Pinus halepensis and *Eucalyptus camaldulensis* Grown in Egypt: A Comparison Between Stem and Branch Properties for Pulp and Paper Making

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The utilization of branchwood as lignocellulosic raw material source for paper production may have the potential of solving the problem of the availability of raw material in the pulp and paper industry. This study therefore compared the chemical composition and fiber morphological indices (according to Franklin's method) of stemwood and branchwood in *Eucalyptus camaldulensis* and *Pinus halepensis* trees grown in Egypt. The statistical analysis showed a significant effect of species, wood type (stem and branchwood), and their interaction on the measured chemical constituents and fiber morphological indices at 0.05 significance level. In both genera, the stemwood exhibited a higher percentage of cellulose and hemicellulose and was lower in lignin, total extractives, and ash than those measured in branchwood. Also in both genera, the stemwood was higher in fiber length, Runkel ratio, rigidity coefficient, Muhlsteph ratio, and Luce's shape factor, and lower in basic density and flexibility coefficient than those in branchwood. Based on the chemical analysis and the fiber morphological indices, the stemwood and branchwood of both species were suitable for paper production with various qualities. Moreover, good correlations were found in both stem and branchwood between the basic density and the fiber wall thickness and fiber lumen diameter. In contrast, there was an independent association between the stemwood basic density and the fiber length, and this relationship in branchwood was positive for both genera.

Keywords: Stemwood; Branchwood; Ash; Muhlsteph ratio; Lignin; Cellulose

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INTRODUCTION

Due to limited forest resources, over the last two decades Egypt has successfully planted several tree species using treated wastewater irrigation systems to increase the forest resources (Zalesny, Jr. *et al.* 2001; Hassan and Tippner 2019). In Egypt, the demand for paper products such as newsprint, paperboards, coated printing and writing papers, liner and fluting, tissue, and specialty paper is essential for various activities that have been dramatically increased (Ministry of State for the Environmental Affairs 2002). Therefore, the search for new sources of paper production is highly required. The production of writing and printing paper was 1.5×10^5 tons in 2018, whereas Egypt imported 3.99×10^5 tons per year (Food and Agriculture Organization 2020).

There are many types of trees growing successfully in Egypt, most of which are hardwoods. Rapidly growing trees have great importance for their wide utilization and include *Eucalyptus camaldulensis* and *Pinus halepensis*, both of which are relatively fast growing. *Eucalyptus camaldulensis* is an evergreen hardwood tree belonging to the Myrtaceae family and originating in Australia; *Pinus halepensis* is a softwood and in the family Pinaceae. The wood from *E. camaldulensis* is usually used for particleboard production, firewood, cellulose derivatives, and paper production. *Pinus halepensis* trees are usually used to prevent soil erosion and as windbreaks, as well as for wooden furniture, cabinets, charcoal, railway ties, and telephone poles (Ilvessalo-Pfäffli 1995; Coppen 2002; Fady *et al.* 2003; Farjon 2010).

Wood is a natural renewable material made up of the three main biopolymers lignin, cellulose, and hemicellulose. It is also comprised of extractives and ash as secondary components. Each chemical component has an important effect when utilizing wood as raw material for pulp and paper production (Rowell 2005). For instance, it is preferable in the pulp and paper industry to use raw material with high cellulose content and low lignin content (Zobel and Van Buijtenen 1989). In general, raw materials that contain a high percentage of cellulose, produce high pulp yield, while those with high lignin content consume more cooking chemicals (Ververis *et al*. 2004). In addition, the percentage of extractive and ash has major effects on the cooking process and the final sheet quality (Panshin and De Zeeuw 1970; Biermann 1996; Housseinpour *et al.* 2010). The high percentage of extractives and ash are undesirable, as they increase normal alkali consumption, increase cooking time, and cause problems during the black liquor recovery (Hillis 1962; Biermann 1996).

Additionally, some fiber biometrical measurements can indicate the quality of the final product, such as fiber length, slenderness ratio, Runkel ratio, flexibility coefficient, and rigidity coefficient (Ona *et al.* 2001; Wimmer *et al.* 2002). The long fibers increase the paper strength, especially the bursting strength and folding endurance of paper (Tamolang and Wangaard 1961; Ona *et al.* 2001). The fibers with low Runkle ratio and high elasticity coefficient are desirable for paper production due to their ability to collapse rapidly in the beating process and enhance the fiber-to-fiber bonding (Downes *et al.* (1997); Ona *et al.* 2001; Ohshima *et al.* 2005b). Fibers with low Luce's shape factor decrease resistance to beating in paper making (Luce 1970).

