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Evaluation on paper making potential of nine *Eucalyptus* species based on wood anatomical features

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ABSTRACT

Eucalypt wood is known worldwide as a raw-material for pulping but only a few species are used by the industry. One of the important features for pulping is the wood structure and anatomy, including cell biometry and cell type proportion. This work makes a prospective study of nine eucalypt species aiming at a pulping use by an early assessment of wood anatomical features. Young 50-month-old trees grown in the same environment of *Eucalyptus camaldulensis*, *Eucalyptus globulus*, *Eucalyptus maculata*, *Eucalyptus melliodora*, *Eucalyptus ovata*, *Eucalyptus propinqua*, *Eucalyptus sideroxylon*, *Eucalyptus tereticornis* and *Eucalyptus viminalis* were studied in relation to wood anatomy, cell biometry and proportion, and morphological fibre ratios. The nine species are structurally similar with typical eucalypt wood features, e.g. diffuse porosity with predominantly solitary vessels and simple perforations plates, and most anatomical differences between species related to rays and axial parenchyma. The wood is in general uniform and the radial variation of cellular dimensions is of small magnitude. The species showed a higher diversity regarding proportion of fibres (15–50%) and morphological characteristics e.g. slenderness ratio (39–48) and flexibility coefficient (0.37–0.65). The eucalypt species position themselves differently as regards the combination of morphological parameters, therefore allowing species targeting for specific paper properties. By considering these indicators, and the relative species growth, it seems promising to further study *E. maculata*, *E. ovata* and *E. sideroxylon* as potential new paper making eucalypt species, in parallel to the prized *E. globulus* and the already used *E. camaldulensis*.

1. Introduction

Most *Eucalyptus* species had their origin in Australia and Tasmania (Boland et al., 1992), but some species were introduced in other regions and are present today in large plantation in temperate, subtropical and tropical areas. This is the case of *Eucalyptus globulus* in Portugal and Spain, *Eucalyptus nitens* in Portugal, Spain, Argentina and Chile, *Eucalyptus grandis* in the sub-tropical and tropical zones of Argentina, China, Brazil, India, South Africa, Uruguay and Vietnam (Forrester et al., 2010; Pereira et al., 2011). In fact, *Eucalyptus* is one of the most valuable and widely planted hardwoods in the world with 18 million ha in 90 countries, in tropical and subtropical regions of Africa, South America, Asia and Australia, and in temperate regions of Europe, South America, North America and Australia (Rockwood et al., 2008).

Eucalypt wood is known worldwide as a raw-material for pulping and most of the plantations are directed for the pulp&paper industry. *E. globulus* was the forerunner and most successful pulpwood in temperate regions due to good tree growth, stem characteristics, wood anatomy and fibre biometry, as well as a favourable pulping chemical quality. In tropical and subtropical regions other eucalypt species are used, such as *E. grandis* and *E. nitens*, as well as different hybrids such as the extensively used urograndis hybrid (*E. grandis* × *Eucalyptus urophylla*) in Brazil. In South Africa, *E. grandis*, *Eucalyptus macarthurii*, *E. nitens* and *Eucalyptus smithii* are used for the pulp&paper industry (Little and Gardner, 2003) and in Thailand, *Eucalyptus camaldulensis* is the main raw material for pulping (Terdwongworakul et al., 2005).

Other eucalypt species have been tested for their pulping aptitude such as *Eucalyptus badjensis*, *Eucalyptus dunnii* (Little and Gardner, 2003), *Eucalyptus tereticornis*, *Eucalyptus microtheca*, *Eucalyptus paniculata* (Khristova et al., 1997; Khristova, 2000), *Eucalyptus citriodora* (Khristova et al., 2006). However the number of species tested is very small in comparison with the over 700 species within the *Eucalyptus* genus (Rockwood et al., 2008).

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One of the important features for pulping is the wood structure and anatomy, including cell biometry and cell type proportion that have been shown to vary between species, tree and age (Foelkel, 2009). In general, a high proportion of fibres is desired, in parallel with a low proportion of fine sized cells i.e. parenchyma, while fibre biometry in relation to length, width and cell wall fraction is related to specific pulp and paper properties. For example, Zobel and Van buijtenen (1989) reported that wood with thick cell walls tends to produce papers with a poor printing surface and poor burst strength. The fibre biometry is important for determination of wood properties that have been recognized as relevant for pulp and paper properties, e.g. the Runkel ratio, wall proportion, flexibility coefficient, Luce's shape factor and slenderness ratio that were suggested as selection indices for quality breeding (Ohshima et al., 2005) and are recognized as important traits for paper evaluation (Amidon, 1981; Kayama, 1968; O'Neil et al., 1996). For example, the Runkel ratio is related to paper conformability and pulp yield, and Luce's shape factor and slenderness ratio are related to paper sheet density and to pulp digestability, respectively (Ohshima et al., 2005). Vessel proportion and size have also an influence on the papermaking process (Amidon, 1981), as well as rays and parenchyma cells that have an effect on the quality of both solid wood and pulp products (Zobel and Van buijtenen, 1989). The ray and parenchyma cells are thin-walled and very short, and therefore contribute little to the strength properties of paper, although they provide a smoother sheet surface. The relationships between cell and pulp properties have also been studied for their within-tree variation (Bhat et al., 1990; Crawford et al., 1972; Malan, 1991).

