

Physical and mechanical properties of wood from *Eucalyptus camaldulensis* clonal plantation

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Abstract:

The technological quality and potential utilization of wood from individual *Eucalyptus* clones under Moroccan plantation conditions remain uncertain, particularly for clone 699 at the age and under the plantation conditions investigated in this study. This study aimed to evaluate the physical and mechanical properties of wood from a nine-year-old *Eucalyptus camaldulensis* clonal plantation (clone 699) in Morocco and to provide evidence on its potential for alternative wood uses. Ten logs from ten different trees were collected and processed into standardized test specimens. Physical characterization included moisture content, basic density, radial, tangential and volumetric shrinkage, and shrinkage anisotropy, while mechanical characterization included dynamic and static modulus of elasticity, bending strength, compression strength, and axial tensile strength. The studied wood showed high basic density (668kg/m³), medium volumetric shrinkage (14,53%), and normal shrinkage anisotropy (2,40), while its mechanical properties were generally in the low-to-intermediate range compared with previously reported *Eucalyptus* materials. Overall, the physical and mechanical characterization provides evidence on the technological quality of nine-year-old clone 699 under the studied plantation conditions and contributes to reducing uncertainty regarding its potential utilization beyond its traditional applications.

Keywords: *Eucalyptus camaldulensis*, mechanical properties, Morocco, wood shrinkage, wood density.

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Introduction

Eucalyptus genus is one of the most widely planted introduced genera in Morocco, owing to its rapide growth, adaptability and economic importance (Zanuncio *et al.* 2020, Amer *et al.* 2021, Yang *et al.* 2022). Eucalyptus plantations occupy an important part of the country's reforested area and include pure stands of *Eucalyptus camaldulensis* and *Eucalyptus grandis*, as well as their hybrids and clones (Marien 1993, Marien and Idrissi 2011). Since the establishment of clonal plantations, genetic selection has been applied to increase productivity and to obtain a homogeneous wood resource for industrial purposes. These plantations are thus an important forest resource, the future utilization of which depends not only on productivity but also on quality and technological properties of the produced wood.

The late 19th century saw the introduction of Eucalyptus to Morocco, and its development was furthered with the founding of the "Cellulose du Maroc" cellulose factory (El Haouzali and Birch 2024). Morocco has been using a genetic improvement method since 1987 to increase productivity and provide a consistent supply to this factory. Developing, choosing, and vigorously growing high-performance interspecific clones based on river red gum (*Eucalyptus camaldulensis* Dehnh.) and rose gum (*Eucalyptus grandis* W.Hill) is the main goal of this approach (Marien 1993). Morocco now has a verified database of about 40 highly productive hybrid clones. A 42200-hectare planted massif has been developed thanks to clonal cultivation (Marien and Idrissi 2011). Thus, the development of clonal plantations has long been primarily driven by Cellulose du Maroc's need for wood.

Following the closure of the facility in 2013, however, the context of eucalyptus wood utilization in Morocco has changed. A few sectors have grown somewhat, such as the manufacturing of charcoal and the use of wood for greenhouse construction and tomato stakes. Nonetheless, standing timber and its assortments have become increasingly less expensive since the facility closed in 2013. This wood is still mostly used for greenhouse construction, stakes, and charcoal manufacture. This circumstance emphasizes the necessity of looking into new

options to guarantee the sector's viability. In fact, eucalyptus clonal wood can be used for a variety of purposes, such as woodworking, furniture, and building materials (Serenini Jr *et al.* 2020, Brunetti *et al.* 2021).

