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For correspondence and editorial enquiries relating to submission of papers and to journal subscription, please e-mail or write to:

KA Sarifah
Forest Research Institute Malaysia (FRIM)
52109 Kepong
Selangor Darul Ehsan
Malaysia

Editors: KA Sarifah (sarifah@frim.gov.my) & S Vimala (vimala@frim.gov.my)
Consulting editor: FSP Ng (tropicalplantman@gmail.com)

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COLLAPSE AND PHYSICAL PROPERTIES OF NATIVE AND PRE-STEAMED *EUCALYPTUS CAMALDULENSIS* AND *EUCALYPTUS SALIGNA* WOOD FROM TUNISIA

Elaieb MT[1], Ayed SB[1], Ouellani S[2], Khouja ML[1], Touhami I[1] & Candelier K[3, 4, *]

[1]*LGVRF, INRGREF, B.P. 10, 2080 Ariana, Tunisia*
[2]*Arrondissement des forêts, Nabeul, rue d'Alger 4029, Nabeul, Tunisia*
[3]*CIRAD, UPR BioWooEB, F-34398 Montpellier, France*
[4]*BioWooEB, Univ Montpellier, CIRAD, F-34398 Montpellier, France*

**kevin.candelier@cirad.fr*

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Eucalyptus is the second major wood species used for Tunisian reforestation since 1957, and they are found around the country in several arboretums. *Eucalyptus* may be an interesting raw material to the Tunisian wood industry. The main obstacle to its industrial exploitation is its natural propensity to incur internal checking, collapse and a high transverse shrinkage during industrial drying process. This study focused on the physical and mechanical properties of reforested *Eucalytus saligna* and *Eucalyptus camaldulensis* from the north west of Tunisia. Moisture content, densities, shrinkages and mechanical properties were determined. Then, the impact of pre-steaming on the physical properties of modified wood was investigated. The results showed that both *Eucalyptus* possess low dimensional stability and mechanical properties compared to other *Eucalyptus* species from Tunisia, Morocco, Australia and Brazil. These wood characteristics were mainly due to their low density and sensitivity to collapse reactions, occurred during drying. Pre-steaming process reduced *Eucalypts* wood moisture content, changing the wood permeability and resulting in a residual collapse recovery and a decrease in wood shrinkage. Pre-steaming treated *E. camaldulensis* and *E. saligna* wood could be valuable as furniture and/or structural material without being submitted to moisture content variation.

Keywords: Collapse phenomenon, densities, mechanical properties, shrinkages, Tunisian *Eucalyptus*

INTRODUCTION

Eucalyptus, a native genus from Australia, belongs to the *Myrtaceae* family and consist of 900 species and subspecies. It is one of the world's most important and widely planted genera. It has been introduced worldwide, including Tunisia, and mainly cultivated for its timber, pulp and essential oils that possess medicinal properties and therapeutic uses (Slimane et al. 2014, Sebei et al. 2015). *Eucalytus* is also known for its melliferous characteristics in the production of high quality honey. This fast-growing species adapted very well to the Tunisian climate and was used to stabilise the costal dunes of northwest Tunisia, reduce erosion and protect the roadsides (Khouja et al. 2001, Dia and Duponnois 2010). Nowadays, *Eucalyptus* is the second major Tunisian reforestation wood species covering 43,000 ha with an annual production of 3 m^3 $annum^{-1}$ ha^{-1}, that gives a potential annual wood production of 120,000 m^3 (FAO 2012). However, the industrial use of these valuable *Eucalyptus* wood remains mainly restricted to fuelwood or pulpwood because of limited research on utilisation of wood; usage of the *Eucalyptus* wood as material is very limited in Tunisia (Kabir et al. 1995). *Eucalyptus* is considered as an invasive wood species that needs to be economically valued. Despite the abundance of the species, only recently efforts have been made towards its full utilisation. Marketing of Eucalyptus products has been hindered by lack of knowledge about its wood properties. However *Eucalyptus* has currently become a subject of interest as raw material for wood composite panels in many tropical and subtropical countries including Thailand, Chile, Brazil and Malaysia (Nacar et al. 2005).

In the coming years, there will be a large supply of Tunisian plantation timber for different segments of the forest market. Thus, the development of *Eucalyptus* solid wood products seems to be very promising at the

national level. The main challenge in developing high value-added products from *Eucalyptus,* such as remanufactured lumber, is the inherent difficulties in drying this species. Because of the natural propensity to internal checking, collapse and a high transverse shrinkage, lumber grade recovery after industrial drying is generally very low. Unacceptable internal checking and collapse after drying, reported in scientific literature for several *Eucalyptus* wood species, confirmed that the commercialisation of *Eucalyptus* as solid wood products remains a great challenge (Northway 1995, Ananias et al. 2014).

Therefore, a good understanding of the relationship between collapse and wood characteristics is needed to successfully process this species into commercial solid wood products. In addition, wood pre-treatment can be performed to improve wood properties and limit checking and recover collapse. A variety of pre-drying treatments is discussed ranging from storage in controlled environments, to various wrapping types, pre-surfacing and pre-heating. Cutting boards radially, rather than tangentially, can also be regarded as a form of pre-drying treatment, as well as the application of an end-coating to freshly sawn logs. Pre-heating green timber prior to drying include steaming microwave treatment and pre-freezing, and boiling (Ellwood 1953, Lee and Jung 1985, Haslett and Kininmonth 1986, Vermaas and Bariska 1995, Zhang et al. 2011, Kong et al. 2017). Such treatments result in increased permeability and drying rate, which reduces wood drying time (Yang and Liu et al. 2018).