Therefore wood anatomical features give an initial evaluation for the potential pulpwood quality of a raw-material. There is an extensive information of wood anatomical data for *E. globulus* including its variation with site, age and genetics, as compiled in Pereira et al. (2011). For other eucalypt species, the information is less i.e. *E. grandis*, *E. tereticornis*, *Eucalyptus saligna* and *E. camaldulensis* (Pereira et al., 2011) as well as for several hybrids (Prinsen et al., 2012), and scarce for *Eucalyptus melliodora*, *Eucalyptus ovata*, *Eucalyptus sideroxylon*, *Eucalyptus viminalis*, *Eucalyptus cypellocarpa*, *Eucalyptus polyanthemos* and *Eucalyptus regnans*.

The perspective of this work is to make a prospective study of a number of different eucalypt species aiming at a possible use for paper making by an early assessment of wood anatomical features allowing comparing the species potential. Young trees grown in the same environment of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *Eucalyptus propinqua*, *E. sideroxylon*, *E. tereticornis* and *E. viminalis* were studied in relation to wood anatomy, cell biometry and proportion, and fibre ratios.

The main purpose is to analyze the comparative paper making potential of these species, but the information is also necessary for solid wood processing since physical behaviour and mechanical properties are affected by anatomical characteristics e.g. fibre proportion and cell wall thickness.

The overall objective is to explore the natural diversity within the genus *Eucalyptus* and to enrich the potential raw-material feedstocks for the industry and the species diversity in forest plantations, in accordance with the continuing interest of the pulp&paper industry in finding new pulpwood species with good paper making potential.

2. Materials and methods

2.1. Materials

The study was done on nine *Eucalyptus* species: *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis*. The trees were grown on an experimental site located in the campus fields of the School of Agriculture, University of Lisbon (ULisbon), at Tapada da Ajuda, Lisboa, Portugal (38°42′ N; 09°10′ W). The region is under the influence of a mesothermal humid climate, with a dry season in the summer extending from June to August, and registering above 10 °C in the coldest month and below or equal to 22 °C in the hottest month. The soil is a Vertisol characterized by a fine, or medium to fine, texture, derived from tuffs or basalts, frequently with limestone on the inferior horizons, or from calcareous rock (in much less extension). The trees were planted from seeds originated from Australia in February 2007 in rows with 3 m × 3 m spacing and without fertilization. The trees were harvested in April 2011, at 50 months of age.

Stem discs with 10 cm thickness were collected at 1.30 m of tree height (DBH). The mean overbark and wood diameters were measured. Two replicates per species were analyzed.

2.2. Anatomical observations

The vessel area was determined from pith to bark, after sample surface sanding, using the Leica software Qwin V 3.5.0, after acquisition of a sequence of images of each radius through a digital camera Leica DFC 320 coupled to Leica Magnifier MZ6. The images were converted to binary format and vessels were clearly identified as separate objects after applying threshold and minimum size settings. The individual size of all the vessels contained along the full length of the radial strip and within a 1-mm-width field was recorded. The number of vessels, the individual vessel area and the vessel location coordinates were recorded per image and positioned along the radial strip total length. The following mean vessel variables were calculated: average vessel area, number of vessels, vessel density (number of vessels per mm^2) and vessel proportion (vessel area percentage in relation to total area).

For microscopy, samples were taken at three radial positions at 30%, 60% and 90% of the radius from pith to cambium. The wood samples were first softened in boiling water and then sectioned with a sliding microtome. Transversal, tangential and radial thin sections with 17 μm thickness were obtained using a micrometre, washed in alcohol, stained with safranin and mounted in Eukitt. Ray height and number of cells were measured from 40 uniseriate rays, on the tangential sections.

The radial variation of fibre length, width and wall thickness was measured on dissociated material (40 fibres per determination) using image analysis assisted by a camera from Leica microscope coupled to EC3 transmitted light Dialux 22 EB and LAS software V4.2. Only complete fibres were measured and fibre width and lumen were determined at mid-length. Cell dissociation was made with Jeffrey's solution during 48 h at 60 °C, washed in water and stored in 70% alcohol.

The proportion of axial parenchyma, fibres, rays and vessels was measured on the transverse sections using a 48 point-grid on successive areas along the radius and using LAS software V4.2.

The determination was made directly on the microscope where the different tissues differentiate clearly by size and colour.

2.3. Anatomical ratios

Runkel ratio, wall proportion, flexibility coefficient, Luce's shape factor and slenderness ratio were calculated according to the following formula, where w is the cell wall thickness, D is the fibre width, d is the fibre lumen width, and L is the fibre length:

Runkel ratio = $2w/d$
Wall proportion = $(2w/D) \times 100$
Luce's shape factor = $(D^2 - d^2)/(D^2 + d^2)$
Flexibility coefficient = d/D
Slenderness ratio = L/D

Table 1
Stemwood diameter, texture and growth ring definition of nine eucalypt species (*E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis)* grown in the same environment at 50 months of age.

Species	Diameter (cm)	Texture	Growth ring
E. camaldulensis	9.5	Fine	Indistinct
E. globulus	11.8	Fine	Indistinct
E. maculate	17.7	Moderately coarse	Indistinct
E. melliodora	8.6	Fine	Indistinct
E. ovata	10.3	Fine	Indistinct
E. propinqua	8.6	Moderately coarse	Fairly distinct
E. sideroxylon	10.6	Fine	Indistinct
E. tereticornis	4.3	Fine	Fairly distinct
E. viminalis	12.2	Moderately coarse	Indistinct

Descriptive terminology follows the IAWA List of Microscopic Features for Hardwood Identification (IAWA Committee 1989).

