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

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A B S T R A C T

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