The steaming of wood is a technique which has been employed for a variety of purposes in the conversion and utilisation of forest products. These include the facilitation of bending, alteration of colour, reduction in levels of growth stress, improvement in dimensional stability, increase in permeability and improvement of penetration by preservatives, facilitation of enzymatic hydrolysis, reconditioning of collapse-prone species and the reduction in drying time and rate during seasoning (Tieman 1929, Greenhill 1938, Perkitny et al. 1959, Campbell 1961, Ellwood and Erickson 1962, MacKay 1971, Chen 1975, Chen and Workman 1980, Shimizu et al. 1983, McGinnes and Rosen 1984, Weik et al. 1984, Lee and Jung 1985, So 1985, Barnes 1986, Cutter and Phelps 1986, Haslett and Kininmonth 1986, Donaldson et al. 1988,). During steaming, the growth stresses of wood can be released by means of microstructural reorganisation and thus, improve the quality of timber (Length and Kamke 2001; Severo et al. 2010; Kiemle et al. 2014). The wood is also softened and growth stress is released as it reaches the glass transition temperature during drying process. The wood ductility is increased due to its improved viscoelastic properties, and finally results in decreased drying cracks and collapse (Calonego et al. 2010).

The objectives of this study were (i) to determine the physical and mechanical properties of reforested *E. camaldulensis* and *E. saligna*, (ii) to evaluate the impact of steam pre-treatment on the physical properties of modified wood and (iii) to identify the potential valorisations of *E. camaldulensis* and *E. saligna* woods in Tunisia. The results obtained could contribute towards the development of a database, useful for planting and processing. It will also be useful for tree breeders and silviculturists to identify the properties that need improvement through breeding selection or forest management strategies.

MATERIALS AND METHODS

Wood selection and sampling

In this study, 50 years old *E. camaldulensisa* and *E. saligna* wood species were chosen to estimate the physical and mechanical properties of *Eucalyptus* wood species from Tunisian reforestation. A total of 3 trees of each wood species were collected from Zarniza arboretum, governorate of Bizerte, regions of Sejnane (37°9' N, 9°7' E), from selected healthy trees, free from defects and alteration, with almost perfectly straight trunk (Figure 1), according to Oger et Lecerq (1997). The *Eucalyptus* trees were selected as representatives of their respective populations within the arboretum (tree dimeter of 40 cm at 1.30 m from the ground).

The climate of this northwest region of Tunisia is sub-humid with an annual rainfall of 927 mm year^{-1}. Average annual temperatures range from 14.9 °C to 18.5 °C. The average maximum temperature of the warmest month reaches more than 35 °C, and the average minimum of the coldest month is around 4 °C. The soil is poorly developed in coastal dunes with leached brown forest in the mountains (Rejeb et al. 1996).

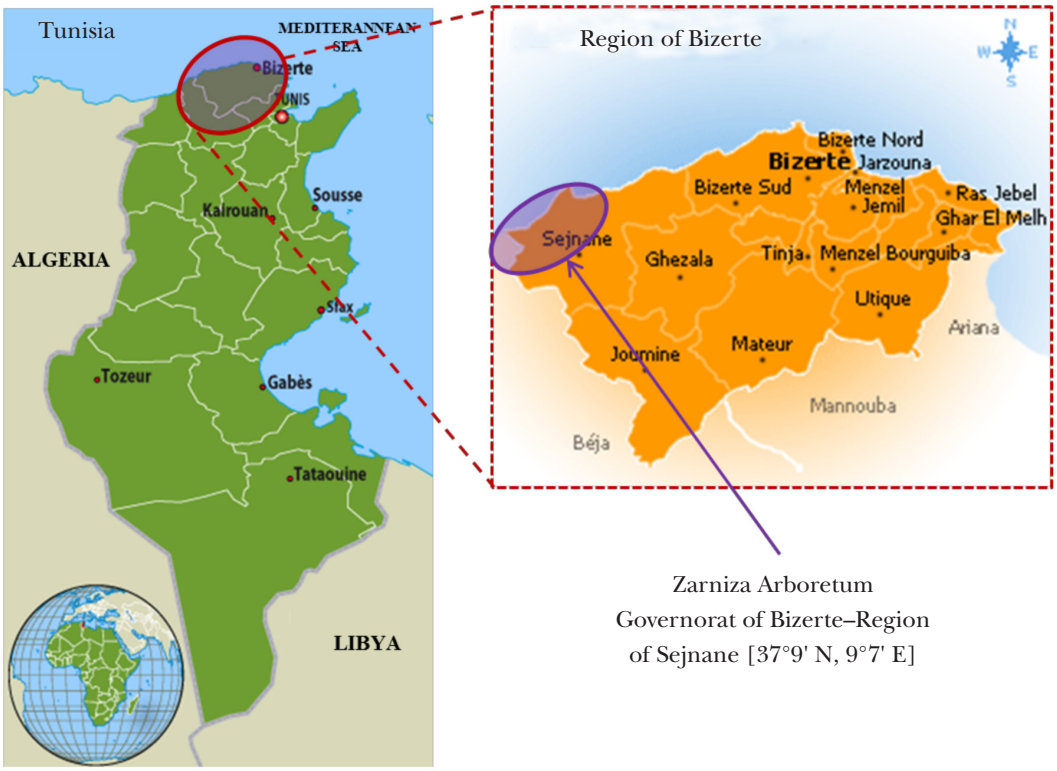

Figure 1 Location of the selected *E. camaldulensis and E. saligna* trees

Physical properties

Wood samples used for the physical and mechanical characterisations do not differentiate the sapwood and heartwood for selected trees, because the sapwood/heartwood ratios are different relating to the trees. The aim of this study is to valorise eucalyptus woods without separating sapwood and heartwood. Wood samples for physical and mechanical tests were randomly chosen from the log, in order to observe the high results generally obtained in such characterisations (Figure 2). An overview of sampling performed on the different trees, for physical and mechanical tests, is shown on Figure 2.

