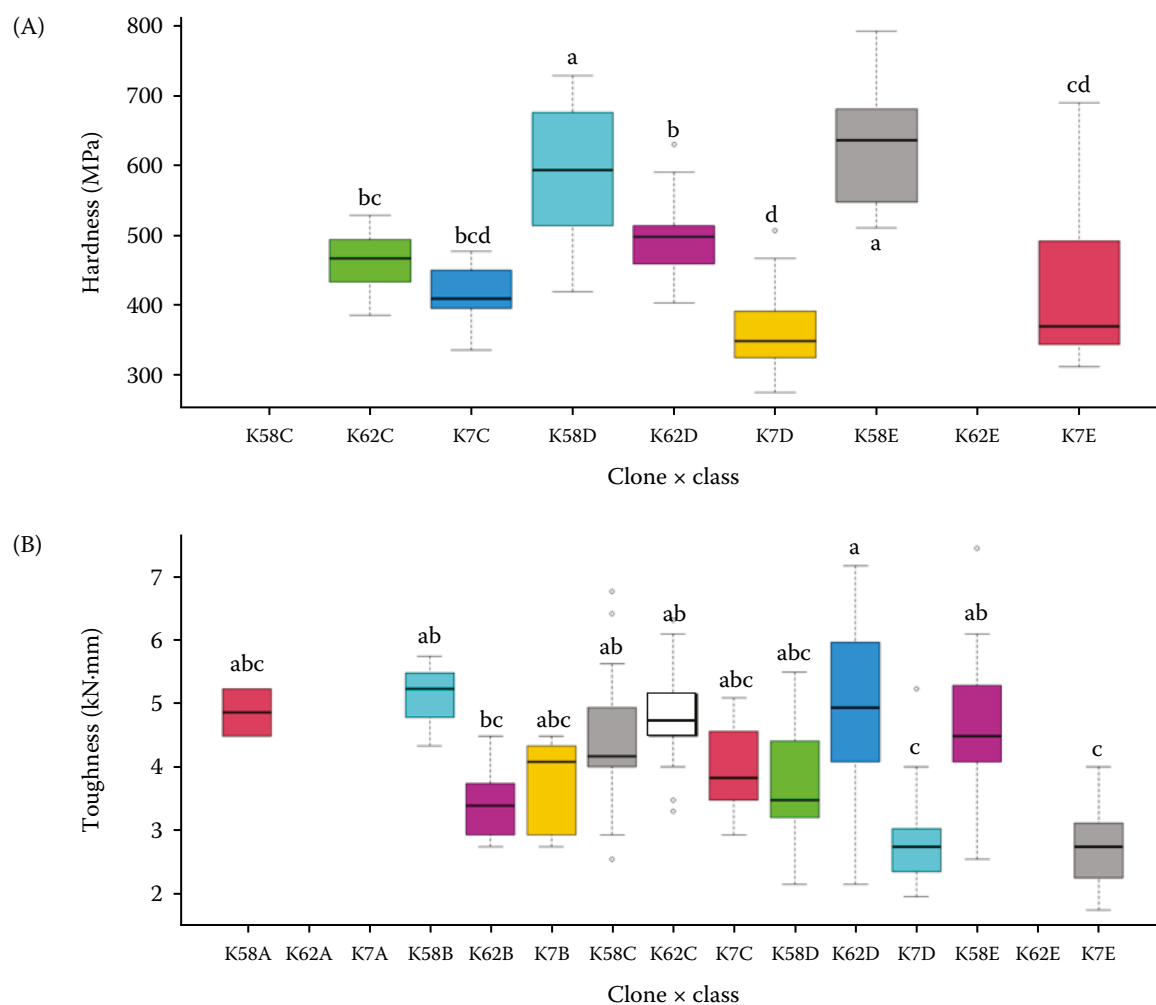


Figure 9. Properties of clones K7, K58, and K62: (A) hardness and (B) toughness

a–d – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

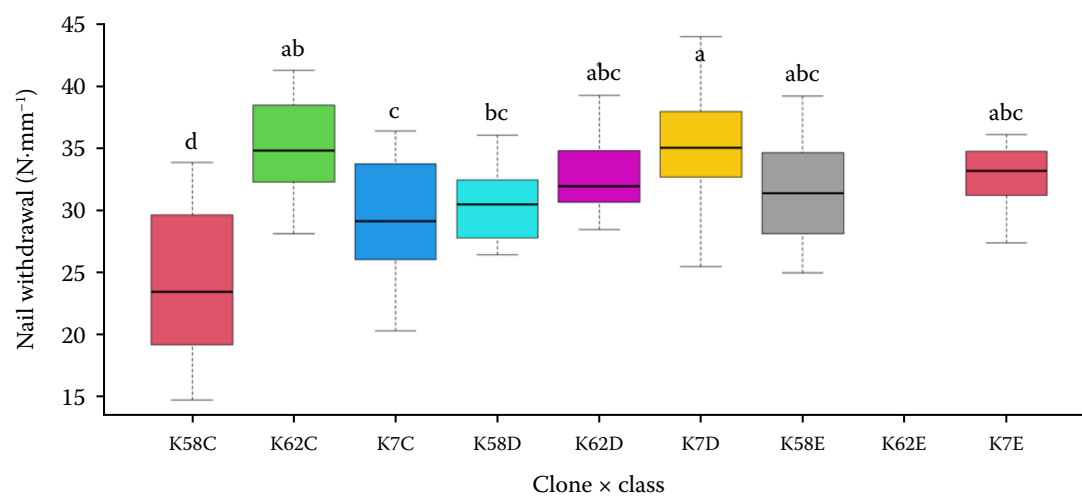


Figure 10. Properties of clones K7, K58, and K62: Nail withdrawal

a–d – post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$)

age, toughness, and nail-holding capability were 14 MPa, 7 N, 44.84 kN·mm⁻¹, and 34 N·mm⁻¹, respectively, for clone K62, while the highest mean hardness was 5.97 kN for clone K58.

ANOVA results in Table 4 show that clone and DBH size have a high significance in nine and seven of ten cases in the mechanical properties, respectively. Instead, the combined effect of clone and DBH size have no statistical significance in half of the cases. In the other half of the cases, the level of significance varied greatly. These results were remarkably different from those of previous studies in Thailand (Hanvongjirawat 2016, 2022, 2023), which involved an investigation of the physical and mechanical properties of older clones K7, K58, and K62. Hanvongjirawat (2016, 2022, 2023) obtained nominal densities from approximately 7-year-old wood (K7, K58, and K62) between 520 kg·m⁻³ and 720 kg·m⁻³. Although the age and density were close to the range observed in this study, it could be verified that each eucalyptus clone was mechanically different from that in previous studies conducted in Thailand. These findings could have arisen due to the grouping of wood samples from two different areas of eastern Thailand. This grouping was considered based on the exact age and same spacing of tree plantation. However, due to the limited use of wood as timber for construction in native forests, the use of juveniles and small woods would be required for timber construction. Therefore, a particular clone and species used for planting should be considered. Small and juvenile eucalyptus wood could be suitable for lumber-based products.

Surface MC, water activity and lumber stress.