Statistical analysis was made using the SPSS software. Analysis of variance (ANOVA) was applied to compare wood fibre length and wall thickness.

3. Results and discussion

3.1. General description

The macroscopic observations of texture, growth ring definition and wood porosity were summarized in Table 1, together with the information on the stemwood diameter.

It was noteworthy that the species differed in growth, with stemwood diameters ranging from 4.5 cm to 17.7 cm in 4 years of growth. The species with the highest diameters were *E. maculata*, *E. viminalis* and *E. globulus* and the smallest trees were from *E. tereticornis*.

The growth rings were indistinct in most of the species, following the general trend in the majority of eucalypt species where growth rings are generally indistinct or not well defined (Dadswell, 1972); rings were however fairly distinct in E. *tereticornis* and *E. propinqua* due to absence of vessels and thickened fibres at ring boundary.

These features have been reported for *E. globulus* (Pereira et al., 2011) and for several other eucalypt species i.e. *E. regnans*, *Eucalyptus delegatensis*, *Eucalyptus obliqua*, *Eucalyptus baxteri*, *Eucalyptus globoidea*, *Eucalyptus muelleriana*, *Eucalyptus macrorhyncha*, *Eucalyptus consideniana* and *Eucalyptus sieberi* (Ilic, 1997, 2002); *E. citriodora*, *E. maculata*, *E. grandis*, *E. saligna*, *Eucalyptus deanei*, *Eucalyptus robusta*, *Eucalyptus resinifera*, *E. propinqua*, *E. punctata*, *E. tereticornis*, *E. camaldulensis*, *Eucalyptus alba*, *Eucalyptus dunnii*, *Eucalyptus cloeziana*, *Eucalyptus pilularis*, *Eucalyptus microcorys*, *Eucalyptus siderophloia* and *E. paniculata* (Alfonso, 1987).

Table 1 Stemwood diameter, texture, growth ring definition and wood porosity type and distribution of nine eucalypt species (*E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis)* grown in the same environment at 50 months of age.

3.2. Anatomical structure

The wood anatomical structure of these nine eucalypt species (Fig. 1) was in general similar notwithstanding the differences in vessel outline, arrangement, type of axial parenchyma and rays, their dimensions and proportion.

All the species showed diffuse porosity, with predominantly solitary vessels, except in *E. maculata* where the vessels are grouped (2 or more vessels); the vessels were generally randomly distributed with an oblique alignment and mostly radial in *E. maculata*; vessels outline was circular to oval, more circular in *E. melliodora*, *E. ovata* and *E. tereticornis*, and more oval in *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. propinqua*, *E. sideroxylon*, and *E. viminalis*. The vessel elements were short with exclusively simple perforation plates and the inter-vessel pits were only observed in vessel tips and the vessel-ray pits were round to oval mostly simple.

The axial parenchyma was scarce to abundant but its arrangement varied being mostly paratracheal vasicentric aliform, somewhat confluent and fairly apotracheal diffuse in *E. globulus*, *E. ovata* and *E. maculata*; and apotracheal diffuse, in short lines, and paratracheal vasicentric in *E. camaldulensis*, *E. melliodora*, *E. propinqua*, *E. sideroxylon, E. tereticornis* and *E. viminalis.* In *E. maculata* it was apotracheal diffuse and in short lines and paratracheal confluent forming tangential bands.

Rays were homogeneous and heterogeneous of type III (i.e. in *E. camaldulensis*, *E. globulus*, *E. ovata*, *E. propinqua* and *E. tereticornis*), with body ray cells procumbent with upright and/or square marginal cells. Rays were mostly uniseriate in *E. globulus*, *E. maculata*, *E. tereticornis* and *E. viminalis*, mostly biseriate in *E. camaldulensis* and *E. propinqua*, equally uniseriate and biseriate in *E. melliodora*, *E. ovata* and *E. sideroxylon*, and rarely triseriate in *E. propinqua*. Alfonso (1987) also described homo and heterogeneous rays of the type III for *E. camaldulensis*, *E. globulus*, *E. propinqua* and *E. tereticornis*. Cell ray with contents were evident i.e. in *E. camaldulensis*, *E. ovata* and *E propinqua*.

In all the species, the fibres were of the libriform type, non-septated, with bordered pits mainly in radial walls. Vasicentric tracheids were present in all the species, and mostly conspicuous in radial sections i.e. *E. maculata*.

Anatomical descriptions with variable detail exist for *E. maculata* (Dadswell, 1972; Oliveira and Freitas, 1970), *E. propinqua* (Oliveira and Freitas, 1970), *E. tereticornis* (Dadswell, 1972; Oliveira and Freitas, 1970) and *E. camaldulensis* (Alfonso, 1987; Dadswell, 1972), *E. ovata* (Oliveira and Freitas, 1970), *E. globulus* (Dadswell, 1972; Pereira et al., 2011), *E. melliodora* and *E. viminalis* (Dadswell,

Table 2
Biometry of vessels (tangential diameter, length, area and frequency), fibres (length, width, wall thickness) and rays (number of cells, height) of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis* grown in the same environment at 50 months of age.

