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Studies on physical, chemical and fibre morphological parameters of three pulpwood species viz. *Eucalyptus*, *Melia* and *Casuarina* for pulp and paper making

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Abstract
Investigations were made on the physical, chemical and fibre morphological parameters and fibre derived indices of three pulpwood species viz. *Eucalyptus*, *Melia* and *Casuarina* for pulp and paper making. *Eucalyptus*, *Melia* and *Casuarina* trees were selected, felled and wood samples were collected from respective plantations established in Forest College and Research Institute, Mettupalayam. Basic density of wood samples were measured using Shimadzu electronic balance attached with specific gravity module. Fibre maceration was done by Jeffrey's method and holocellulose and lignin content by Tappi method. Basic density and fibre morphological parameters showed significant variation (at 1%) between species. The highest basic density was observed for *Casuarina* followed by *Eucalyptus* and the minimum for *Melia*. The high fibre length and fibre wall thickness was observed for *Casuarina* followed by *Eucalyptus* and *Melia*. The fibre diameter and fibre lumen width was highest for *Melia* followed by *Casuarina* and *Eucalyptus*. Chemical composition was almost same for all the species; holocellulose ≈73% and lignin ≈23%. Studies on suitability of species for paper making showed that *Eucalyptus* is preferred in terms of its moderate basic density and optimum fibre morphological parameters. Low fibre length of *Melia* and high fibre wall thickness of *Casuarina* adversely affected its paper making properties. However in terms of fibre derived indices, *Melia dubia* was found to be most suitable for paper making followed by *Eucalyptus* and *Casuarina*.

Keywords: *Melia, Casuarina, Eucalyptus,* fibre morphology, cellulose, lignin, pulpwood, runkel ratio

Introduction
Eucalyptus, *Casuarina equisetifolia* and *Melia dubia* are fast-growing woody plants with the high potential as a fiber material for pulp and paper industry. Increasing demand of international trade in wood products, especially for pulp and paper, resulted in tremendous growth of fast growing short rotation tree plantation across the world. The scenario is same in India also where there is huge demand for pulp and paper. The Indian paper industry is highly fragmented consisting of small, medium and large sized paper mills having capacities ranging from 10 to 1500 tonnes per day employing wood, agro residues and recycled waste paper as major raw materials. In India, 813 pulp and paper mills produce only 14.9 MMT which accounts for 3.7% of the global paper production. Low operational capacities of Indian pulp and paper mills are mainly due to acute shortage of fibrous raw materials available to the industry (Jain 2015) [21]. Consequently, this has led to an intensive study to explore and create new fast growing tree species for pulp and paper industries. Particularly, researchers tends to find new species that have short rotation and high yield with excellent wood properties attributed to pulp and paper. Last several decades, *Eucalyptus*, an exotic fast growing tree from Australia, was commonly used in pulp and paper industry across the world. In India, because of growing demand for pulp, researchers found out two alternative species for *Eucalyptus*: *Casuarina equisetifolia* and *Melia dubia*.
(Horn 1978) [18] Stated that in the future, It would be necessary for the paper industry to rely much more on currently less-desirable hardwood species for their products. Today, in India it has witnessed that the paper industries are depending exclusively on hardwoods for meeting their raw material requirements. Major paper industries in southern India, like ITC Ltd, Tamil Nadu Newsprint & Papers Ltd (TNPL) etc. are using hardwood pulp, especially *Eucalyptus*, *Casuarina equisetifolia* and *Melia dubia* for their production.

These Industries and research institutes like Institute of Forest Genetics and Tree Breeding (IFGTB), Coimbatore, and Forest College and Research Institute (FC&RI), Mettupalayam had developed high yielding short rotation clones of *Eucalyptus*, *Casuarina equisetifolia* and *Melia dubia* for high quality pulp production. To advance their utility for pulp and paper industry, it is essential that the physical, chemical and fiber morphological properties of wood which provide for optimum performance in paper manufacture to be known. Hence the present study aimed to compare physical, chemical and fibre morphological properties of three hardwoods namely *Eucalyptus*, *Casuarina equisetifolia* and *Melia dubia*.