Table 5 presents the surface MC, water activity and lumber stress values for all the tree clones. The results showed that the surface MC of clone K7 was between 54.01% and 60.19%, and that of K58 was between 35.25% and 41.60%. In addition, the surface MC of clone K62 ranged from 37.64% to 51.56%. For water activity, the clone K7 values ranged from 0.88 to 0.90, while those of the clones K58 and K62 ranged from 0.87 to 0.89. These results covered all DBH classes. Regarding the lumber stress, all the lumber samples exhibited case-hardening based on the prong test. Surface MC, water activity and lumber stress were considered important factors that impacted the risk of fungal growth and defects in wood logs (Ye et al. 2014; Lie et al. 2019a; Yin, Liu 2021; Lapage et al. 2022). The eucalyptus clone K7 log had the highest surface MC, and the surface MC was significantly different among all the clones; therefore, the clone had an effect on the surface MC. The surface MC of the large log was significantly greater than that of the small log for clones K7, K58, and K62. In addition, for wood stress development during log drying, it was shown that all lumber stresses were case-hardened, likely due to the leaning stems of the trees caused by the windy season, although there was narrow branching in eucalyptus compared with other species (Moore et al. 2008). The results of surface MC and water activity indicate the risk of quality deterioration. The study did not include the isolation of fungal species. However, it is important to note that this range of water activity could cause the growth

Table 4. Significance of clone and class on mechanical properties (ANOVA)

Mechanical properties	Fixed terms: <i>F</i> -value		
	clone	class	clone × class
MOR	30.70***	31.89***	1.98 ^{NS}
MOE	28.87***	6.96***	2.43*
Compress parallel to the grain	1 327.20***	15.55***	3.59**
Compress perpendicular to the grain	3 127.27***	0.92 ^{NS}	2.36*
Tension perpendicular to the grain	0.95 ^{NS}	101.21***	0.99 ^{NS}
Shear parallel to the grain	21.02***	5.58***	1.65 ^{NS}
Cleavage	17.99***	10.58***	0.46 ^{NS}
Hardness	74.79***	2.12 ^{NS}	2.16 ^{NS}
Toughness	25.03***	1.87 ^{NS}	5.31***
Nail withdrawal	19.38***	13.70***	4.40***

P* < 0.05; *P* < 0.01; ****P* < 0.001; ^{NS} not significant; ANOVA – analysis of variance; MOR – modulus of rupture; MOE – modulus of elasticity

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Table 5. Surface *MC*, water activity, and prong test results of eucalyptus clones K7, K58, and K62 planted in eastern Thailand