Species	Vessels				Rays		Fibre		
	Tangential diameter (μm)	Length (μm)	Area (mm^2)	Frequency (nr/mm^2)	N° cells	Height (μm)	Length (mm)	Width (μm)	Wall thickness (μm)
E. camalduleis	80 ± 19	218 ± 52	0.004 ± 0.002	11	11	148 ± 56	0.670 ± 75	17 ± 0.8	4 ± 0.1
E. globulus	72 ± 23	273 ± 53	0.005 ± 0.0005	18	9	153 ± 47	0.716 ± 34	16 ± 0.9	5 ± 0.3
E. maculata	79 ± 11	195 ± 69	0.008 ± 0.0002	14	9	141 ± 59	0.794 ± 14	18 ± 1	5 ± 0.7
E. melliodora	79 ± 17	197 ± 49	0.007 ± 0.0009	19	6	129 ± 4	0.777 ± 92	17 ± 2	4 ± 0.2
E. ovata	127 ± 19	173 ± 47	0.009 ± 0.0009	13	8	142 ± 53	0.719 ± 49	16 ± 2	4 ± 0.1
E. propinqua	62 ± 12	212 ± 48	0.006 ± 0.0008	23	8	164 ± 73	0.755 ± 300	17 ± 1	4 ± 0.3
E. sideroxylon	54 ± 9	164 ± 32	0.009 ± 0.002	25	9	116 ± 31	0.742 ± 12	16 ± 3	4 ± 0.2
E. tereticornis	88 ± 13	268 ± 50	0.006 ± 0.0002	27	8	141 ± 42	0.777 ± 11	17 ± 0.4	4 ± 0.1
E. viminalis	81 ± 11	183 ± 42	0.004 ± 0.0002	9	9	155 ± 45	0.806 ± 49	19 ± 1	3 ± 0.5

1972). The observations made here are in accordance with such descriptions.

3.3. Cell biometry and proportion

The quantification of anatomical features was summarized in Table 2 for cell biometry and in Table 3 for cell type proportion. Each anatomical feature showed differences between the nine eucalypt species.

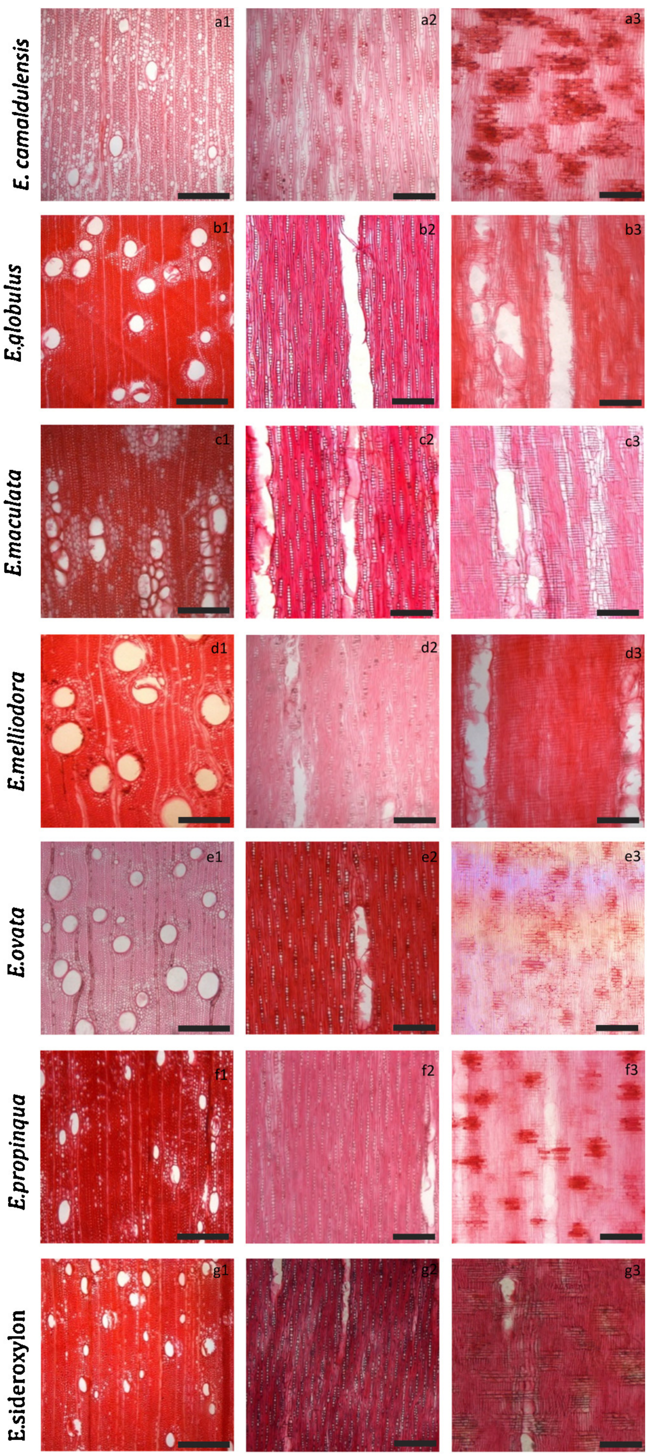

Fig. 1. Microscopic structure of the transverse (a1–i1), tangential (a2–i2) and radial (a3–i3) sections of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis* and *E. viminalis*. Scale bar = 50 μm (right column) and 150 μm (central and left column).