Materials and Methods

Materials

The study material was collected from clonal plantations of respective species established in Forest College and Research Institute, Mettupalayam. Three trees from each species were selected based on individual tree superiority for height, diameter at breast height and straightness of stem through index selection method. The selected trees were felled, cleared (removed branches and exfoliating outer bark) and then converted into billets of one meter length. The transverse discs collected from billets were further converted to smaller specimens for undertaking studies on wood physical, chemical and anatomical properties. For this discs were cut into two transverse halves. One half was used for estimation of basic wood density and basic wood specific gravity and the other half was used for studying chemical properties of wood i.e. holocellulose and lignin estimation. For basic wood density and basic wood specific gravity measurements five wood blocks of dimensions 2cm × 2cm × 2cm were taken from one half of the transverse discs. Wood blocks taken from other half of the transverse discs were converted into fine powder by ball milling for 10-12 minutes for the estimation of holocellulose and lignin content. About 10- 20 g powder was prepared from each sample. For fibre morphological study, wood shavings were taken from billets randomly.

Methodology

Estimation of basic wood density and basic wood specific gravity

Wood specific gravity of the samples were determined using a specific gravity module attached to a precision electronic balance (Schimadzu AUY 220). Basic density and basic specific gravity measurement were estimated based on weight at oven dry condition and volume at green condition. To obtain volume at green condition, the samples were prepared and measured immediately after felling the tree. Oven dry weight was measured after drying the wood samples in an oven, set at an approximately constant temperature of 102°C ±1°C, for such a time as is needed to make its weight constant.

$$\text{Basic density of wood} = \frac{\text{Oven dry weight (g)}}{\text{Volume of saturated wood sample (Green volume) (cm}^3\text{)}}$$

$$\text{Specific gravity of wood} = \frac{\text{Basic density of wood sample}}{\text{Density of water}}$$

Estimation of Fibre Morphological Parameters by Maceraton

Maceration of the wood samples was done using Jeffrey's method (Sass 1951) [52]. For maceration, Jeffrey's solution was used and it was prepared by mixing equal volumes of 10 per cent potassium dichromate and 10 per cent nitric acid. Radial chips of wood shavings were taken from billets. These chips were boiled in the maceration fluid for 15-20 minutes so that the individual fibres were separated. Then these test tubes were kept for 5-10 minutes so that the fibres settled at the bottom. The solution was discarded and the resultant material was thoroughly washed in distilled water until traces of acid were removed. The samples were stained using safranin and mounted on temporary slides using glycerine as the mountant. Microscopic examination and quantification of slides were done using an image analyzer (Labomed-Digi 2). It consists of a microscope, digital camera and PC (Personal computer). The digital camera provides digitized images which are analysed by the computer software (Labomed DigiPro-2). The software provides several classes of measurements like length, diameter, area and count.

Estimtion of chemical properties; holocellulose and lignin percentage

For the chemical analysis 10-20 gm of dried wood chips were powdered using Wiley mill. Wood powder sieved through a 40-mesh but retained over 60 mesh was then subjected to chemical analysis for calculating percentage of holocellulose and acid insoluble lignin. The extractive free samples were analysed for holocellulose (TAPPI T 249 cm−00 "Holocellulose in wood") and lignin (TAPPI T 222 cm−02 "Acid insoluble lignin in wood and pulp") (Tappi 2006) [62].

Extractive free wood powder

Soluble sugars, phenolic compounds and other extractives were removed from wood powder by treating with water and different organic solvents in Soxhlet apparatus. One gram wood powder was weighed in labelled cellulose thimble (extraction thimble 25x70 mm) and the mouth was bunged with cotton wool. The thimble was kept in Soxhlet apparatus and boiled for 30 minutes in distilled water (80 ml). This was extracted in ethyl alcohol for 30 minutes (80 ml) followed by 10 minutes rinsing. The next stage of extraction was carried out using ethyl alcohol and toluene (1:1; 40+40 ml) for 30 minutes followed by 10 minutes rinsing. Final extraction was carried out with acetone (10 ml) for 5 minutes boiling followed by 7 minutes rinsing. The thimble was removed from the Soxhlet and kept open for 24 hours. The dried extractive free residue was taken out carefully from the thimble using spatula to a pre weighed and labelled plastic tube and was kept in desiccators for holocellulose and acid insoluble lignin estimation.