In Egypt, pulp and paper production is focused on few lignocellulosic raw materials and is generally concentrated on rice straw, bagasse, and *Eucalyptus* stemwood (Ministry of State for the Environmental Affairs 2002). However, the limited availability of the raw materials suitable for pulp and paper production prevents increased production of paper to meet the increasing needs. In other wood product sectors, such as in the wood-based panels industry, successful efforts have been devoted to using pruning wastes for particleboard production (Nemli *et al.* 2004; Lykidis *et al.* 2014). Likewise, studies need to be conducted investigating the suitability of pruning wastes for pulp and paper production as a potential alternative to stemwood. Few studies have discussed the difference in wood properties between branchwood and stemwood in various tree species, especially from a chemical point of view. For example, Kiaei *et al.* (2014) compared the chemical composition and the fiber morphology between stemwood and branchwood of *Prunus domestica*. Dadzie *et al.* (2015) compared the natural durability between stemwood and branchwood of *Entandrophragma cylindricum*. Dadzie *et al.* (2016a) studied the differences in density, mechanical properties, and the anatomical features between stemwood and branchwood of *Khaya ivorensis* and *Entandrophragma cylindricum*. Dadzie (2019) studied the variations in selected microstructure characteristics and termite resistance between stem and branchwood of *Pterygota macrocarpa* and *Terminalia* *superba*. Very little information exists in the literature about the variation in full chemical constituents and fiber morphology between stem and branchwood of *E. camaldulensis* and *P. halepensis*, especially those grown in arid and semi-arid regions. Therefore, this study examined the suitability of stemwood and branchwood of *Eucalyptus camaldulensis* and *Pinus halepensis* irrigated with treated wastewater for pulp production through measuring their chemical composition and fiber morphological indices.

EXPERIMENTAL

Materials

Two tree species, *Eucalyptus camaldulensis* (nine logs) and *Pinus halepensis* (seven logs) grown in the Egyptian-Chinese friendship plantation forest, Monoufia, Egypt, under a trickle irrigation system with treated wastewater, were used in this study. The age and diameter of *E. camaldulensis* and *P. halepensis* were 18 years old and 15.45 to 18.19 cm, and 20 years old and 18.84 to 26.5 cm, respectively. The branchwood diameter range was between 0.8 and 3 cm and 1.5 and 4.7 cm for *E. camaldulensis* and *P. halepensis*, respectively.

Methods

Determination of chemical constituents

The total extractive content was obtained through the extraction successively in toluene/ ethanol mixture, ethanol, and water using a Soxhlet extractor. The percentage of extractive content was calculated based on the oven-dried weight of samples (ASTM D1105-96 2013). Ash content was determined according to ASTM D1102-84 (2013). The prepared samples were put in a muffle at 600 °C until the elimination of all carbon. The percentage of ash content was calculated based on the moisture-free weight of the samples. The insoluble lignin was determined according to (ASTM D1106-96 2013). The wood powder was placed in a beaker with 15 mL of sulphuric acid (72 %) and let to stand with repeated stirring for 2 h. The mixture was transferred quantitatively into a 1- liter flask with 560 mL water to dilute the concentration to 3%. The solution was boiled for four hours under reflux, then filtered into a crucible and dried. The percentage of lignin was calculated based on the oven-dried weight of the samples. The cellulose content was determined according to Kürschner and Hoffer (1929), using the method outlined by Browning (1967). One gram of extractive-free wood particles (40 to 60 mesh) was refluxed with three successive portions of a mixture of concentrated nitric acid and ethanol in a water bath, and then the residue filtered in crucible G3, washed with hot water, dried, and the cellulose content was determined as a percentage of the oven-dried weight of the wood samples. The hemicellulose content was calculated by subtracting the sum of all the determined chemical constituents, including ash and total extractives from 100. The cellulose/lignin (C/L) ratio was also calculated, as it could be used when comparing the different raw materials used in the paper industry. The high C/L ratio indicates that the raw material contains high cellulose and low lignin.

Density and fiber morphological indices

The wood's basic density was determined using the oven-dried weight of samples and the green volume according to ASTM D2395 (2002) using the following equation,

$$BD = W_o / V_g \quad (1)$$

where BD is the basic density of wood (gm.cm^{-3}), W_o is the oven-dried weight of the specimen (gm), and V_g is the green volume (cm^{-3}).

Basic density is based on oven-dried mass and green volume, which are invariant and reproducible; thus, it is the best indicator of wood density (Walker 2006).

Fibers were macerated using Franklin's method through placing wood chips in a mixture of anhydrous acetic acid and hydrogen peroxide (Franklin 1946). The fiber biometrical measurements and their derived characteristics associated with pulp and paper properties were measured according to Wangaard (1962), Rydholm (1965), Luce (1970), and Ona *et al.* (1996),

$$RR = (2 \times F_{WT}) / F_L \quad (2)$$

$$SR = F_L / F_D \quad (3)$$

$$FC = F_{LD} / F_D \quad (4)$$

$$RC = F_{WT} / F_D \quad (5)$$

$$\text{Muhlsteph ratio} = \frac{(F_D^2 - F_L^2)}{F_D^2} \quad (6)$$

$$\text{Luce's shape factor} = L\frac{(F_D^2 - F_{LD}^2)}{(F_D^2 + F_{LD}^2)} \quad (7)$$

where RR is the Runkel ratio, SR is the slenderness ratio, FC is the flexibility coefficient, RC is the rigidity coefficient, F_L is the fiber length (μm), F_{WT} is the single wall thickness (μm), F_D is the fiber diameter (μm), and F_{LD} is the fiber lumen diameter (μm).

To calculate the percentage increase or decrease of the measured properties between the stemwood and branchwood, the following equation was used,

$$\text{Percentage (increase or decrease)} = [(A - B) / A] \times 100 \quad (8)$$

where A is the stem wood value and B is the branchwood value.

Statistical Analysis

A two-way analysis of variance (ANOVA) general linear model procedure was conducted to analyze the effects of wood species, wood type (stem and branch), and their interaction on the wood chemical constituents and fiber morphological indices. The comparison between means was done employing a Fisher's LSD test at 0.05 significance level. The Pearson correlation was used to describe the relationship between the basic density and the measured fiber morphological indices. The data were analyzed using Minitab statistical software (Minitab LLC., ver. 17.1.0, State College, PA, USA).