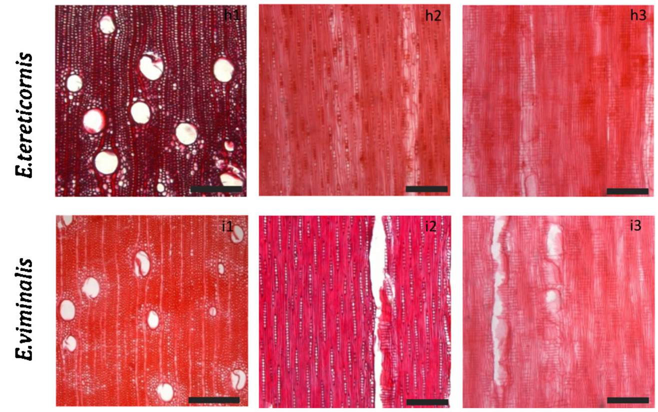

Fig. 1. (*Continued.*)

As regards vessels, their number per mm^2 ranged between 9 (*E. viminalis*) and 27 (*E. tereticornis*), with tangential diameters from 54 μm (*E. sideroxylon*) to 127 μm (*E. ovata*), mean vessel area between 0.004 mm^2 (*E. camaldulensis* and *E. viminalis*) and 0.009 mm^2 (*E. ovata* and *E. sideroxylon*), and vessel element length from 164 μm (*E. sideroxylon*) to 273 μm (*E. globulus*).

Rays had between 6 (*E. melliodora*) and 11 cells (*E. camaldulensis*) with a height from 129 μm (*E. melliodora*) to 164 μm (*E. propinqua*).

The mean fibre length ranged between 0.67 mm (*E. camaldulensis*) and 0.81 mm (*E. viminalis*), fibre width between 16 μm (*E. globulus*, *E. ovata* and *E. sideroxylon*) and 19 μm (*E. viminalis*) and wall thickness between 3 μm (*E. viminalis*) and 5 μm (*E. globulus* and *E. maculata*).

Comparison of cell biometry to published values is easy for *E. globulus* for which many quantitative anatomical studies were made, as compiled in Pereira et al. (2011), although direct comparisons with values reported in the bibliography are difficult due to differences in sampling (e.g. tree age) and methodology. Regarding fibre biometry, fibre length values between 0.78 mm and 1.12 mm were reported (Jorge et al., 1997; Miranda et al., 2001; Tomazello Filho, 1987; Tomé et al., 1996), cell wall thickness between 4 μm and 12 μm (Miranda and Pereira, 2002; Miranda et al., 2003; Tomazello Filho, 1985) and 21.3 μm for fibre width (Miranda et al., 2003). A vessel frequency between 4 and 27 vessels per mm^{-2} with a tangential diameter between 170 μm and 221 μm, and mean vessel area between 0.002 mm^2 and 0.021 mm^2 were reported in the literature (Dadswell, 1972; Carvalho, 1962; Hudson et al., 1996; Wilson et al., 1998).

Some information about the other species could also be found in the literature.

Table 3
Cell type proportion (%) of vessels, fibres and rays of *E. camaldulensis*, *E. globulus*, *E. maculate*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis* grown in the same environment at 50 months of age.

Cell type proportion (%)				
Species	Vessels	Rays	Fibre	Parenchyma
E. camaldulesis	31	17	44	8
E. globulus	25	19	33	21
E. maculata	19	29	29	23
E. melliodora	22	22	22	22
E. ovata	25	15	50	10
E. propinqua	21	19	33	25
E. sideroxylon	20	22	35	21
E. tereticornis	21	23	35	16
E. viminalis	23	31	25	21

E. camaldulensis: 89–108 μm tangential vessel diameter, 13–22 vessels mm^{-2}, 383–408 μm vessel length, 0.809–0.880 mm fibre length, 5 μm fibre wall thickness, and 349 μm ray height (Alfonso, 1987; Dyer, 1992; Veenin et al., 2005).
E. maculata: 97–119 μm tangential vessel diameter, 4–12 vessels mm^{-2}, 474 μm vessel length, 990 μm fibre length, and 5 μm fibre wall thickness (Alfonso, 1987; Oliveira and Freitas, 1970).
E. ovata: 45–163 μm tangential vessel diameter, 0.763–1.342 mm fibre length, and 10.6–16.5 μm fibre width (Oliveira and Freitas, 1970).
E. propinqua: 84 μm tangential vessel diameter, 439 μm vessel length, 0.990 mm fibre length, 5 μm fibre wall thickness (Alfonso, 1987).
E. sideroxylon: 6–13 vessels mm^{-2} (Searson et al., 2004).
E. tereticornis: 96–114 μm tangential vessel diameter, 9–12 vessels mm^{-2}, 435–463 μm vessel length, 0.908–1.08 mm fibre length, 4 μm fibre wall thickness and 324 μm ray height (Alfonso, 1987; Carvalho, 1962; Dyer, 1992; Sharma et al., 2005).

In general the values found in this work were at the lower range of those reported in the literature, certainly because the analysis was made on younger trees than those studied in the referenced publications.