Relative humidity

To measure the humidity of trees, a wooden disk of 50 mm thickness was cut at 1.35 m from the ground for each selected tree (Figure 2). Then, wooden disks with dimensions of 20 × 20 × 10 mm (along the grain) were cut from the samples, according to the repartition presented in Figure 3a. Profiles of humidity repartition within the wooden disks were drawn and moisture content calculated using the following equation:

$$\text{EMC}\ (\%) = 100 \times \frac{(m_h - m_0)}{m_0} \qquad (1)$$

Where m_h is the green mass of the initial sample and m_0 is the oven-dried mass of the wood sample.

Density and shrinkage

To perform the physical tests, two wooden disks of 50 mm thickness were cut at 1.40 m from the ground for each selected tree; one disk to determine the native wood properties and the other to evaluate pre-steaming process on wood collapse phenomenon (Figure 2). Selection of the samples was similar for the two disks (in position, distance to pith and azimuth angle from the north) in order to obtain a good comparison between native and steamed wood samples. To avoid errors during sampling, extreme cases such as excessively knotty trees, presence of reaction wood or slope grain were taken into account (ISO 4471 1982). From each disk, samples of 3 cm width, from bark to bark, were cut in both directions; N-S and E-W (Figure 3b). These samples were then cut into strips of 2 cm thickness. In total, the density and shrinkage measurements (with and without steaming) were

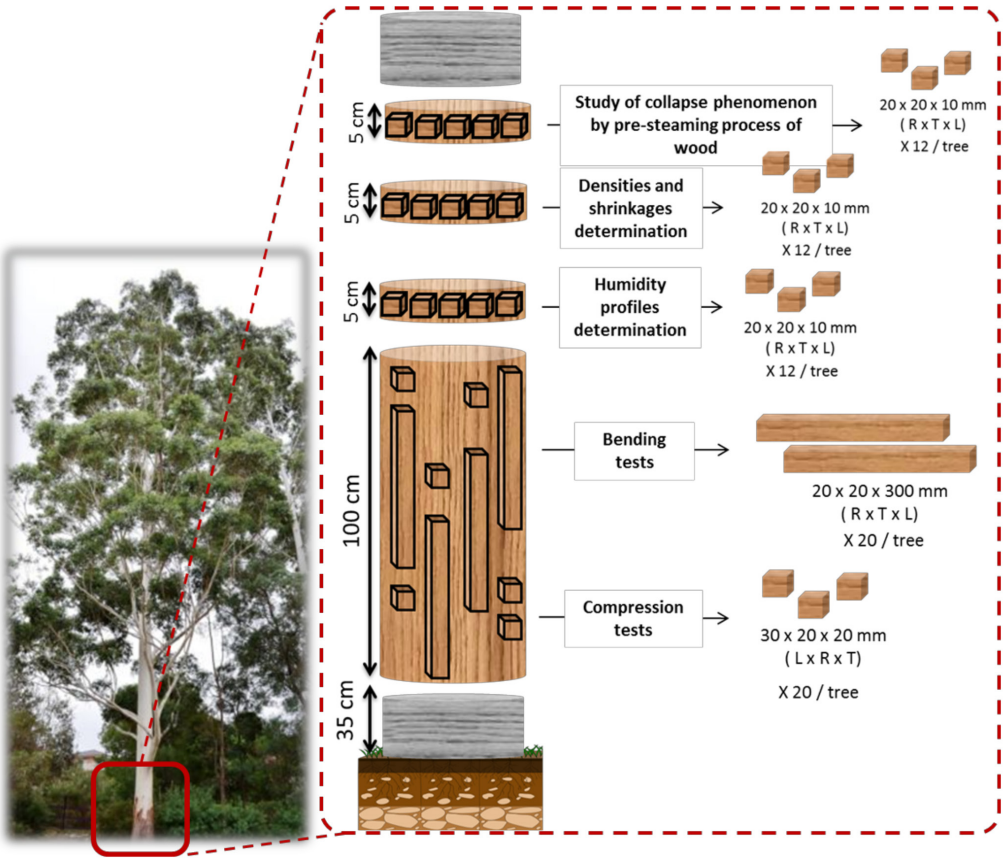

Figure 2 Overview of *Eucalyptus* wood sample selection for the physical and mechanical analyses

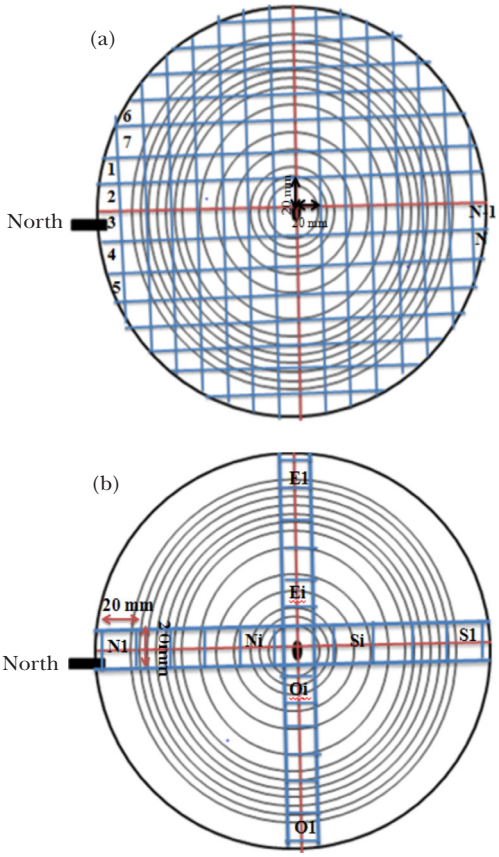

Figure 3 Wood sample repartition for humidity (a), densities and shrinkages (b) determination tests

carried out on 165 samples for both wood species, *E. camaldulensis* and *E. saligna*.