RESULTS AND DISCUSSION

Comparison of chemical properties of stem and branch wood

The average values of the chemical composition of the stemwood and branchwood for *Eucalyptus camaldulensis* and *Pinus halepensis* are presented in Table 1. The two-way analysis of variance showed that the species, wood type (branch and stemwood), and the interaction between them had a significant effect on all the determined chemical constituents at 0.05 level of significance. The Fisher's LSD test showed that there were significant differences in the chemical components among the stemwood and branchwood of both species at 0.05 significance level, except for those between the ash content in *P. halepensis* stemwood and *E. camaldulensis* stemwood. The cellulose and hemicellulose of the *E. camaldulensis* stemwood were higher by 11.6% and 10.5%, respectively, than their counterparts in branchwood. A similar trend was also observed in *P. halepensis*, where the cellulose and hemicellulose average values were higher in the stemwood than those in the branchwood. The C/L ratio was higher in the stemwood than those in the branchwood for both genera. In contrast, the branchwood showed higher lignin, extractive, and ash contents than those measured in stemwood for both genera.

Table 1. Chemical Composition of Stemwood and Branchwood for *E. camaldulensis* and *P. halepensis*

Chemical Composition	*E. camaldulensis*				*P. halepensis*			
	N	Stem Wood	Branch Wood	Percentage Difference	N	Stem Wood	Branch Wood	Percentage Difference
		Mean	Mean			Mean	Mean	
Cellulose (%)	6	49.21[a] (3.06)	43.51[b] (1.22)	+11.6%	6	45.32[c] (1.71)	41.93[d] (1.84)	+7.5%
Hemicellulose (%)	6	19.33[a] (0.77)	17.31[b] (0.73)	+10.5%	6	24.27[c] (1.56)	22.82[d] (1.55)	+6%
Lignin (%)	6	19.60[a] (0.82)	21.98[b] (0.86)	-12.1%	6	25.78[c] (1.32)	26.82[d] (1.49)	-4%
C/L Ratio	6	2.5[a] (0.2)	1.98[b] (0.09)	+20.8%	6	1.76[c] (0.1)	1.56[d] (0.11)	+11.4%
Total Extractives (%)	6	11.44[a] (0.67)	15.72[b] (0.50)	-37.4%	6	4.17[c] (0.25)	7.41[d] (0.39)	-77.7%
Ash (%)	6	0.42[a] (0.05)	1.48[b] (0.10)	-252.4%	6	0.46[a] (0.02)	1.02[c] (0.10)	-121.7%

Note: Means with the different letter in the same row were significantly different from each other at 0.05 significance level; values in parentheses were standard deviation; positive and negative signs indicate an increase and decrease from the stemwood values, respectively; C/L is cellulose to lignin ratio

Generally, a high percentage of cellulose in raw materials indicated a higher pulp yield. The acceptable α-cellulose content in the lignocellulosic raw materials for pulp production was greater than 40% (Ververis *et al.* 2004; Kiaei *et al.* 2014). Accordingly, both raw materials in this study, including the branchwood, had higher cellulose content than 40%, which predicts good pulp yield and high tensile strength for the produced paper (Madakadze *et al.* 1999). It is worth mentioning that a high percentage of hemicellulose retained in the pulp after the cooking process improves the swelling characteristics of pulp and paper, strength characteristics, and reduces the energy consumed during beating (Biermann 1996; Wang *et al.* 2014). Table l reveals the range of the stemwood and branchwood hemicellulose values, which predict that produced paper would have acceptable strength properties. Generally, lignin is an undesirable polymer, and its removal during pulping requires high amounts of energy and chemicals (Cao *et al.* 2014). In addition, higher lignin percentages in raw materials reduce the chemical pulp yield and the fiber strength (Gülsoy and Şimşir 2018). Notably, the results revealed that the branches from both species had higher lignin contents compared with the stemwood. Therefore, additional pulping time, higher temperature, and chemical charge may be required for branchwood than for stemwood to reach the suitable cooking condition. However, the recommended percentage of acid-insoluble lignin for common pulp raw materials is below 30% (Ververis *et al.* 2004). The stemwood and branchwood for both genera were below this percentage, implying that there would be no difficulties during the chemical cooking process. Dutt and Tyagi (2011) reported higher acid insoluble lignin content (33.2%) than the reported value in the current study for *E. camaldulensis* that was aged one-year and grown in India. As previously mentioned, the branchwood's total extractive content was higher than that found in the stemwood. This higher quantity of extractives in raw materials prepared for pulp production can cause many problems such as yield reduction, inhibition of cooking reactions, negative effects on the black liquor recovery, and corrosion of pulping equipment (Hillis 1962). Accordingly, soaking in hot or cold water before the cooking process to remove the extractives may improve the properties of the resulting paper. Hassan *et al.* (2020) studied *E. camaldulensis* and *P. halepensis* trees that were younger (15 to 16 years-old) than those reported in the current study and prepared for particleboard production. They found that the total extractive content were 9.26% and 3.16% for *E. camaldulensis* and *P. halepensis*, respectively, which is lower than the reported values in the current study. The branchwood also had higher ash content than that found in the stemwood. High ash content may affect chemical consumption during cooking, pulp washing, and beating (Biermann 1996).