The wood structure as regards cell type proportion in the stemwood cross-section (Table 3) showed considerable differences between species: vessels corresponded from 19% (*E. maculata*) to 31% (*E. camaldulensis*), fibres from 25% (*E. viminalis*) to 50% (*E. ovata*), rays from 15% (*E. ovata*) to 31% (*E. viminalis*) and parenchyma from 8% (*E. camaldulensis*) to 25% (*E. propinqua*).

In the literature, values were reported for older trees: *E. globulus* with 11–13% vessels, 64–67% fibres, 6–7% axial parenchyma and 14–16% rays (Bamber, 1985; Ona et al., 2001) and for *E. camaldulensis* with 16–18% vessels, 49% fibres, 14% axial parenchyma, and 20–21% rays (Ona et al., 2001). For a similar tree age, a recent study on pulped material of several eucalypt hybrids (Prinsen et al., 2012) showed that were differences in the vessel content between hybrids.

3.4. Radial variation

The radial variation of cell biometry was indicative of age trends and constitutes valuable information e.g. when an evaluation is made in earlier ages than the normal rotation. This was the case here, since the trees were evaluated at 4 years of age and the normal rotation in Portugal is 9–12 years (about 6 years in subtropical regions).

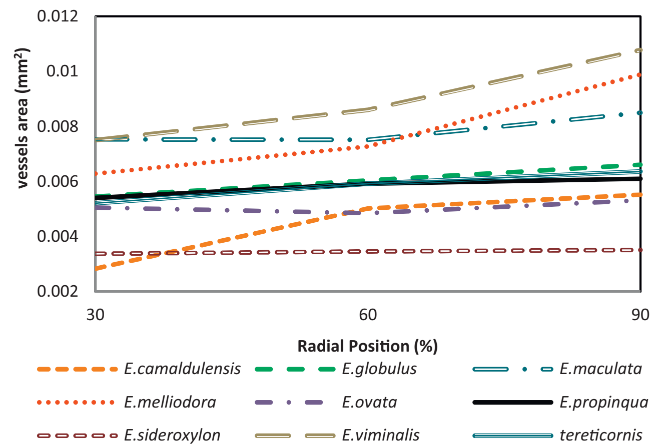

Fig. 2. Radial variation of vessel area, measured at 30%, 60% and 90% of the radius, of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis* grown in the same environment at 50 months of age.

The radial variation of vessel area was shown in Fig. 2. It is practically constant in *E. sideroxylon*, *E. propinqua*, *E. ovata*, *E. maculata*, *E. tereticornis* and *E. globulus*, and increases in *E. viminalis*, *E. melliodora* and *E. camaldulensis*. The variance analysis indicated that species, radial position and their interaction influenced significantly the vessels area ($p < 0.001$).

This radial pattern confirmed earlier reports on vessel area variation for *E. globulus* (Leal et al., 2007; Pereira et al., 2011; Ramírez et al., 2009; Tavares et al., 2011; Wilson et al., 1997, 1998). The same radial pattern was also found in *E. regnans* (Dadswell, 1958), *E. grandis* (Taylor, 1973) and *E. nitens* (Mckimm and Ilic, 1987).

The radial variation of fibre length, width and wall thickness is shown in Fig. 3. Fibre wall thickness was constant along the radius in *E. tereticornis*; increased to mid-radius and decreased afterwards in *E. camaldulensis*, *E. globulus* and *E. melliodora*; decreased in *E. propinqua* and in *E. sideroxylon*; and increased in *E. maculata*. However there was an overall narrow variation among the species.

There were several studies on radial patterns: Brasil and Ferreira (1979) found a radial increase of wall thickness for *E. grandis*, as well as Tomazello Filho (1987) for *E. globulus*, *Eucalyptus pellita* and *Eucalyptus acmenioides*, while Sharma et al. (2005) found a radial decrease for *E. tereticornis*, *E. propinqua* and *E. sideroxylon*.

The fibre length radial variation showed different patterns: it increased radially in *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. propinqua* and *E. sideroxylon*; increased to mid-radius and decreased subsequently in *E. ovata* and *E. viminalis*; and decreased

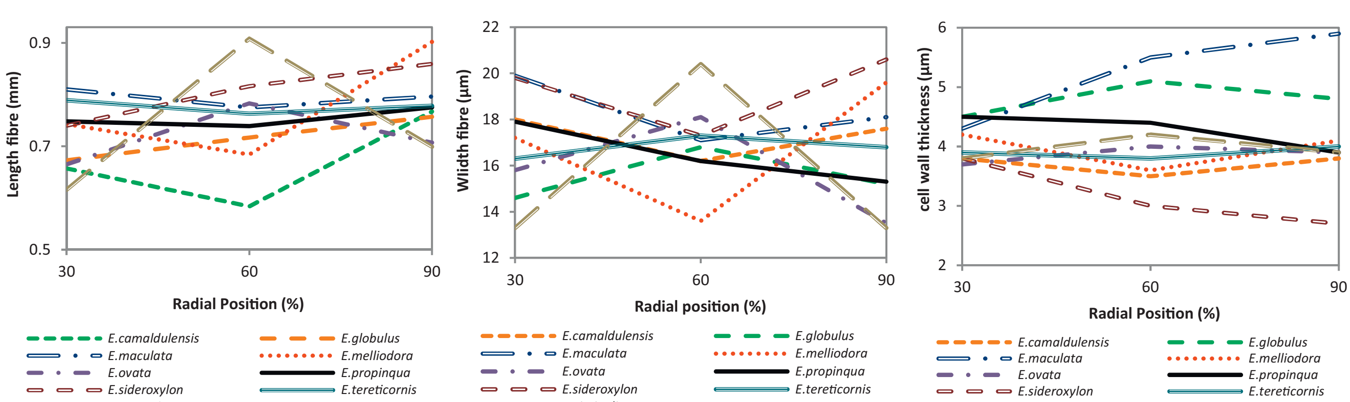

Fig. 3. Radial variation of fibre length, width and wall thickness, measured at 30%, 60% and 90% of the radius, of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis* grown in the same environment at 50 months of age.