Density

Basic density, air-dried density (after conditioning in a climatic room at 20 °C and 65% RH) and oven-dried density (after conditioning in an oven at 103 °C) (D_{m12}, D_{m0}) of the wood samples were determined according to International Organization for Standardisation Standards using wood specimens of 20 × 20 × 10 mm (along the grain) (ISO 13061-2 2014). The shape factor ($\beta t\ \beta r^{-1}$) was the ratio between tangential and radial shrinkage. The densities were determined by the gravimetric method (Haygreen and Bowyer 1996).

$$D_b = \frac{m_0}{V_h} \quad (2)$$

$$D_{m0} = \frac{m_0}{V_h} \quad (3)$$

$$D_{m12} = \frac{m_{12}}{V_{12}} \quad (4)$$

Where m_h is the humid mass of the initial sample, m_0 is the oven-dried mass of the wood sample, and m_0 and m_{12} are the oven-dried and air-dried weight of the sample (g), respectively; D_b is the basic density of wood (g cm^{-3}), D_{m0} is the oven-dried density of wood (g cm^{-3}) and D_{m12} is the air-dried density of wood (g cm^{-3}); V_h is the green volume of the specimen (cm^3), V_0 is the oven-dried volume of the sample and V_{12} is the air-dried volume of wood sample.

Shrinkage without steaming

Shrinkage (β) [tangential (βt), radial (βr), longitudinal (βl) and volumetric (βv) of the wood samples were determined according to International Organization for Standardisation Standards using wood specimens of 20 × 20 × 10 mm (along the grain) (ISO 4469 1981). The shape factor ($\beta t\ \beta r^{-1}$) was the ratio between tangential and radial shrinkage. Volumetric shrinkage was measured using the following equation:

$$B_v = \frac{(V_h - V_0)}{V_h} \times 100 \quad (5)$$

Similar operations were used to determine tangential (βt), radial (βr) and longitudinal (βl) shrinkages, using dimensional variation of the respective orientation.

Shrinkage with steaming

In order to avoid the collapse phenomenon, each wood specimen was placed into a chamber with adjustable temperature and relative humidity for progressive reconditioning until mass stabilisation of 16% moisture content. After reconditioning, samples were autoclaved at 90 °C, 2.5 bars, for 30 min. Mass and 3-dimensional measurements were taken for each sample, prior to drying at 103 °C until mass stabilisation.

Mass and 3-dimensional measurements of the dried samples, and shrinkage (β_0) [tangential (βt_0), radial (βr_0), longitudinal (βl_0) and volumetric (βv_0)] of the pre-streamed wood samples were determined in the same way as for shrinkage without steaming (ISO 4469 1981). The shape factor ($\beta t_0\ \beta r_0^{-1}$) without collapse was also determined.

Comparison between shrinkage with or without steaming

In order to evaluate the collapse phenomenon effect on wood shrinkage, Indicators of Collapse Recovery (IRC), in the three directions, were determined according to the following formula:

$$IRC\ (\beta_v) = \frac{(\beta_v - \beta_{v0})}{\beta_v} \times 100 \quad (6)$$

Similar operations were used to determine tangential IRC (βt), radial IRC (βr), IRC longitudinal (βl) shrinkages, and IRC(βt/βr), using dimensional variation of the respective orientation.

Mechanical properties

To perform mechanical resistance tests, three point bending (MOR) and compression tests were carried out for each of the selected wood tree samples, and results were compared. A universal mechanical test machine was used for the measurements. Samples were conditioned in a climate-controlled room with 65% RH and at 22 °C, for the time required to stabilise the samples weights.

Bending test

Three point static bending tests were carried out according to EN 408 (2010). The sample size was 300 × 20 mm × 20 mm^3 (L × R × T). The moving head speed and span length were 0.09 mm s^{-1} and 260 mm, respectively. The load deformation data obtained were analysed to determine the modulus of rupture (MOR). The tests were replicated on 20 samples from each selected *Eucalyptus* tree.

Compression strength parallel to grain

Compression tests were carried out according to EN 408 (2010). Deviating from the norm, a reduced specimen size of 30 × 20 × 20 mm^3 (L x R x T) was used. The moving head speed was 0.09 mm s^{-1} to ensure wood sample rupture within 1.5 to 2 minutes. The load deformation data obtained were analysed to determine the modulus of rupture (MOR). A total of 20 collapsed wood specimens per selected tree were tested.

Statistical analyses

Statistical analyses (one-way analysis of variance) using Fisher test and JMP 10.0.2 program were performed. The effects of pre-streaming process on *E. camaldulensis* and *E. saligna* on wood densities and shrinkages properties were evaluated using ANOVA and Duncan's comparison test. Such analysis allows to class results into several categories from A to C. Systems which are not connected by the same letter are largely different at the 5% level.

RESULTS AND DISCUSSION

Moisture content

Table 1 gives the minimal, maximal and average values of initial moisture contents of *E. camaldulensis* and *E. saligna* trees at 1.40 m from the ground, just after felling. On average, the initial moisture contents were 75.14% for *E. camaldulensis* wood and 87.27% for *E. saligna* wood, with respective minimal values of 59.80% and 36.95% and maximal values of 122.65% and 116.71%. The moisture content of both *eucalyptus* wood species were relatively close. In comparison with other *Eucalyptus* species, moisture content of *E. camaldulensis and E. saligna* were similar to those found in close geographical locations. Sahbeni (2014) found initial moisture content values of 82.9% and 101.5% for *E. bicostata* and *E. coriacea* woods from Souniat arboretum in Tunisia. Even if these trees grew and were felled in similar conditions with those of the present study, moisture content comparison is still needed. Elaieb et al. (2017) highlighted that moisture content of fresh felled *E. loxophleba* and *E. salmonophloia* in Northeast Tunisia were 37.1% and 37.8%, respectively. However, the initial *eucalyptus* wood moisture can be largely variable. Ananias et al. (2014) found wood initial moisture content ranging from 132 to 200% for different *E. nitens* trees from Las Mellizas site in Rucamanque farm, located near the city of Huepil in the eighth region of Chile.