Comparison of Density and Fiber Morphological Indices of Stem and Branch Wood

Basic density and fiber morphological indices (fiber length, Runkel ratio, coefficient of flexibility, slenderness ratio, Muhlsteph ratio, coefficient of rigidity, and Luce's shape factor) of stemwood and branchwood for the two studied species are presented in Table 2.

Wood density is an important parameter to assess the quality of raw materials for pulping. Wood density influences the fiber morphology and the final paper properties (Rudie 1998). Downes *et al.* (1997) reported that raw materials with basic densities between 400 and 600 $kg.m^{-3}$ were more preferable for paper manufacturing. Using low-density woods increases the tensile and bursting strength of the produced paper (Yahya *et al.* 2010). It is obvious that the branchwood basic density was significantly higher than that of stemwood at the 0.05 significance level for both species. The mean values of the stemwood and branchwood were 0.66 and 0.63 $g.cm^{-3}$ for *E. camaldulensis* and 0.57 and 0.55 $g.cm^{-3}$ for *P. halepensis*, respectively. These results agreed with a study conducted by Gurau *et al.* (2008) on maple wood, which found that the density of the stemwood and branchwood was 0.62 and 0.7 $g.cm^{-3}$, respectively. Okai *et al.* (2004) found that the density of branch and stemwood were 0.459 and 0.433 $g.cm^{-3}$, respectively, for *Terminalia ivorensis* wood. Similar properties were found in *Aningeria robusta* wood, with mean values of stemwood and branchwood of 0.50 and 0.56 $g.cm^{-3}$, respectively. In another study conducted by Dadzie *et al.* (2016b) that compared the density of stemwood and branchwood of two wood species grown in Ghana, it was found that *Terminalia superba* branchwood density values (643 $kg.m^{-3}$) were higher than for stemwood (557 $kg.m^{-3}$), while the density of *Pterygota macrocarpa* branchwood (647 $kg.m^{-3}$) was slightly lower than that of stemwood (656 $kg.m^{-3}$).

Table 2. Basic Density and Fiber Morphological Indices of Stem and Branchwood for *E. camaldulensis* and *P. halepensis*

Fiber Morphological Indices	*E. camaldulensis*				*P. halepensis*			
	N	Stem Wood Mean	Branch Wood Mean	Percentage Difference	N	Stem Wood Mean	Branch Wood Mean	Percentage Difference
Basic density ($g.cm^{-3}$)	21	0.63[a] (0.02)	0.66[b] (0.05)	-4.8%	21	0.55[c] (0.03)	0.57[d] (0.07)	-3.6%
Fiber length (mm)	80	0.86[a] (0.16)	0.70[b] (0.07)	+18.6%	401	2.81[c] (0.58)	2.19[d] (0.61)	+22.1%
RR	80	1.64[a] (0.2)	0.96[b] (0.1)	+41.5%	401	0.33[c] (0.03)	0.25[d] (0.01)	+24.2%
FC	80	0.43[a] (0.01)	0.54[b] (0.02)	-25.6%	401	0.74[c] (0.02)	0.79[d] (0.08)	-6.8%
SR	80	47.6[a] (13.3)	50.5[b] (11.2)	-6.1%	401	78.9[c] (10.4)	72.7[d] (13.1)	+7.9%
RC	80	0.29[a] (0.07)	0.23[b] (0.07)	+20.7%	401	0.12[c] (0.01)	0.01[d] (0.001)	+91.7%
Muhlsteph ratio (%)	80	80.0[a] (8.5)	68.6[b] (5.4)	+14.3%	401	44.8[c] (5.2)	36.7[d] (3.1)	+18.1%
Luce's shape factor	80	0.68[a] (0.14)	0.54[b] (0.13)	+20.6%	401	0.30[c] (0.12)	0.23[d] (0.11)	+23.3%

Note: Means with the different letter in the same row were significantly different from each other at 0.05 significance level; values in parentheses are standard deviations; positive and negative signs indicate an increase and decrease from the stemwood values, respectively; *RR* is Runkel ratio, *FC* is flexibility coefficient, *SR* is slenderness ratio, and *RC* is rigidity coefficient.

In a study performed by Zhao *et al.* (2018) on *Populus ussuriensis*, it was found that the stemwood density was higher than that of branchwood. In general, the majority of the previous studies and the present study indicated that the density of branchwood is generally higher than that of stemwood, which may be attributed to the slower growth rate of the branches and the presence of reaction wood compared with the stemwood (Tsoumis 1991). Timell (1986) reported that the formation of compression wood is normal in branches compared with stemwood due to the increasing weight during branch growth. Moreover, the high extractive content may contribute to the high density of branches. It is worth mentioning that the high density of *E. camaldulensis* is not desirable for the chemical pulp and paper industry. Therefore, to improve its properties in pulp or paper utilizations, this species may be mixed with lower density raw materials such as *P. halepensis* wood.