The potential for such alternative uses depends, however, on the technological characteristics of the wood. Wood intended for building should be very strong, rigid, and dimensionally stable (Lima *et al.* 2018, Hein *et al.* 2012). In the case of furniture and woodworking, the wood should have attractive appearance qualities as well as good workability for machining and finishing. Achieving these requirements necessitate innovative recovery processes. Consequently, understanding the physical and mechanical characteristics of wood from different clones is crucial. Despite this, studies on this subject related to Moroccan plantations are scarce (Famiri *et al.* 2011, Amer *et al.* 2019, Amer *et al.* 2020, Amer *et al.* 2021, El Haouzali and Birch 2024). This limited knowledge creates uncertainty regarding the technological quality and potential utilization of wood produced by individual clones under Moroccan plantation conditions. In particular, characterization of the physical and mechanical properties of clone 699 is needed to provide evidence on its wood quality at the age and under the plantation conditions investigated in the present study. Such characterization is also necessary to compare the observed properties with previously reported values and to determine whether the wood presents characteristics that could support consideration of alternative uses. The interpretation of these results must nevertheless remain proportional to the experimental design, which is limited to the studied clone, age and plantation conditions.

To address this research problem, the present study focuses on the physical and mechanical characterization of wood from a Moroccan clonal Eucalyptus plantation. The physical characterization includes moisture content, basic density, and shrinkage, while the mechanical characterization includes the static and dynamic modulus of elasticity, stress rupture in four-point bending, axial compression, and axial tension. By combining these physical and

mechanical properties, the study aims to provide a more comprehensive characterization of the wood quality of clone 699 and to contribute evidence for evaluating its potential utilization beyond its traditional applications.

Materials and methods

Sampling and specimen preparation

The material used in this study included ten trees of clone 699 (river red gum (*Eucalyptus camaldulensis* Dehnh.)), obtained from 9-year-old plantation located in the area around Casablanca, in Morocco (Figure 1). Details on site characteristics are presented in Table 1. The ten trees were chosen randomly, their diameters ranged between 19 and 22 cm. From each tree, a one-meter-long butt log was removed.

Table 1: Growth site characteristics.

Soil	Clay
Bioclimate	Semi-arid
Average annual rainfall	350 mm
Altitude	410 m
Terrain type	Flat

One disc 2 cm thick was removed from each tree at base level, for initial moisture content measurement. Each log was cut longitudinally into planks which were stored and allowed to

dry naturally for ten weeks. The dried planks were then converted into specimens for various physical and mechanical tests. For each log, specimens were selected to cover the full range of radial positions and to ensure that no visible defects were present. Dimensions and number of different specimens are given in Table 2. Prior to sample cutting, the planks had been conditioned at 60 ± 2 % relative humidity and $20\pm1^\circ\text{C}$ for 2 weeks to reach the equilibrium state.



Figure 1: Plantation site and typical logs harvested from clone 699.

Initial moisture content

The moisture content (MC) is the mass of water ($m_h - m_0$) contained in the wood, expressed as a ratio to the mass of the oven-dry wood (m_0) on a percentage basis and calculated as follows

Equation 1:

$$MC = \frac{(m_h - m_0)}{m_0} \times 100 \quad (1)$$

The initial moisture content was quantified on the ten 2 cm thick disks. These have been measured, immediately after felling trees, for the green weight (m_h). Then, they were oven-dried at $103 \text{ }^{\circ}\text{C} \pm 2 \text{ }^{\circ}\text{C}$ until a constant anhydrous weight was attained.

Basic density

The basic density (D_b) was determined according to Equation 2, cited by Polge (1966), where m_s is the saturated mass and m_0 is the anhydrous mass. The saturated state was obtained by the integral saturation method (Keylwerth 1954), consisting of boiling the wood samples for at least 15 hours. The anhydrous mass was obtained after oven drying at $103 \pm 2^{\circ}\text{C}$ until a constant weight was attained.

$$D_b = \frac{1}{\frac{m_s}{m_0} - 0,347} \quad (2)$$

Shrinkage

Wood shrinkage was evaluated by measuring radial shrinkage (S_R), tangential shrinkage (S_T), volumetric shrinkage (S_V) and anisotropy of shrinkage (S_A). It was ascertained in accordance with the French standard NF B 51-006 (1985), on the same specimens used for basic density measurement.

Table 2: Number of samples used per test.