The studied *E. camaldulensis* and *E. saligna* woods was characterised by low initial moisture content wood, when being felled. The results showed that initial moisture content repartition

Table 1 Wet moisture contents average values: minimum and maximum values of *E. camaldulensis and E. saligna* woods

	Moisture contents (%)				
Wood species	Min (%)	Max (%)	Average (%)	SD (%)	CV (%)
Eucalyptus camaldulensis	59.80	122.65	75.14	9.52	13.56
Eucalyptus saligna	36.95	116.71	87.27	13.30	15.33

SD = standard deviation, CV = coefficient of variation

within the tree is different between *E. camaldulensis* and *E. saligna* woods. Figure 4 shows that the moisture content of *E. saligna* wood increased progressively from the pith to bark, whereas the opposite was observed for *E. Camaldulensis* wood. The mean values of moisture content for *E. saligna* increased from 40% for the core wood, 85% for transition wood area to 120% for sapwood. On the contrary, the mean values of moisture content for *E. camaldulensis* decreased from 120% for the heartwood, 85% for transition wood area to 60% for sapwood (Figure 5).

According to literature, moisture content of fresh felled eucalyptus trees vary relating to the wood species. Elaieb et al. (2017) and Ananias et al. (2014) found similar trends in initial wood moisture content distribution within *E. loxophleba*, *E. salmonophloia* and *E. nitens* tree. The results showed that initial moisture content of heartwood was considerably higher than transition and sapwoods. However, Fromm et al. (2001) highlighted that moisture content of various *Spruce* and *Oak* trees decreases from early wood to late wood.

Density

Air-dried density (Dm_{12}) is commonly used to compare different woods. Basic density (D_b), oven-dried density (Dm_0) and air-dried density (Dm_{12}) were measured on each *E. camaldulensis* and *E. saligna* wood sample. Average values, maximal and minimal values of the different densities and coefficient of variations are presented in Table 2.

D_b, Dm_{12} and Dm_0 were 0.639 ± 0.014 g cm^{-3}, 1.001 ± 0.014 g cm^{-3} and 0.772 ± 0.028 g cm^{-3} for *E. camaldulensis* and 0.544 ± 0.070 g cm^{-3}, 0.804 ± 0,019 g cm^{-3} and 0.739 ± 0,020 g cm^{-3} for *E. Saligna,* respectively.

E. camaldulensis and *E. saligna* wood species is classified as heavy wood ($D_{m12} > 0.95$) and from mid-heavy wood ($0.65 > D_{m12} > 0.80$) to heavy wood ($D_{m12} > 0.95$), respectively (Campredon 1967).

Similar results were showed by a study conducted on 61 different *Eucalytus* tree species from Austalia (including *E. camaldulensis*, *E. platycorys*, *E. loxophleba* and *E. salmonophloia),*

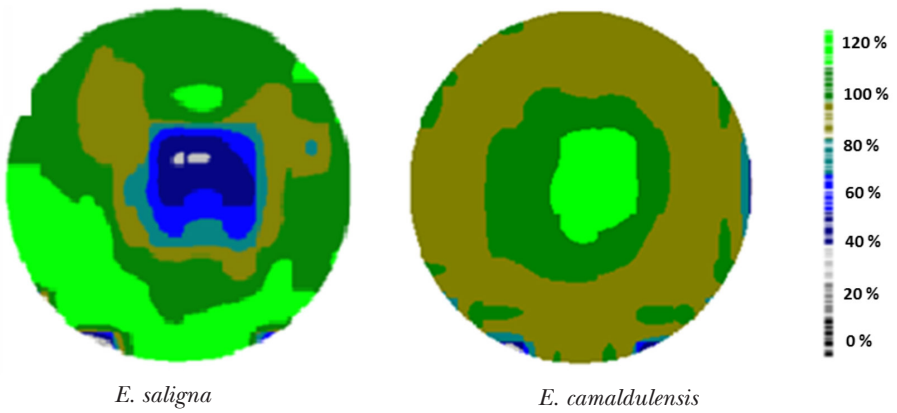

Figure 4 Moisture content repartition within *E. camaldulensis* and *E.saligna* trees

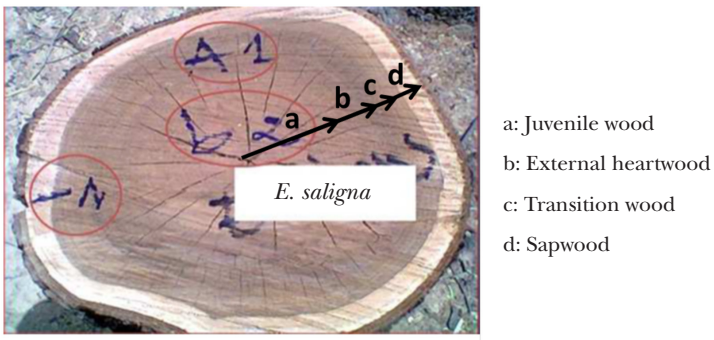

Figure 5 Location and definition of juvenile wood, heartwood, transition wood and sapwood

Table 2 Values of air dried, anhydrous and basic densities of *E. camaldulensis and E. saligna*