Fiber morphological indices—such as fiber length, width, and wall thickness— and their derived values are some of the most important parameters used to determine the wood's suitability as a raw material in the cellulosic pulp and paper industry (Ilvessalo-Pfäffli 1995; Wimmer *et al.* 2002). Several studies have used these parameters to predict the mechanical strength properties of paper (Wimmer *et al.* 2002). The two-way analysis of variance showed that the species, wood type (branch and stemwood), and the interaction between them had a significant effect on all the measured fiber morphological indices at the 0.05 level of significance. Fisher's LSD test showed that there were significant differences in the fiber morphological indices among the stemwood and branchwood of both species at the 0.05 significance level. Generally, from the data presented in Table 2, for *E. camaldulensis*, the fiber length, *RR*, *RC*, Muhlsteph ratio, and Luce's shape factor of the stemwood were higher by 18.6%, 41.5%, 20.7%, 14.3%, and 20.6% than their counterparts in branchwood, respectively. While the *FC* and *SR* of stemwood were lower by 25.6% and 6.1% than those measured in branchwood. For *P. halepensis*, the fiber length, *RR*, *SR*, *RC*, Muhlsteph ratio, and Luce's shape factor of the stemwood were higher than their counterparts in branchwood, while the *FC* was lower in stemwood than in branchwood. Fiber length is the most important indicator for the suitability of raw materials in the pulp and paper industry, as longer lengths are preferred. It is also directly proportional to the paper strength (Zobel and Van Buijtenen 1989).

It is clear from Table 2 that the average fiber length ranged from 0.70 mm (*E. camaldulensis* branchwood) to 2.81 mm (*P. halepensis* stemwood). Both the stemwood and branchwood fiber lengths for *E. camaldulensis* were short according to the classification of Metcalfe and Chalk (1979) that indicates that fiber lengths less than 0.9 mm are described as short and those above 1.6 mm are long fibers. In the current study, the fiber length value for *P. halepensis* branchwood was longer than the stemwood and branchwood values of *E. camaldulensis*. Haddad *et al.* (2009) reported a lower fiber length value (1.63 mm) than the reported value in the current study for *P. halepensis*. Ilvessalo-Pfäffli (1995) reported an average fiber length of 2.6 mm for *P. halepensis*. It is noteworthy to mention that some grades of printing and writing papers need both short and long fibers together to yield good printability and strength (Sadiku and Abdukareem 2019). The fiber length value reported herein for *E. camaldulensis* was higher than that measured for the same species grown in Sudan (0.76 mm) (Gamal and Abdelgadir 2015). The fiber length measured for *Eucalyptus globulus* stump wood at six different sites ranged from 0.812 to 1.121 mm (Gominho *et al.* 2014). The fiber length's average value reported for *P. nigra* juvenile wood was 1.12 mm.

Based on the results of the current study, the average Runkel ratio (*RR*) ranged from 0.25 (*P. halepensis* branchwood) to 1.64 (*E. camaldulensis* stemwood). The *RR* values recorded for *E. camaldulensis* in previous studies were 0.425 (Ona *et al.* 2001), 0.50 (Ohshima *et al.* 2005b), and 1.1 (Dutt and Tyagi 2011). The previously recorded values in the literature are lower than the reported values in the present study. Gominho *et al.* (2014) reported that the average *RR* measured for *E. globulus* stump wood was 1.4 ± 0.3. In comparison with another pine species, the *RR* was 0.66 for *Pinus radiata* (Bektaş 2018), 0.41 for *Pinus ponderosa* (Farsi and Kiaei 2014), and 0.38 for *P. nigra* (Akgul and Tozluoglu 2009). Generally, *RR* lower than 1 is most suitable for producing paper with desirable properties (Kpikpi 1992) as it affects negatively on the fiber-to-fiber bonding and positively on the pulp yield (Biermann 1996; Ohshima *et al.* 2005b). The high values of *RR* indicate that the fibers are less elastic and thick-walled with low bonded areas, and this affects negatively on the fiber-to-fiber bonding (Dutt and Tyagi 2011). The *RR* strongly depends on the cell wall thickness therefore, it has a positive effect on pulp yield (Ona *et al.* 2001; Ohshima *et al.* 2005b). Although some studies indicated that an *RR* above 1 would reduce the paper's mechanical properties (Bektaş *et al.* 1999), Valkomies (1969) mentioned that a fiber's Runkel ratio up to 1.5 would produce paper with satisfactory quality. Thus, the stemwood and branchwood of *P. halepensis* and the branchwood of *E. camaldulensis* were more suitable than *E. camaldulensis* stemwood for pulp and paper production. These results indicate that the *E. camaldulensis* stemwood fibers are less flexible in comparison with the other raw materials studied.

The average values of the stemwood and branchwood flexibility coefficient (*FC*) ranged from 0.43 (*E. camaldulensis* stemwood) to 0.79 (*P. halepensis* branchwood). A higher *FC* average value of 0.68 was reported by Ohshima *et al.* (2005a) for *E. camaldulensis* grown in Western Australia. Ona *et al.* (2001) reported a mean value of 0.704 for the same species. Dutt and Tyagi (2011) reported a higher *FC* value (0.48) than the reported value (0.43) in the current study for *E. camaldulensis* aged one year and grown in India. Akgul and Tozluoglu (2009) reported an average *FC* of 0.73 for *Pinus nigra*. Bektaş *et al.* (1999) classified the fibers according to their elasticity into four groups, from high elastic to very rigid fibers. According to this classification, fibers having FC values of < 30%, 30-50%, 50-75%, and > 70% are described as very rigid, rigid, elastic, and highly elastic, respectively. Accordingly, *P. halepensis* stemwood and *E. camaldulensis* branchwood belong to the elastic fiber group, while *P. halepensis* branchwood and *E. camaldulensis* stemwood belong to the highly elastic and rigid fibers groups, respectively. When the fiber has a high flexibility coefficient value, the resulting paper could have good strength characteristics, particularly good tensile and bursting strength.