Estimation of holocellulose

TAPPI method (TAPPI T 249 cm-00) was followed for the estimation of holocellulose in wood (Tappi, 2006) [62]. For this, two and half gram (O.D.) extractive-free wood powder was placed into 250 ml flasks with small watch glass covers. The samples were then treated with 80 ml of distilled water, 0.5 ml of cold glacial acetic acid, and one gram of $NaClO_2$.The flasks were then placed into a water bath maintained between 70°C-80°C. Every hour for three hours 0.5 ml of cold glacial acetic acid and 1 g of $NaClO_2$ were added and the contents of the flasks were stirred constantly with glass rod. Care was taken to avoid the formation of clumps. At the end of three hours, the flasks were cooled until the temperature of the flasks was reduced to 25°C. The contents of the flasks were filtered into G-2 glass crucibles of known weight followed by recycling. The residues were washed with acetone. The crucibles were then oven-dried at

105±2°C, then cooled in desiccators, and weighed until a constant weight was reached. The following formula was used to determine the holocellulose content in samples

$$\text{Holocellulose (\%)} = \frac{\text{(W2-W1)}}{\text{Oven dry weight of sample}} \times 100$$

Here, W2 stands for weight of crucible plus sample and W1 stands for weight of empty crucible

Estimation of Klason Lignin or Acid Insoluble Lignin

TAPPI method (TAPPI T 222 cm-02) was followed for the estimation of acid insoluble lignin in wood and pulp. (Tappi, 2006) [62]. for this, one gram oven-dried extractive-free wood powder was placed in 100 ml beakers. 15 ml of cold sulfuric acid (72%) was added slowly in each beaker while stirring and mixed well. The reaction proceeded for two hours with frequent stirring. After two hours the specimens were transferred by washing it with 560 ml of distilled water into 2,000 ml flasks, diluting the concentration of the sulfuric acid to three percent. The flasks were placed on hot plates for four hours. The flasks were then removed from the hot plates and the insoluble materials were allowed to settle. The contents of the flasks were filtered by vacuum suction into G-3 glass crucibles of known weight. The residues were washed with distilled water and then oven-dried at 105±2oC. Crucibles were then cooled in desiccators and weighed until a constant weight was obtained. The following formula was used to obtain the Klason lignin content in samples:

$$\text{Lignin (\%)} = \frac{\text{(W2-W1)}}{\text{Oven dry weight of sample}} \times 100$$

Here, W2 stands for weight of crucible plus sample and W1 stands for weight of empty crucible.

Results and Discussion

Basic Density

Among all the wood properties, density is the most important and the most widely studied characteristic which correlates with numerous morphological, mechanical, physiological, and ecological properties (Jerome *et al*. 2006) [22]. A lot of studies on wood specific gravity have been conducted previously for finding variation within and between species. The basic density of hardwoods is a complex characteristic which varies with species, age, growth rate, edaphic and climatic conditions, anatomy (proportion of different cell types), extractive content, moisture content etc. (Brown and Hills 1984; Raymond and Muneri 2001; Zobel and Buijtenen 1989) [6, 49, 73]. The present study revealed that there is a significant variation in basic density of three species (Table 1). The highest basic density was obtained for *Casuarina equisetifolia* (656.10 kg/m^3) followed by *Eucalyptus sp.* (547.90 kg/m^3) and the minimum for *Melia dubia* (401.30 kg/m^3). The high basic density of *Casuarina equisetifolia* might be due to relatively high proportion of thick walled fibres. The fibre morphological data substantiated this. Presence of large vessels may attributed to comparatively low basic density of *Eucalyptus* as compared to *Casuarina equisetifolia*. High lumen width and very low fibre wall thickness of *Melia dubia* contributed to its low basic density values. The obtained basic density values of three species were within the range of basic density values reported by others.