	Wood species	Min	Max	Average	SD (%)	CV (%)
D_{m12} (g cm^{-3})	*Eucalyptus camaldulensis*	0.993	1.017	1.001	0.014	0.014
	Eucalyptus saligna	0.651	1.173	0.804	0,019	0,009
D_{m0} (g cm^{-3})	*Eucalyptus camaldulensis*	0.742	0.798	0.772	0.028	0.037
	Eucalyptus saligna	0.413	0.673	0.738	0.020	0.127
D_b (g cm^{-3})	*Eucalyptus camaldulensis*	0.629	0.655	0.639	0.014	0.021
	Eucalyptus saligna	0.363	0.687	0.544	0.070	0.130

SD = standard deviation, CV = coefficient of variation

that *Eucalytus* wood basic density was between 0.690 and 0.940 g cm^{-3}. In Tunisia, studies on wood characterisation were conducted in the past two years on local *Eucalptus* wood species: *E. bicostata*, *E. cinerea*, *E. coriacea, E. maidenii*, *E. torquata* and more recently on *E. loxophleba* and *E. salmonophloia* woods (Selmi et al. 2014, Dridi 2015, Elaieb et al. 2017). The respective basic densities of these wood species are 0.630, 0.619, 0.711, 0.691, 0.870, 0.860 and 0.894 g cm^{-3}. Comparing the results from the current study with those from other Tunisians *Eucalyptus* species, *E. camaldulensis and E. saligna* seem to be classified among the lightest Tunisian *Eucalyptus* woods.

Finally, the large differences observed between minimal and maximal values of D_b, D_{m0} and Dm_{12} in *E. saligna*, could be explained by the lower density of its juvenile wood than those of its sapwood.

Shrinkage and shape factors

Shrinkage analyses shows the volumetric (βv), tangential (βt), radial (βr), longitudinal (βv) shrinkages and shape factor (βt βr^{-1}) values of *E. camaldulensis* and *E. saligna* (Figure 6). These results showed clearly that *E. camaldulensis* wood is more sensitive to moisture content variations than *E. saligna* wood. Indeed, the average value of shape factor of *E. camaldulensis* (2.16) was higher than those of *E. saligna* (1.81). The volumetric, tangential and radial shrinkage average values of *E. camaldulensis and E. saligna* were 25.2 and 22.1% (βv), 17.9 and 14.5% (βt), 8.1% and 7.9% (βr), respectively. The *E. camaldulensis* and *E. Saligna* were classified as wood with a high volumetric shrinkage (βv > 13%), a high tangential shrinkage (βt > 10%) and a high radial shrinkage (βr > 6.5%). According to the literature, shrinkage of Tunisian *E. camaldulensis and E. saligna* woods are relatively close to those of other *Eucalyptus* species such as *E. loxophleba* (βt βr^{-1} = 2.5) and *E. salmonophloia* (βt βr^{-1} = 1.2) from Tunisia, *E. globulus* (βt βr^{-1} = 1.6) from Morocco, *E. citrodiora* (βt βr^{-1} = 1.43) and *E. grandis* (βt βr^{-1} = 1.64) from Brazil and *E. torquata* (βt βr^{-1} = 1.27) from Tunisia (Segura 2007, El Alami 2013, Sahbani 2014, Selmi 2014, Dridi 2015, Elaieb et al. 2017).

Influence of steam pre-treatment on wood properties

In some *Eucalyptus* species, wood shrinkage is often preceded by collapse phenomenon (Sesbou and Nepveu 1978). Previous studies highlighted shrinkage variations of *Eucalyptus* wood species occurring above the wood fiber saturation point (Elaieb et al. 2017). This trend is probably due to wood collapse reaction. Indeed, collapse of the cells during drying is commonly observed in certain timber species and is particularly pronounced in some members of the genus *Eucalyptus* (Berry and Roderick 2005). Collapse is defined as a form of irregular shrinkage occurring above the fiber saturation point (Assouad 2004, Tazrout et al. 2012). The most common explanation for collapse is capillary tension. One of the causes of collapse is that the cell walls cannot withstand the surface tension of the water that is removed from the lumen of the fibers. On the other hand, macroscopic stresses arising in the wood during drying have been suspected to contribute to collapse, and have been claimed by some workers to be the sole cause of the phenomenon (Greenhill 1938, Stamm and Loughborough 1942). However,