Table 4
The anatomical ratios (Runkel ratio, wall proportion, flexibility coefficient, slenderness ratio, Luce's factor) of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis*, and *E. viminalis* grown in the same environment at 50 months of age.

Species	Runkel ratio	Wall proportion %	Flexibility coefficient	Slenderness ratio	Luce's factor
E. camaldulensis	0.79 ± 0.21	43.5 ± 6.5	0.56 ± 0.06	39.4 ± 7.7	0.51 ± 0.08
E. globulus	1.75 ± 0.58	62.0 ± 7.6	0.37 ± 0.07	47.1 ± 8.8	0.74 ± 0.08
E. maculata	1.6 ± 0.8	57.8 ± 12	0.42 ± 0.12	44.6 ± 9.9	0.69 ± 0.15
E. melliodora	1.0 ± 0.41	48.4 ± 9.9	0.51 ± 0.09	47.2 ± 9.3	0.57 ± 0.12
E. ovata	1.1 ± 0.54	50.0 ± 9.6	0.49 ± 0.09	46.9 ± 10.5	0.6 ± 0.1
E. propinqua	1.17 ± 0.34	52.7 ± 7.3	0.47 ± 0.07	46.7 ± 7.8	0.63 ± 0.09
E. sideroxylon	1.2 ± 0.52	52.4 ± 10	0.47 ± 0.1	48.4 ± 8.8	0.62 ± 0.12
E. tereticornis	0.95 ± 0.34	47.5 ± 8.1	0.52 ± 0.08	47.8 ± 11	0.56 ± 0.1
E. viminalis	0.54 ± 0.22	34.1 ± 8.9	0.65 ± 0.08	43.3 ± 9.9	0.39 ± 0.11

to mid-radius and increased subsequently in *E. tereticornis* and *E. maculata*. These findings deviated from the general view that the fibre length showed a gradual increase from pith to periphery in *Eucalyptus* (Foelkel, 2005); the radial pattern of fibre length increasing with cambium age has been found for several species i.e. *E. globulus* (Pereira et al., 2011; Tavares et al., 2004; Tomazello Filho, 1987) in *E. camaldulensis* (Sadegh and Kiarei, 2011), *E. terecticornis* (Sangeeta, 2012) or *Eucalyptus urograndis* (Quilhó et al., 2006).

Fibre width also showed different radial variation between species: a decrease to mid-radius and a subsequent increase in *E. camaldulensis*, *E. maculata*, *E. melliodora* and *E. sideroxylon*; an increase to mid-radius and then a decrease in *E. globulus*, *E. ovata*, *E. propinqua*, *E. tereticornis* and *E. viminalis*. The radial increase of fibre width for *E. globulus* was reported by Tomazello Filho (1987). Veenin et al. (2005) reported for *E. camaldulensis* a radial decrease of fibre width.

The between species differences in fibre variables were statistically significant ($p < 0.001$) and the interaction of species/radial position also had a significant influence. The radial position influenced fibre length with statistical influence but not fibre width and wall thickness.

There were significant differences between species and radial positions in relation to height rays ($p < 0.001$).

3.5. Morphological ratios

Table 4 summarizes the mean values for the various fibre ratios showing that there is a variation between species. *E. globulus* reported the highest Runkel ratio, wall proportion and Luce's factor (1.8, 62% and 0.5 respectively), factors that were related to the fact that this species has comparatively thin and thick walled fibres (Table 2). *E. viminalis* had the lowest Runkel ratio, wall proportion and Luce's factor (0.5, 34% and 0.4 respectively), associated to its thin walled and wide fibres (Table 2). For the same reasons but with opposite results, *E. viminalis* showed the highest flexibility coefficient (0.65) and *E. globulus* the lowest value (0.37).

Slenderness also varied between species. *E. sideroxylon* showed the highest slenderness ratio and *E. camaldulensis* the lowest (48 and 39 respectively). Regarding flexibility coefficient, the highest value was reported for *E. viminalis* and *E. camaldulensis* and the lowest value was found for *E. globulus* and *E. maculata*.

There were few references on morphological ratios of eucalypts. Ohshima et al. (2005) reported for Luce's factor and slenderness for *E. camaldulensis* 0.37 and 57, and for *E. globulus* 0.44 and 60, respectively. Ona et al. (2001) found mean Runkel ratios of 0.42 and 0.39, and flexibility coefficients of 0.69 and 0.73 for *E. camaldulensis* and *E. globulus* respectively. Ferreira et al. (2013), reported a Runkel ratio of 0.45 for commercial *E. globulus* pulp, however the older ages of the trees in these studies do not allow direct comparison with those of the present work.