	Sample shape	Samples number per tree	Total number
Moisture content	2 cm thick Disk	1	10
Infradensity and shrinkage	Cube (20x20x20 mm ³)	10	100
Vibration test and four-point bending test	Specimen made according to French standard NF B 51-006 (1985)	10	100
Compression test	Specimen made according to French standards NF B 51-007 (1985)	10	100
Tensile test	Specimen made according to French standards NF B 51-017 (1988)	10	100

Vibration test

To estimate the dynamic modulus (MOE_D) by a nondestructive test method, the BING bending vibration method was used for 100 samples (Figure 2). This is a fully automated system

designed by CIRAD-Forêt following work by Bordonne (1989) (CIRAD 2012). The technique is also known as the resonance method, as it takes into account the resonance frequencies of a beam from its response to an impact. This allows determination of the bending and compression module by analysis of the natural vibration spectrum of a piece of wood (Brancheriau and Baillères 2002, Hein *et al.* 2010). The interpretation of the spectrum of the natural frequencies is based on the fact that the ratio of elastic modulus to density (specific modulus) of a material is proportional to the speed of signal propagation in the material. To obtain the dynamic modulus (MOED), each specimen was placed on elastic supports so as to generate free vibrations. An exciting impulse was produced through percussion bending perpendicular to the grain in edgewise direction with a hammer at the opposite side of the output transducer (Figure 2). The input and output signals were transmitted via a low pass filter to an acquisition card on a computer and recorded as described in Brancheriau and Baillères (2003).



Figure 2: Device used for measuring the dynamic modulus of elasticity.

Four-point bending test

A four-point bending test was performed in accordance with the French standards NF B 51-008 (1987) and NF B 51-016 (1987). The test was carried out on the same samples used for the vibration method. It was performed on a universal testing machine (Figure 3), of 100 kN capacity, to measure static modulus of elasticity (MOE_s) and bending strength (MOR_B). The span between lower supports was 320 mm; the distance between two loading points was 160 mm (1 free and 1 fixed); the diameter of roller bearings was 60 mm; and the test was conducted at a rate of 10 mm/min.

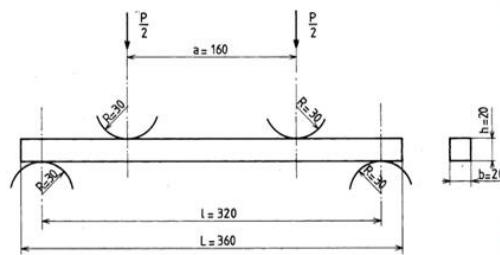


Figure 3: Setup and device of the four-point bending test.

Compressive and tensile tests

These tests were conducted using the same apparatus used for the bending test. compressive strength (MOR_C) and tensile strength (MOR_T), were evaluated following the French standards NF B 51-007 (1985) and NF B51-017 (1988).

Statistical analysis

A one-way analysis of variance (ANOVA) was conducted to evaluate the effect of tree identity on the physical and mechanical properties of the studied wood. ANOVA was used to determine whether the ten trees sampled from the clone 699 plantations differed significantly from one another. Changes were deemed significant at a 95 % confidence level ($p < 0,05$). The relationship between dynamic and static modulus of elasticity was assessed using Pearson's correlation coefficient (r). Statistical analyses were conducted using Statistica software.

Results and discussion

Green moisture content

The average moisture content (MC) of the sampled trees is 117,7 % (Table 3). It is slightly higher than that noted by Amer *et al.* (2017) on a clone of rose gum (*Eucalyptus grandis* W.Hill) and on a clone of river red gum (*Eucalyptus camaldulensis* Dehnh.). Yang *et al.* (2022) also reported lower values in the case of ampupo (*Eucalyptus urophylla* S.T.Blake) × rose gum (*Eucalyptus grandis* W.Hill) wood. However, Rezende *et al.* (2010) and Zanuncio *et al.* (2013) had reported higher values. According to Table 3, the green moisture content does not seem to

vary between the trees. The absence of significant differences in green moisture content among trees indicates limited variation within the sampled population under the conditions investigated. The similar age and site conditions could have played a role in this pattern, but cannot alone account for this observed result. The green moisture content noted, showed that the wood of the clone 699 can be sawn or peeled, without any prior water treatment.