Clone	Inch class	Surface <i>MC</i> (%)	Water activity (%)	Prong test (%)
K7	< 2.00	NA	NA	NA
	2.00–3.99	54.01 ± 3.45 ^{bc}	0.89 ± 0.04 ^a	100% case-hardening
	4.00–5.99	56.29 ± 6.28 ^b	0.88 ± 0.03 ^a	100% case-hardening
	6.00–7.99	57.24 ± 4.59 ^{ab}	0.90 ± 0.04 ^a	100% case-hardening
	> 8.00	60.19 ± 4.75 ^a	0.89 ± 0.03 ^a	100% case-hardening
	mean	57.54 ± 6.29	0.87 ± 0.03 ^a	100% case-hardening
K58	< 2.00	35.25 ± 6.29 ^f	0.89 ± 0.04 ^a	100% case-hardening
	2.00–3.99	38.89 ± 7.28 ^{ef}	0.89 ± 0.02 ^a	100% case-hardening
	4.00–5.99	41.07 ± 7.80 ^e	0.87 ± 0.03 ^a	100% case-hardening
	6.00–7.99	40.45 ± 10.42 ^e	0.89 ± 0.04 ^a	100% case-hardening
	> 8.00	41.60 ± 7.31 ^e	0.89 ± 0.01 ^a	100% case-hardening
	mean	40.10 ± 8.30	0.87 ± 0.03	100% case-hardening
K62	< 2.00	NA	NA	NA
	2.00–3.99	37.64 ± 6.82 ^{ef}	0.88 ± 0.04 ^a	100% case-hardening
	4.00–5.99	46.93 ± 4.59 ^d	0.87 ± 0.03 ^a	100% case-hardening
	6.00–7.99	51.56 ± 4.63 ^c	0.89 ± 0.04 ^a	100% case-hardening
	> 8.00	NA	NA	NA
	mean	49.95 ± 6.36	0.87 ± 0.04	100% case-hardening

^{a–f} Post hoc Tukey's HSD test results, different letters represent significantly different values for a given parameter ($P < 0.05$); data are expressed as the means ± SD (standard deviation); *MC* – moisture content; NA – not enough samples

of fungal species. Although the minimal moisture content required for mould growth was not well understood, an acceptable agreement was reached that a sustained relative humidity greater than 80% at the wood surface could allow moulds to develop (Carll, Wiedenhoef 2009; Ojanen et al. 2010; Viitanen et al. 2010; Tsongas, Riordan 2016; Glass et al. 2017). The moisture content, particularly water activity, was a key factor in mould growth that had been linked to differences in the extent of mould growth among fungal species (Lie et al. 2019a, b). However, some species had higher levels of mould resistance than all other wood species, especially heartwood; for example, the heartwood of red and white oaks was undesirable for mould growth (Arango et al. 2020). However, environmental factors, such as the presence of active fungal spores, adequate temperature, sufficient moisture, nutrient substrate, oxygen (species dependent), and lack of biocidal agents (suitable pH, no toxic materials), still had significant effects on the growth of fungi (Lepage et al. 2022). Detection and species identification of all mould present in mouldy buildings is the first step toward resolving the cause and effect

of building-related illness (sick building syndrome), so the choice of sampling method is essential. Air and dust samples have been taken in order to associate mould exposure and health problems.

CONCLUSION

Eucalyptus, as a raw material in Thailand, is mainly supplied for the pulp and paper industries, which require young trees to increase pulp yields, although old trees are still needed for lumber and veneer supplies. The demand for young trees (juvenile wood) as a raw material in the wood industry is still met by the Thai market. Although there is specimen-to-specimen variation and a lack of consistently clear effects, there is significant evidence of eucalyptus clones and log size effects on the mechanical properties. Therefore, the findings of this study can be used to develop and update grading standards for fast-growing eucalyptus clones for particular engineered wood products. Wood density varies according to the clone type. The wood density of trees from clone K58 is greater than that of trees from the other clones. This

difference can be attributed mainly to the large *DBH* classes of the stem. A greater *DBH* is associated with a greater taper value. The clone K7 has lower *MOR* values (45 MPa) than clones K58 (54 MPa) and K62 (57 MPa) in terms of means. This trend was also detected with other properties; an exception was the *MOE* of K58, with its mean value of 17 MPa, whereas other clones had about 21 MPa. Therefore, it can be stated that clone K7 had slightly lower strength and clone 58 lower stiffness than the other clones. Generally, the values for each clone were getting higher as *DBH* size increased in a consistent manner. This trend seems to be especially strong over 200 mm *DBH* classes in each clone type. In conclusion, the physical and mechanical properties of butt logs were depending on *DBH* size. If the selective sorting method can be carried out in the timber supply chain, the larger *DBH* log classes could have the potential to utilise a wider range of end-products. All lumber stresses are case-hardening, and water activity showed the potential risk of moulding. The limitations of this study are the inadequate number of samples in some *DBH* classes. Our study gives useful information to stakeholders, especially about the small size stems, which have been only a few times under research focus. Additionally, our study scrutinised three clones at the same time to bring to daylight their similarities and differences, which has not been carried out before.

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