Table 4 The morphological ratios (Runkel ratio, Wall proportion, Flexibility coefficient, Slenderness ratio, Luce's factor) of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis* and *E. viminalis* grown in the same environment at 50 months of age.

3.6. Anatomy-based paper making potential

The overall structure of the nine eucalypt species was rather uniform, with a fair distribution of vessels across the material, as shown in Fig. 1, and without conspicuous layered arrangements with very different structure e.g. fibre cross-sectional dimensions. The radial variation of cell biometry was also of small magnitude (Figs. 2–3). These were favourable characteristics for a homogeneous pulping process and fibre properties.

However the proportion of cell types are a crucial anatomical parameter to forecast pulping yields and a high proportion of fibres is a pre-requisite for good yields. In fact, small sized cells e.g. radial and axial parenchyma are lost during pulp screening, and vessels are destroyed to a large extent during pulp refining. In the nine eucalypt species, an analysis of the cell type proportion (Table 3) shows that the proportion of fibres is less favourable for *E. melliodora* and *E. viminalis*.

Morphological characteristics are among the first indicators to be evaluated for screening of potential fibrous raw-materials for paper production. It is generally known that paper structure and mechanical behaviour depend on the specific fibre features (Bronkhorst, 2003; Clark, 1978; Rydholm, 1965). For instance, fibre length positively influences tensile and burst strength, fibre diameter and wall thickness increase tear resistance, and slenderness increases fibre flexibility and the chances of forming well bonded paper.

The morphological ratios that were calculated (Table 4) can be grouped into those that are mostly determined by the wall thickness in relation to the transverse dimension of the fibres (e.g. Runkel ratio, wall proportion, Luce's factor and flexibility) and those related with the fibre length e.g. the slenderness ratio. The former relate with fibre stiffness: for instance, the higher the relative importance of the cell wall, the more rigid is the fibre which may lower its conformability and fibre-fibre contact (Patt et al., 2006). In this case the most rigid fibres would be those of *E. globulus*, *E. maculata* and the less rigid those of *E. viminalis* and *E. camaldulensis*. The slenderness ratio is related with fibre length and width and influences paper sheet density and increases tearing resistance (Agnihotri et al., 2010). The species with the lowest slenderness was *E. camaldulensis*. In spite of the variation that was found between the nine eucalypt species, they are overall suited for pulp and paper sheet formation. Nevertheless their specific anatomical characteristics may be used for targeted paper properties, as Fig. 3 shows when plotting flexibility and slenderness.

It is clear that other than anatomical factors will influence paper pulp aptitude, namely the chemical composition (Pereira et al., 2003). Nevertheless combining the cell type proportions (Table 3) and morphological ratios (Table 2), and also taking into account the comparative growth on the species in the same environment (Table 1), it seems promising to look in more detail to the pulping

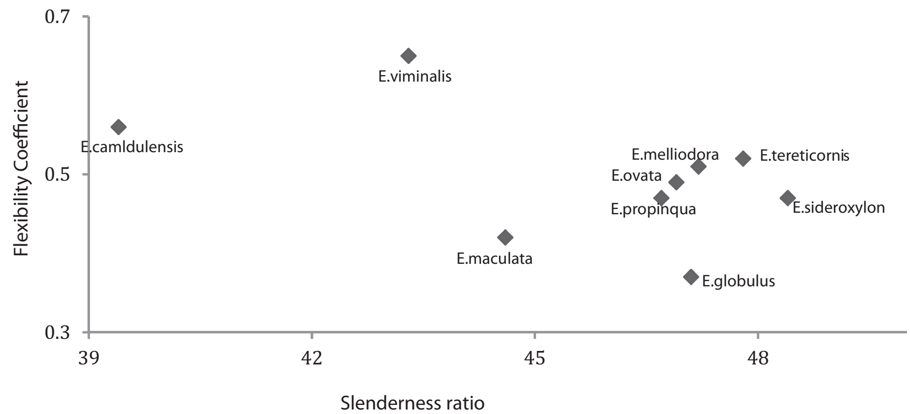

Fig. 4. Slenderness ratio and flexibility coefficient of *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis* and *E. viminalis* grown in the same environment at 50 months of age.

performance of *E. maculata*, *E. ovata* and *E. sideroxylon* as potential new pulpwood eucalypt species, in parallel to the prized *E. globulus* and the already used *E. camaldulensis* (Fig. 4).

4. Conclusions

The nine *Eucalyptus* species – *E. camaldulensis*, *E. globulus*, *E. maculata*, *E. melliodora*, *E. ovata*, *E. propinqua*, *E. sideroxylon*, *E. tereticornis* and *E. viminalis* – are structurally similar with typical eucalypt wood features, e.g. diffuse porosity with predominantly solitary vessels and simple perforations plates. Most anatomical differences between the species relate to the rays and axial parenchyma.

The species showed a higher diversity regarding their prospective pulping potential given by the proportion of fibres and morphological characteristics. The eucalypts position themselves differently as regards the combination of different morphological parameters, therefore allowing species targeting for specific paper properties. By considering these indicators, and taking into account the relative species growth, it seems promising to further study *E. maculata*, *E. ovata* and *E. sideroxylon* for their pulping performance as potential new paper making eucalypt species, in parallel to the prized *E. globulus* and the already used *E. camaldulensis*.

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