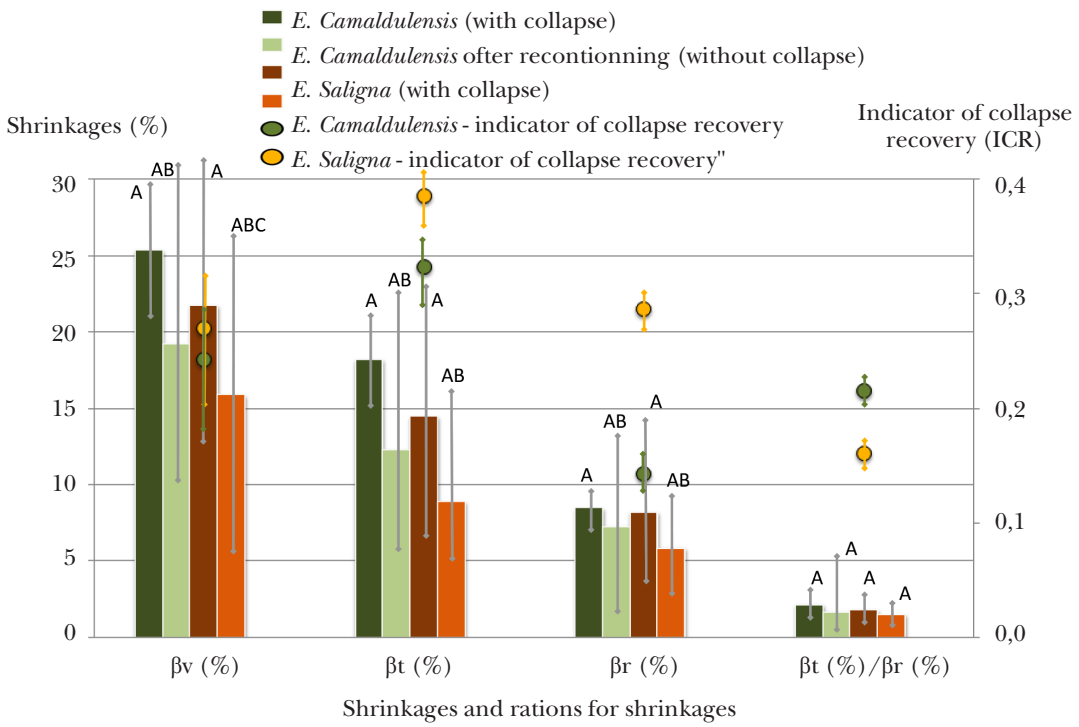

Figure 6 Average values of shrinkages and indicator of collapse recovery (ICR) in different orientation of *E. camaldulensis* and *E. saligna* before (with collapse) and after conditioning (without collapse)

literature also acknowledges that collapse can occur below the fiber saturation point (Almeida et al. 2008).

Because of the natural propensity to internal checking, collapse and a high transverse shrinkage, the *Eucalyptus* wood grade recovery, after industrial drying, is generally low (Haslett 1988). Anecdotal industrial experience suggests that *Eucalyptus* woods recovery after industrial drying could be as low as 20–30% for the thicker sawn sizes (Ananias et al. 2014). Unacceptable internal checking and collapse after drying was also reported in scientific literature for *Eucalyptus* wood (Ananias et al. 2009). This internal checking and collapse make the commercialisation of some *Eucalyptus* solid wood products unviable for the moment.

The steaming of wood is a technique which has been employed, for several years, for a variety of purposes in the conversion and utilisation of forest products, including reconditioning of collapse-prone species (Tieman 1929, Greenhill 1938). Through such steam treatment process, wood absorb a small amount of moisture and resume its initial shape which decreases the effect of collapse. While such applications are valuable in improving wood utilisation, steaming has disadvantages in that it may reduce the strength of the wood (Campbell 1961, Rosen and Laurie 1983, Stubenvoll 1985) and increase shrinkage, collapse and checking susceptibility during drying (Greenhill 1938, Kauman 1961, Liang 1981, Haslett and Kininmonth 1986). Nevertheless, there remains some disagreement with respect to the effect of pre-steaming on shrinkage and associated degrade.

Figure 6 shows that the mean values of shrinkage in pre-streaming conditioned *E. camaldulensis* and *E. saligna* wood were lower than those of control specimens. However, the dispersion of pre-treated woods shrinkages was wider than those from control samples, which does not highlight that steam pre-treatment has a significant effect on wood physical properties. In addition, according to IRCs indicators, *E. saligna* seems to be more sensible to collapse than *E. camaldulensis*. In fact, whatever the wood direction, IRC values from *E. saligna* wood shrinkage was higher than those from *E. camaldulensis* wood shrinkage.

The results confirmed those obtained by previous studies on other *Eucalyptus* wood species. Ananias et al. (2014) highlighted that shrinkage before reconditioning and collapse of *E. regnans* wood showed highly significant increases in pre-steamed material with the exception of

sapwood, but shrinkage after reconditioning was not significantly changed by pre-steaming for any data group. Campbell (1961) reported that steaming treatments of 2 to 4 h duration increase drying rates considerably without increasing the incidence of collapse. Further, in *E. delegatensis* shrinkage before reconditioning and shrinkage after reconditioning (2–4 h steaming) were not significantly different from controls (Campbell 1961). Unlike Haslett and Kininmonth (1986), who observed unacceptable levels of internal or surface checking after 2 h of pre-steaming in *Nothofagus fusca*, Campbell (1961) observed less checking in *E. obliqua* after pre-steaming, although collapse was greater. In oak, Lee and Jung (1985) found fewer end checks and slightly less collapse and honeycombing after 4 h of pre-steaming at 100 °C than in control specimens.
A number of hypotheses have been advanced to account for changes in wood properties due to steam pre-treatment:

(i) Changes in chemical bonding among cell wall constituents or heat degradation are notably by lignin and hemicelluloses and changes in wood extractives (Kauman 1961, Kininmonth 1971, Kubinsky 1971, Salud 1976, McGinnes and Rosen 1984)
(ii) In terms of liquid tension theory, the preconditions for collapse development are high impermeability, water-saturated cell lumens and relatively weak cell walls (Tiemann 1915).

An increase in wood permeability together with a reduction in initial moisture content should produce a reduction in collapse. This decrease in moisture content in presteamed material was interpreted as reflecting changed permeability, likely responsible for the changed level in residual collapse of pre-steamed material (Ananias et al. 2014).

Density

As found by shrinkage properties determination, Db measurements of untreated and steam pre-treated *E. Saligna* and *E. camaldulensis* woods showed higher sensitivity to collapse of *E. saligna* compared to those of *E. camaldulensi*. These results were consistent with previous studies which reported that collapse in *Eucalyptus* wood species tend to be higher when density of wood is lower (Kingston and Risdon 1961, Ananias et al. 2009). Chafe (1986) recognised that collapse increases proportionally to the increase in green moisture content and reduction in basic density. Figure 7 shows that the mean loss in density after steam pre-treatment of *E. saligna* (= 0.09) is higher than for *E. camaldulensis* (= 0.01). Although statistically not significant, it was