The slenderness ratio (*SR*) is also called the relative fiber length or felting power. It is an indirect indicator of the paper tear index and pulp digestibility (Rydholm 1965; Ona *et al.* 2001). The average values ranged between 47.6 (*E. camaldulensis* stemwood) and 78.9 (*P. halepensis* stemwood). Dutt and Tyagi (2011) reported a higher *SR* value (53.33) than the reported value in the current study for *E. camaldulensis* that was aged one-year and grown in India. Akgul and Tozluoglu (2009) reported an average *SR* of 33.62 for *Pinus nigra*. Generally, it is recommended that the *SR* exceeds 33 to produce paper with acceptable properties (Xu *et al.* 2006). The stemwood and branchwood for both species in the current study had higher values than the recommended value; thus, both species including branches can be predicted to produce paper with good mechanical strength properties, mainly tearing strength. The highest rigidity coefficient (*RC*) was 0.29, recorded for *E. camaldulensis* stemwood, while the lowest average value, 0.01, was for *P. halepensis* branchwood. Dutt and Tyagi (2011) reported a higher *RC* value (0.53) than the value reported in the current study for *E. camaldulensis* that was aged one-year and grown in India. Akgul and Tozluoglu (2009) reported an average Muhlsteph ratio of 0.14 for *Pinus nigra*. Generally, Tamolang and Wangaard (1961) reported that, in paper manufacturing, it is generally desirable for the rigidity coefficient to be less than 0.5. In the present study, the mean values for both genera were below this recommended value. The average Muhlsteph ratio ranged from 36.7 (*P. halepensis* branchwood) to 80 (*E. camaldulensis* stemwood). Fibers with a lower Muhlsteph ratio had a thinner cell wall, which is preferred in paper production. Akgul and Tozluoglu (2009) reported a slightly higher Muhlsteph ratio value (47.28) for *Pinus nigra* than that reported in the current study. Luce's shape factor data showed that the branchwood of *P. halepensis* had the lowest value (0.23), while the *E. camaldulensis* stemwood had the highest value (0.68). This fiber morphological factor is important, as it affects the paper sheet density (Ona *et al.* 2001; Ohshima *et al.* 2005b). Moreover, it indicates the resistance of the raw material during the beating process; accordingly, a low value is preferable (Luce 1970). Generally, the results of the current study were within the range obtained for other raw materials suitable for paper production (Ververis *et al.* 2004). Ona *et al.* (2001) reported a lower Luce's shape factor value (0.338) than the present study's reported value for *E. camaldulensis* grown in Western Australia. Gominho *et al.* (2014) reported that the average Luce's shape factor measured for *E. globulus* stump wood was 0.69 ± 0.06.

It is worth mentioning that removing the bark from the branches may require advanced technology and thus may lead to an increase in the production cost. Moreover, it is expected that the presence of the branches bark may reduce the screened pulp yield and may increase the rejected pulp after the cooking process. Therefore, additional study is needed to investigate whether utilizing the branches including the bark of the two studied species will affect paper characteristics or not.

Relationships Among Density and Fiber Morphology of the Two Studied Species

Correlation coefficients (r) between the basic density and fiber length, fiber lumen diameter, and the fiber wall thickness of stemwood and branchwood are presented in Figs. 1 through 6.

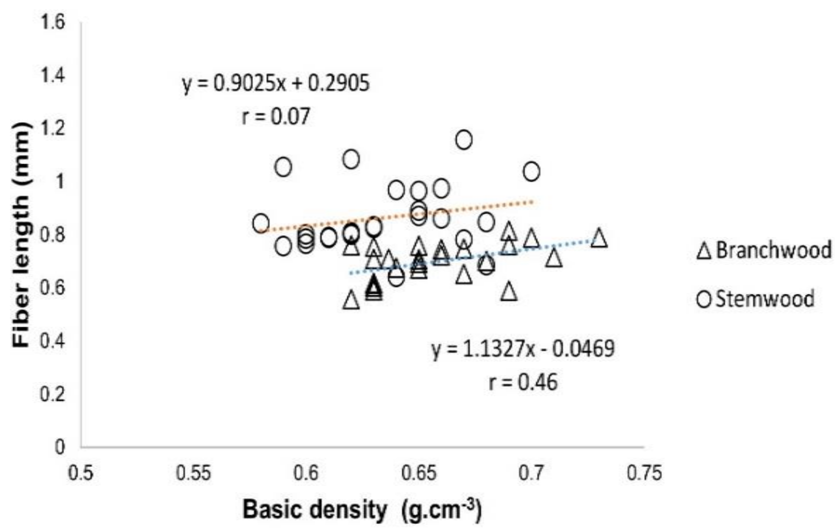

Fig. 1. Relationship between the basic density and fiber length for *E. camaldulensis*