Table 3: Mean values of studied properties.

	MC (%)	D _b (kg/m ³)	S _R (%)	S _T (%)	S _V (%)	S _A	MOE _D (MPa)	MOE _S (MPa)	MOR _B (MPa)	MOR _C (MPa)	MOR _T (MPa)
Mean	117,69	668,65	4,40	10,54	14,53	2,40	16861,03	13027,74	76,67	38,03	66,06
Standard deviation	7,35	63,97	0,23	0,71	0,75	0,18	1491,65	1136,84	7,30	7,21	7,23
Coefficient of variation	6,24	9,6	5,1	6,73	5,17	7,40	8,8	8,7	9,5	18,96	10,94
Maximum	127,95	784,86	5,67	12,04	17,08	2,75	19265,30	14934,34	94,80	56,11	84,07
Minimum	104,62	555,62	4,10	8,71	12,74	1,99	11673,21	9049	62,73	24,19	52,77

MC: Moisture content; D_b: Infradensity; S_R: Radial shrinkage; S_T: Tangential shrinkage; S_V: Volumetric shrinkage; S_A: Shrinkage anisotropy; MOE_D: Dynamic modulus; MOE_S: static modulus; MOR_B: Bending strength; MOR_C: Compression strength; MOR_T: Tensile strength.

Basic density

The average basic density (D_B) is 668,65 kg/m³. This average is similar to the values reported by Gérard *et al.* (1995) for *Eucalyptus* clones. It is lower than that cited by Loulidi *et al.* (2012). However, it is higher than those mentioned in findings reported for *Eucalyptus* clones (Lima *et al.* (2001), Zanuncio *et al.* (2015), Amer *et al.* (2017), Serenini Jr *et al.* (2020)). The difference in wood density between this study and previous reports may be due to the genotype of the clones, to differences in location, and/or tree age. Numerous studies have reported a large genetic variation in wood density and a moderate to strong heritability for wood density (Zobel and Jett 1995, Wu *et al.* 2011, Pima *et al.* 2018). The environmental influence on wood density

was also observed by a variety of studies. For example: Ibanez *et al.* (2017) and Costa *et al.* (2020). Nonetheless, Zhang *et al.* (2003) and Batista *et al.* (2010) had highlighted that most of the variance in wood density. is due to clone.

According to the ANOVA (Table 4). basic density showed significant between-tree variation. This variability was not large. with the coefficient of variation in the range of 10 % (Table 3). This result is like other reports that have confirmed low variation between neighboring trees of the same age for *Eucalyptus* clones. The coefficients of variation that have been reported were also below 10 % (Gominho *et al.* 2001, Quilho and Pereira 2001, Carrillo *et al.* 2015). These observations deviate from the general view that in eucalyptus density. within-tree variation can easily exceed 50 % even in plantations developed on the same site and time (Wilkes 1988). This discrepancy may be attributed to the difference in sampling technique or genotypic uniformity of the seed source. The high basic density of the studied wood may be advantageous for certain industrial applications. However, it may limit its suitability for applications where low weight is a primary requirement, such as lightweight packing materials. Further studies are needed to assess its suitability for specific end uses.

Shrinkage

The radial, tangential and volumetric shrinkage noticed values are close to the values recorded by Batista *et al.* (2010) for 10-year-old rose gum (*Eucalyptus grandis* W.Hill) clones. However, they are lower than those detected in Amer *et al.* (2019), assessing two 9-year-old clones, one of rose gum (*Eucalyptus grandis* W.Hill) and another of river red gum (*Eucalyptus*

camaldulensis Dehnh.). Statistical analysis (Table 4) showed that the shrinkage behavior can vary by individual tree. Such variation was also reported by Kang and Lee (2004) and Listyanto *et al.* (2020). This variability would be related to the inter-tree variability of the density. Indeed, Zhang *et al.* (2021) confirm that wood density affects wood shrinkage significantly, but no significant correlation, between density and shrinkage, was found for our samples.