According to (Sukla, Gandhi, and Sangal 1981) [59] the basic density of *Eucalyptus* hybrids of different age group from different localities is varying from 514 to 721 kg/m^3. The other studies reported that the basic density ranged from 458 to 802 kg/m^3 across different *Eucalyptus* species, its hybrids and clones (Kamala, Kumar, and Sudheendra 1996; Kothiyal *et al*. 1998, 2011) [25, 30]. The average basic density of wood samples of *Eucalyptus* hybrid taken for this study was included within the range of values obtained in earlier studies. For *Casuarina equisetifolia*, the average basic density was recorded as 656.10 kg/m^3, which was also in agreement with the previous studies. Chowdhury *et al*., (2009) [7] reported that the basic density of *Casuarina equisetifolia* varied from 630 to 730 Kg/m^3 in radial direction within a tree. In an another study, the wood densities (oven-dried condition) of 4.5 year old trees of seedling origin planted in Sadival, India varied from 590 to 710 kg/m^3 (Nicodemus *et al*. 1996) [35]. *Casuarina equisetifolia* clones developed by IFGTB and planted in Tamil Nadu showed variation in specific gravity (oven dry basis) which ranged from 594 to 830. For *Melia dubia*, the average specific gravity (401.30 kg/m^3) obtained was similar to the value reported by others; 418.70 kg/m^3 for three year old tree reported by (Saravanan *et al*. 2014) [51].

Table 1: Average basic density of wood samples of *Eucalyptus* sp., *Casuarina equisetifolia*, and *Melia dubia*

Sl. No.	Species	Basic density (Kg/m^3)
1.	*Eucalyptus sp.*	547.90 (16.02)
2.	*Casuarina equisetifolia*	656.10 (34.11)
3.	*Melia dubia*	401.30 (14.29)
	Total	535.10 (108.54)**

(** 1 % significant, values in parenthesis are standard deviation)

Fibre Morphology

Fiber characteristics such as fibre length, fibre dimeter, fibre wall thickness and fibre lumen width are important parameters which determine suitability of wood as raw material for pulp and paper industry (Kayama 1979) [27]. The fibre length and fibre diameter values of wood samples of three species was comparatively higher than the values reported in previous studies (table 2). In the present study the wood samples were collected from genetically superior clonal plantations of respective species established in Forest College and Research Institute, Mettupalayam. Earlier research on wood properties of clones of these three species showed that clones were phenotypically superior in terms of fibre characteristics. i.e. fibre length and fibre diameter. In the present study the maximum fibre length was obtained for *Casuarina equisetifolia* (1521.022 µm) followed by *Eucalyptus sp.* (1392.622 µm) and the minimum for *Melia* dubia (1011.668 µm). For fibre diameter, the ascending order of values were 29.949 µm for *Melia dubia*, 22.770 µm for *Casuarina equisetifolia* and 18.919 µm for *Eucalyptus sp.* Swaminathan, Rao, & Shashikala, (2012) [60] who reported the average fibre length and fibre diameter as 1055.50 µm and 37.50 µm respectively for *Melia dubia* was similar to the present study. Saravanan *et al*. (2014) [51] reported the average fibre length and fibre diameter of 1245 µm and 29.20 µm respectively for five year old *Melia dubia* trees. The average fibre length and fibre diameter of *Casuarina equisetifolia* clones developed by Institute of Forest Genetics and Tree Breeding was 1452.41 µm and 25.19 µm respectively (Vishnu 2013) [63]. These values were in par with the values obtained in the present study; 1517.58 µm for fibre length and 22.72 µm for fibre diameter. The fibre length and fibre diameter of *Eucalyptus* hybrid (1388.139 µm and 18.823 µm respectively) showed comparatively higher values than the values recorded by others; 907 µm and 12.54 µm for three year old clones (Sreevani and Rao 2013) [58] and 872 µm and 14.7 µm for six year old clones (Behera *et al*. 2016) [3].

Table 2: Average fibre length, fibre diameter, fibre wall thickness and fibre lumen width of wood samples of *Eucalyptus sp.*, *Casuarina equisetifolia*, and *Melia dubia*.