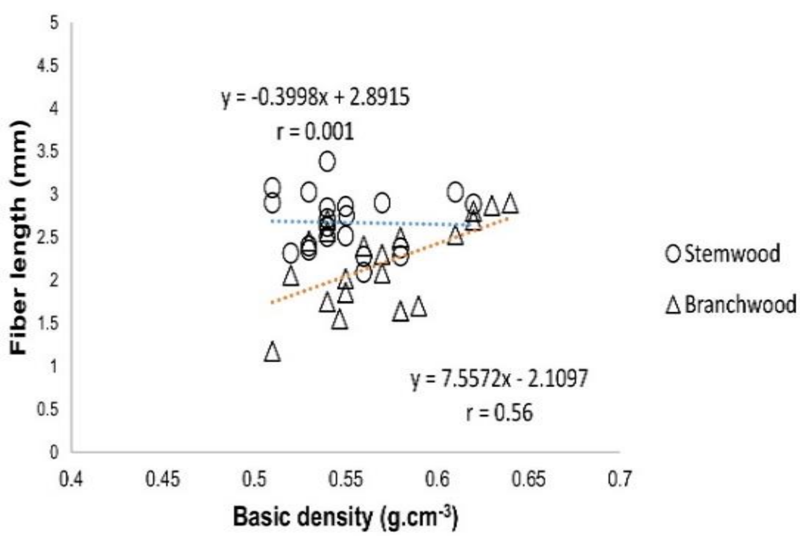

Fig. 2. Relationship between the basic density and fiber length for *P. halepensis*

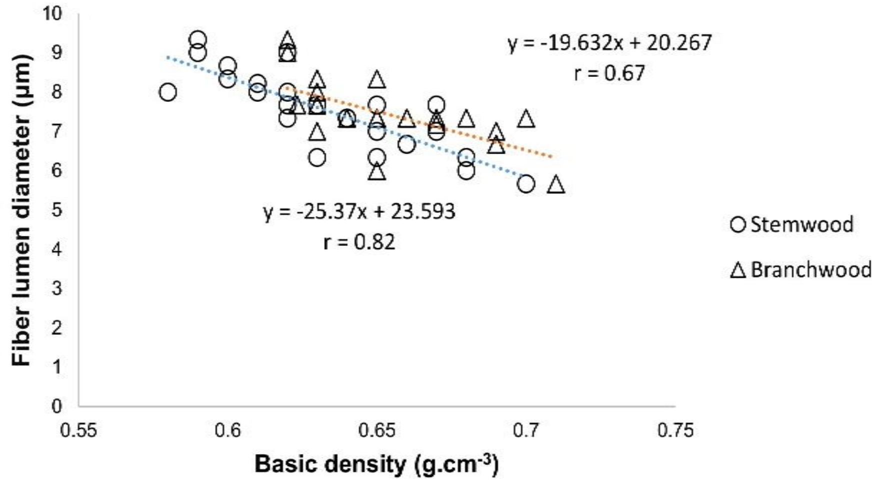

Fig. 3. Relationship between the basic density and fiber lumen diameter for *E. camaldulensis*

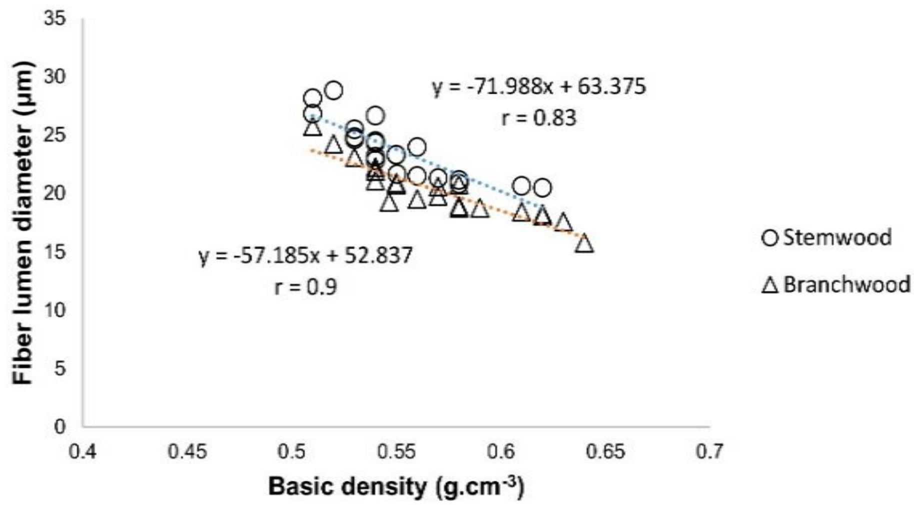

Fig. 4. Relationship between the basic density and fiber lumen diameter for *P. halepensis*

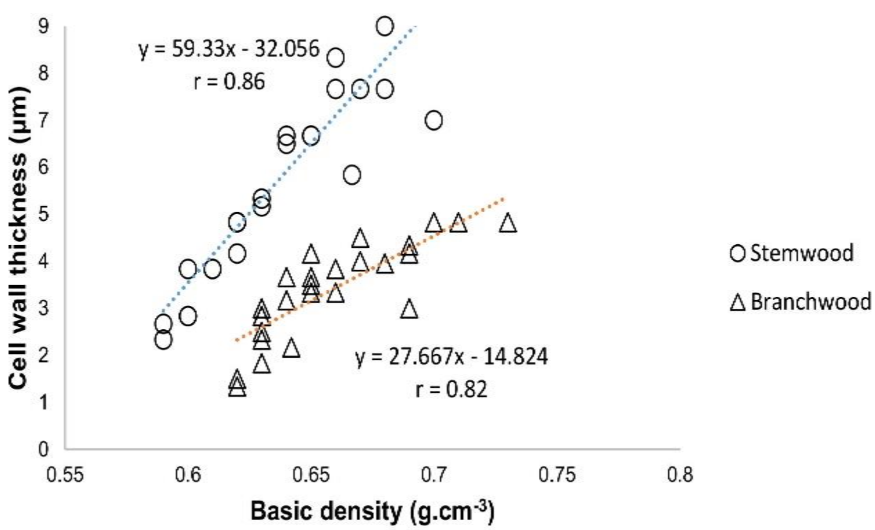

Fig. 5. Relationship between the basic density and wall thickness for *E. camaldulensis*