Table 4: ANOVA results according to the tree factor.

	F	P	DF
Infradensity	7,01*	0,00	9
Radial shrinkage	21,19*	0,00	9
Tangential shrinkage	15,10*	0,00	9
Volumetric shrinkage	24,89*	0,001	9
Shrinkage anisotropy	2,12*	0,03	9
Dynamic modulus of elasticity	22,97*	0,00	9
Static modulus of elasticity	20,96*	0,001	9
Bending strength	0,36	0,71	9
Compression strength	0,19	0,66	9
Traction strength	0,17	1,00	9

F: F-Statistic

P: P-value

DF: Degree of freedom

*: Significant variance at a 95 % confidence level.

According to its volumetric shrinkage, the studied clone can be classified in the group of medium volumetric shrinkage (González *et al.* 1997). The observed shrinkage values may be partly explained by the young age of the trees and the possible predominance of juvenile wood, as reported in the literature (Serenini Jr *et al.* 2020). Similarly, the possible contribution of tension wood may also be considered, as its occurrence and influence on wood properties have been reported (Washusen and Ilic 2001). With respect to the anisotropy, clone 699 can be considered normal quality (Serenini Jr *et al.* 2020). This is close to the typical findings of Spear and Walker (2006) who reported that the range of normal anisotropy is 1,5-2,5.

This shrinking causes clone 699 to be a wood requiring careful drying in manufacture to avoid excessive loss. If put into service at close to the moisture content at which it will remain in service, wood remains in place quite satisfactorily. Quarter-sawing makes it possible to attenuate this strong retractability. Thermal treatment is also a way of improving the dimensional stability of this wood.

Modulus of elasticity

In comparing the noticed dynamic modulus (Table 3) with similar data for rose gum (*Eucalyptus grandis* W.Hill) clones from Brazilian and Moroccan plantations (Hein *et al.* 2012, Amer *et al.* 2021), our samples showed higher values. Lima *et al.* (2018) found a mean value of 17900 MPa for dynamic modulus in rose gum (*Eucalyptus grandis* W.Hill) wood, value higher than that found in this study. The average static modulus (Table 3) is higher than that of Amer *et al.* (2021), but lower than those reported, for rose gum (*Eucalyptus grandis* W.Hill), by Ruy *et al.* (2018) and Brunetti *et al.* (2021).

Even with the young age of the sampled trees, presenting only juvenile wood, our sample is classified as medium rigidity wood (Gerard *et al.* 2012). On the other side, an inter-tree variation is observed in our sample set (Table 4) about dynamic and static modulus. The noticed disparity in our data and between our data and the literature, on the other hand, could be related to the density variation. De Boever *et al.* (2007) state that the modulus of elasticity is strongly positively correlated with density.

An excellent positive correlation was found between static modulus and dynamic modulus, with high statistical significance at the 99 % confidence level ($r = 0,76$). It was also shown that

dynamic modulus (using Timoshenko approximation) was always slightly higher than static MOE, as observed many times in the literature (Yang *et al.* 2003, Baar *et al.* 2015, Rahayu *et al.* 2015, El Haouzali *et al.* 2020). According to Baar *et al.* (2015), the reason behind this trend may be attributed to the viscoelastic behavior of wood. The significant positive relationship observed between MOEd and MOEs ($r = 0,76$) supports the potential use of dynamic modulus as a non-destructive indicator of wood stiffness in the studied material.