Sl. No.	Species	FL (µm)	FD (µm)	FWT (µm)	FLW (µm)
1.	*Eucalyptus sp.*	1392.622 (168.958)	18.919 (3.943)	5.510 (1.471)	7.898 (3.020)
2.	*Casuarina equisetifolia*	1521.022 (239.983)	22.770 (3.893)	8.103 (1.473)	6.565 (2.723)
3.	*Melia dubia*	1011.668 (154.426)	29.949 (5.062)	3.177 (0.958)	23.594 (5.044)
	Total	1308.021** (288.343)	23.867** (6.300)	12.690** (8.593)	5.589** (2.403)

(FL-Fibre length, FD- Fibre diameter, FWT-Fibre wall thickness and FLW-Fibre lumen width) (** 1% significant, values in parenthesis are standard deviations)

Fibre wall thickness and fibre lumen width also showed significant variation between species. Interestingly fibre wall thickness (7.898 µm) and fibre lumen width (5.510 µm) of *Eucalyptus sp.* were superior as compared to previous studies. (Sreevani and Rao 2013) [58] reported the maximum fibre wall thickness of 5.72 µm and the minimum lumen diameter (lower value is superior) of 7.33 µm for *Eucalyptus* clones. For *Casuarina equisetifolia*, both fibre wall thickness (6.565) and fibre lumen width (8.103 µm) were in par with values reported by (Vishnu 2013) [63]: 7.763 µm and 9.630 µm respectively. For *Melia dubia* fibre lumen width and fibre wall thickness were 23.594 µm and 3.177 µm respectively which was less than 6.9 µm and 24.3 µm respectively reported by (Swaminathan, Rao, and Shashikala 2012) [60].

Chemical composition: holocellulose and lignin content

All the three species did not show much difference in their chemical composition. The holocellulose content was around 74% for all species (Table 3). Minimum lignin percentage was reported for *Eucalyptus* (22%) followed by *Melia dubia* (23%) and then *Casuarina equisetifolia* (24%). (Parthiban *et al*. 2011) [45] reported that lignin content of 25 short rotation *Casuarina* hybrid clones ranged between 24.2 and 27.8 per cent. Another study by (Vishnu 2013) [63] showed that lignin per cent of *Casuarina equisetifolia* clones ranged from 21 to 29 per cent. (Klash *et al*. 2010) [28] compared the chemical composition of several eucalypt species and found that *E. grandis* clone had the largest amount of lignin (21%). *Melia dubia* of different age gradations, from one to five years, showed that holocellulose and lignin per cent ranged from 69 to 75 and 24 to 30 respectively.

Table 3: The chemical composition of three species namely *Eucalyptus sp.*, *C. equisetifolia*, and *M. dubia*.

Species	Holocellulose (%)	Lignin (%)
Eucalyptus sp.	74	22
C. equisetifolia	73	24
M. dubia	74	23

Suitability of *Eucalyptus sp.. C. equisetifolia, and m. dubia* wood for pulp and paper making

Basic density simply explains the amount of wood substance present per unit volume. It has a significant effect on the quality and yield of pulp and paper products and on strength and utility of solid wood products. It appears to influence machinability, conversion, strength, paper yield and many other properties (Wimmer *et al*. 2002) [70]. It is realized from many other studies (Dinwoodie 1966; Watson *et al*. 1952; Watson and Holder 1954) [11, 68, 69] that wood density is a major factor in the ultimate performance of fiber as a raw material for pulp. Many research works on wood properties and pulp and paper properties reported that increase in wood specific gravity are accompanied by increase in tear index, bulk, air permanence, freeness, bending stiffness, light scattering and opacity, while it reduces tensile index, stretch, bursting strength, breaking length, Tensile Energy Absorption (T.E.A) and fold endurance (Malan, Male, and Venter 1994; du Ploy 1980) [33, 46]. According to (Ramirez *et al*. 2009) [48] high densities produce bulkier, more porous sheets with lower tensile and burst index and high tear index. Lower density woods mainly produce denser sheets with high tensile strength. (Ikemori, Martins, and Zobel 1986) [20] suggested that wood density which is in the range of 480-570 kg/m^3 is ideal for paper and pulp making. In the present study, *Eucalyptus sp.* is ideal in terms of density or basic specific gravity. *Melia dubia* and *Casuarina equisetifolia* can also be used for pulping because its density values are in par with ideal range of density values. Judicial mixing of *Casuarina equisetifolia* and *Melia dubia* pulp along with *Eucalyptus* pulp can produce paper with desirable physical, mechanical and structural properties.