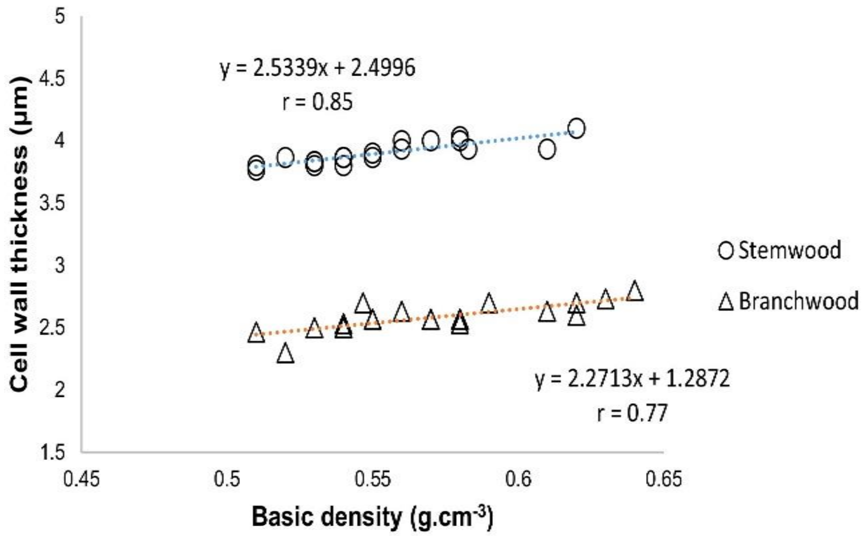

Fig. 6. Relationship between the basic density and wall thickness for *P. halepensis*

There was no obvious relationship between the stemwood fiber length and the basic density. However, there was a significant positive relationship between the same variables in branchwood for *E. camaldulensis* (r = 0.46) and *P. halepensis* (r = 0.56). In contrast to the results of the present study, Wimmer *et al.* (2002) found a negative correlation between wood density and fiber length (*r* = -0.44). Zubizarreta Gerendiain *et al.* (2009) reported a negative correlation between earlywood density and fiber length (*r* = -0.43) in Norway spruce grown in Finland. Quilhó *et al.* (2006) reported that there was a significant positive correlation between basic density and fiber length in *Eucalyptus grandis* × *E. urophylla*.

The cell wall thickness of both the stemwood and branchwood were positively and strongly correlated with the basic density for both species, with correlation coefficients (*r*) above 0.7. These results agreed with those of Hidayati *et al.* (2014), who found a significant positive correlation (*r* = 0.54) between basic density and wall thickness for 12-year-old teak grown in Indonesia. Xu *et al.* (2006) indicated that there was a positive correlation between double cell wall thickness and basic density for *Eucalyptus grandis*. Moreover, the present study indicated that there were strong negative correlations between the fiber lumen diameter and the basic density of stemwood and branchwood for both species. The correlation coefficient (*r*) ranged from 0.67 (*E. camaldulensis* branchwood) to 0.9 (*P. halepensis* branchwood).

CONCLUSIONS

The stemwood and branchwood of *E. camaldulensis* and *P. halepensis* were studied for their chemical and fiber morphological indices to provide basic information on the feasibility of using these raw materials for pulp and paper production.

1. Among the tested raw materials, the highest values of cellulose, C/L ratio, Runkel ratio, Rigidity coefficient, Muhlsteph ratio, and Luce's shape factor were observed in *E. camaldulensis* stemwood, whereas, the highest values of basic density, extractives, and ash content were found in the *E. camaldulensis* branchwood. On the other hand, the

highest values of hemicellulose content, slenderness ratio, and fiber length were noticed in *P. halepensis* stemwood, while the *P. halepensis* branchwood had the highest values in lignin and flexibility coefficient.

2. Two-way analysis of variance revealed that the species, wood type (branch and stemwood), and the interaction between them affected significantly on the determined chemical constituents and the fiber morphological indices at 0.05 significance level.
3. Based on the results of the chemical composition and fiber biometric characteristics, all the studied raw materials—and even the branches—are suitable for pulp and paper production with various characteristics. Based on the present findings, it can be suggested that mixing *P. halepensis* branchwood with *E. Camaldulensis* stem or branchwood could lead to improving the paper quality.
4. The results showed that there were significant positive correlations between the basic density and the fiber length in branchwood of both species, while there were independent associations between both variables in the stemwood of both species. Good negative correlations were found between the basic density and the fiber lumen diameter in both stem and branchwood of the two studied species. The correlation coefficient ranged from 0.67 (*E. camaldulensis* branchwood) to 0.9 (*P. halepensis* branchwood). Moreover, strong positive relationships were observed between the basic density and the cell wall thickness in branch and stemwood of both species with correlation coefficients ranged from 0.77 (*P. halepensis* branchwood) to 0.86 (*E. camaldulensis* stemwood) .

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