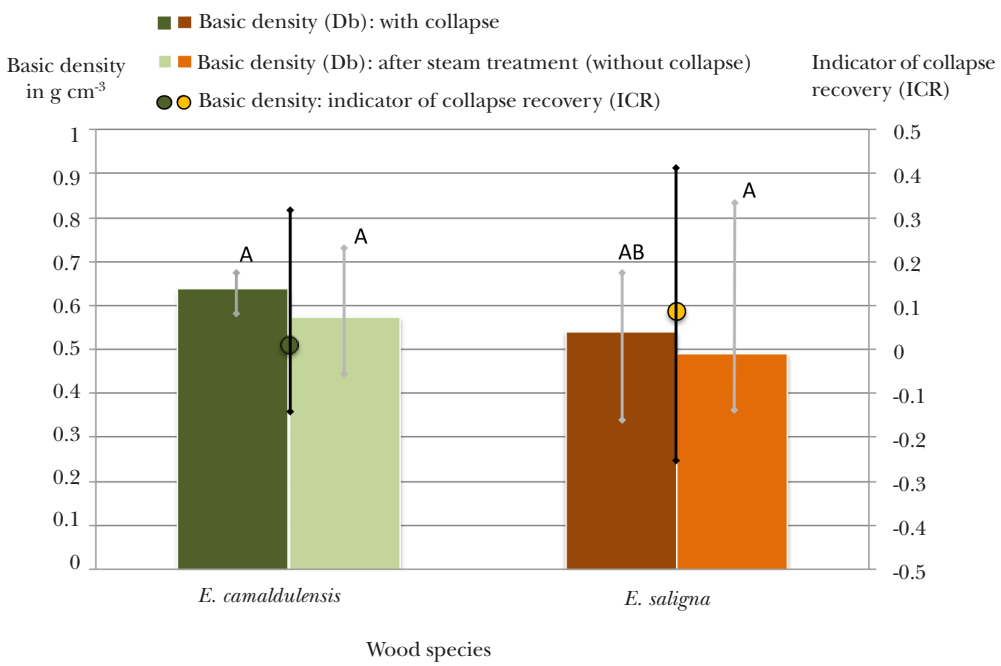

Figure 7 Average values of basic density (Db) and indicator of collapse recovery (ICR) of *E. camaldulensis* and *E. saligna* before (with collapse) and after conditioning (without collapse)

observed that steam pre-treatment slightly decreased D_b for both *Eucalyptus* wood species. This decrease in density could be explained by the removal of extractives and low degradation of hemicelluloses. However, according to results, disparity and lower mean value of IRC (positive and negative values around 0.0), steam pre-treatment does not significantly affect the D_b of *E. saligna* and *E. camaldulensis*.

Mechanical properties

The mechanical test results of *E. saligna* and *E. camaldulensis* woods conditioned at a temperature of 20 °C and 65% RH are shown in Table 3. The MOR average values of *E. camaldulensis* and *E. saligna* woods were respectively 80.01 MPa and 53.75 MPa in bending and 39.62 MPa and 31.72 MPa in compression. Previous studies show that *E. camaldulensis* and *E. saligna* wood species can be classified as having medium (55 MPa < σc < 75 MPa) and low (σb < 75 MPa) static bending strength respectively, and low axial compressive strength (σc < 45 MPa) (Collardet and Besset 1998).

In comparison with literature, the results of *E. saligna* and *E. camaldulensis* woods had lower bending and compression strength properties than other Tunisian *Eucalyptus* species. Ghodhbéne (2014) characterised Tunisian *E. cinerea* and *E. maidenii* wood and found bending strength values of 132.5 MPa and 107.2 MPa, and compression strength values of 54 MPa and 48.7 MPa. Sahbani (2014) found similar results for *E. bicostata* with a compression strength value of 50.40 MPa. Elaieb et al., (2017) showed that MOR average values of Tunisian *E. loxophleba* and *E. salmonophloia* woods were 95.8 MPa and 97.2 MPa in bending test and 56.3MPa and 56.9 MPa in compression test, respectively. Thus, the species is classified as having high static bending strength and medium/high axial compressive strength (Collardet and Besset 1998).

The lower mechanical properties of *E. saligna* and *E. camaldulensis* woods than those of other *Eucalyptus* wood species from Tunisia could be due to their higher sensitivity to collapse and lower density.

CONCLUSION

The study focused on the physical and mechanical properties of north-western *E. saligna* and *E. camaldulensis* woods issued from Zarniza arboretum of the Sejnane region. The study was conducted on three trees each of *Eucalyptus* wood species from one geographical location. However, the results obtained cannot be generalised. Both species of *Eucalyptus* had lower physical and mechanical properties than other *Eucalyptus* wood in Tunisia and other countries such as Brazil, Australia and Morocco, probably due to their sensitivity to collapse phenomenon. Due to collapse reactions, *E. saligna* and *E. camaldulensis* remain lowly exploited by lumber manufacturing industry in Tunisia, for the development of commercial solid wood products. The steam pre-treatment technique was found effective in recovering much of the collapse. It could be advantageously applied in Tunisia and other countries with *Eucalyptus* industries for better valorisation of ligneous products. This study showed that steam pre-treatment of *E. saligna and E. camaldulensis* could improve wood properties and allow them to be used as material to produce flooring, interior joinery, furniture, glulam and light frame for wood construction, in Tunisia.

Table 3 Mechanical properties of Tunisian *E. saligna* and *E. camaldulensis* woods: bending strength (σb) and compression strength (σc)

	Wood species	Min	Average	Max	SD[a]	CV[b]
σb (MPa)	*Eucalyptus camaldulensis*	10.72	80.01	125.50	15.26	0.19
	Eucalyptus saligna	4.04	53.75	99.75	11.86	0.21
σc (MPa)	*Eucalyptus camaldulensis*	5.53	39.62	54.89	7.70	0.15
	Eucalyptus saligna	8.16	31.72	44.27	7.24	0.08

[a]standard deviation, [b]coefficient of variation

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