Bending strength

The average strength in bending assay is 76,67 MPa (Table 3). By referring to Gérard *et al.* (2012), this average is a weak strength. The associated standard deviation reveals low dispersion. Despite this dispersion, there was no significant difference between trees (Table 4). The values obtained in the present work are lower than those observed by Gonçalves *et al.* (2009) and Acosta *et al.* (2007), in rose gum (*Eucalyptus grandis* W.Hill) clones. On the other side the studied clone (699) is more resistant than the six rose gum (*Eucalyptus grandis* W.Hill) clones tested by Serenini Jr *et al.* (2020). The two clones tested by Amer *et al.* (2021) are also weakly resistant to bending. The disparity noted may be partly related to differences in wood density, as density is generally positively associated with wood strength (Balboni *et al.* 2020). As shown by De Boever *et al.* (2007), inter-clonal differences in bending strength may also be associated with other wood characteristics, including fiber length.

Compression strength

Tests showed an average value of 38,03 MPa. According to Gérard *et al.* (2012), the studied wood can be considered as weak in axial compression. It is closer to the rose gum (*Eucalyptus grandis* W.Hill) clones studied by Zanuncio *et al.* (2018). The tree effect was revealed as insignificant (Table 4). These results are similar to those reported by Benin *et al.* (2017) for parallel compression wood from 6-year-old *Eucalyptus benthamii*. However, our results are lower than those of Amer *et al.* (2021) who evaluated 9-year-old rose gum (*Eucalyptus grandis* W.Hill) and river red gum (*Eucalyptus camaldulensis* Dehnh.) clones. The values cited by Serenini Jr *et al.* (2020) for five rose gum (*Eucalyptus grandis* W.Hill) clones are also higher than ours.

On the other side, a lowest value (27 MPa) was found by Ferreira *et al.* (2020), when assessing 7-year-old rose gum (*Eucalyptus grandis* W.Hill) clone. The differences between the clone 699 and the other clones, in terms of compressive strength, would be linked to the density. Numerous studies have confirmed this link (Bektas *et al.* 2002, Chowdhury *et al.* 2012, Adetayo and Dahunsi 2017). Zanuncio *et al.* (2018) relate inter-clonal variability of compressive strength to microfibril angle. According to these authors lower microfibril angle is associated with higher compressive strength. However, microfibril angle was not measured in the present study, so its potential contribution to the compressive strength of clone 699 cannot be directly determined.

Tensile strength

The axial tensile strength noticed is about 66,06 MPa, it doesn't vary significantly depending on the tree (Table 3 and Table 4). Our samples show a higher tensile strength than that noted by Amer *et al.* (2021) on a clone of rose gum (*Eucalyptus grandis* W.Hill) and on a clone of river red gum (*Eucalyptus camaldulensis* Dehnh.). When evaluating river red gum (*Eucalyptus camaldulensis* Dehnh.). Awan *et al.* (2012) determined that tensile strength was recorded as 60 MPa. In turn, Frank and Marto (2014) obtained 115 MPa for the mean tensile strength of wood from southern blue gum (*Eucalyptus globulus* Labill.). When testing sydney blue gum (*Eucalyptus saligna* Sm.) wood, Nogueira *et al.* (2019) reported an axial tensile strength equal to 95,50 MPa.

Conclusion

In this study, we present the physical and mechanical characterization of wood from a nine-year-old *Eucalyptus camaldulensis* clone (clone 699) planted in a Moroccan clonal plantation. The wood was characterized by high basic density, medium volumetric shrinkage and normal shrinkage anisotropy. When compared to values reported for other species and clones of *Eucalyptus*, its mechanical properties were generally in the low to intermediate range. The results help reduce the uncertainty about the technological quality of wood produced by this clone, and provide a basis to think about alternative uses beyond its traditional applications. Further studies with more clones and sites must mostly be concentrated on: the assessment of

practices integrating sawing and drying processes, the analysis of the viability of alternative silvicultural measures and hybridization to improve the wood quality and to confirm the potential utilization of clonal Eucalyptus wood in Morocco.

Authorship contributions

H. E. H.: Conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft, writing – review & editing. B. E. B.: Investigation, data curation, formal analysis. M. A: Resources, investigation.

Conflict interest

The authors declare no conflicts of interest.

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