Cellulose and lignin are major structural as well chemical components of wood. Species with high cellulose and less lignin content is most suitable for pulp and paper production. Along with wood fibre morphology, wood chemistry also determines key paper qualities such as strength, opacity, porosity, and bulk (Cotterill and MacRae 1997) [8]. Paper strength also depends on the lignin and cellulose content of raw plant materials. While considering pulp and paper making, the amount of cellulose in wood is positively related with pulping yield whereas lignin is negatively correlated (Amidon 1981; Wallis, Wearne, and Wright 1996) [1, 64, 71]. In this regard all three species are very suitable for pulp and paper making since the high holocellulose content resulted in high pulp yield. According to the rating system developed by (Nieschlag *et al*. 1960) [36], plant materials with 34 and over cellulose content were characterized as promising for pulp and paper manufacture from a chemical composition point of view. Though cellulose content was not calculated separately, the high holocellulose content is a clear indication of high percent of cellulose (more than 34%). According to (Madakadze *et al*. 1999) [32] cellulose content is directly proportional to pulp mechanical strength and especially tensile strength. The cellulose content relates to the amount of pulp that can be obtained from wood. The higher the cellulose content in a tree, the more pulp the tree will produce (Sykes *et al*. 2003) [61]. Increasing the amount of cellulose content in wood will reduce pulping costs and increase the efficiency of the pulp and paper mill.

The present study revealed that lignin contents were also at satisfactory levels (<30%) for all species which makes these species suitable for pulp and paper making. (Kojimal *et al*. 2007) [29] reported that Klason lignin content in wood was inversely correlated with pulp sheet density, which is an important characteristic affecting the physical properties of pulp. On the other hand, increased amount of lignin content in wood will increase pulping cost by necessitating the chemical breakdown of lignin, which is an expensive process. So reducing the lignin content in wood could save processing costs for the pulping industry (Sykes *et al*. 2003) [61].

The relationship between wood pulp fibre morphology and paper properties has been extensively studied over the years. The properties of pulp and paper products highly depend on the dimensions of the fibres forming the products and on the ability of these fibres to bind to each other in a fibre network. It has become increasingly important to identify key fibre dimensions that can be used to predict ultimate pulp and papermaking performance in industrial level. Fibre length influences most of the pulp strength properties. (Wright and Sluis-Cremer 1992) [71] found out positive correlation between fibre length and tear index for *Pinus rdiata* and *P. elliottii*. Fibre length influence burst strength, tear strength, folding endurance and tearing resistance of the paper (El-Hosseiny and Anderson 1999; Haygreen and Bowyer 1996; Ona *et al*. 2001; Wangaard and Williams 1970) [15, 17, 42, 66]. According to (Ademiluyi and Okeke 1979) [1] higher quality paper in terms of tearing resistance can be produced from longer fibres. According to (Downes and Raymond 1997) [12], fibre length, fibre diameter and wall thickness are the most important fibre dimensions considered for pulp and paper manufacture. (Monteoliva, Senisterra, and Marlats 2005) [34] reported that fiber anatomical properties have a major influence on the quality of pulp and paper products. Species having higher fiber length is preferred for pulp and paper production because a better fiber network is achieved, resulting in higher paper strength (Amidon 1981; Dadswell and Watson 1962; Dinwoodie 1966; Scurfield 1976; Seth and Page 1988; Wangaard 1962; Wardrop 1969) [2, 10, 11, 54, 55, 65, 67]. (Horn 1978) [18] reports that increase in raw material fiber length enhance the tearing strength of hardwood pulps. As the number of binding points for a single fibre increases with its length, the tensile and tear strength of paper are both found to be increased with fibre length in weakly bonded sheets, whereas in a well-bonded sheet, the tear and tensile strength depend less on fibre length (Niskanen 1998; Seth and Page 1988) [37, 54]. Since, the length of fibre greatly affects the strength of the pulp and the paper made from it (Kaila and Aittamaa 2006) [24] paper made from *Casuarina equisetifolia* and *Eucalyptus* is expected to show higher quality than *Melia dubia* with shorter fibres. An increase in fiber length resulted in increased pulp yield, tear index, bending stiffness, freeness, burst strength and permanence, whereas reduction in fiber length reduces the physical strength properties with reduced soda demand (El-Hosseiny and Anderson 1999; Labosky and Ifju 1981; Malan, Male, and Venter 1994; du Ploy 1980; Wimmer *et al*. 2002) [15, 31, 33, 46, 70].

Fibre cross-sectional dimensions strongly affects pulp and paper properties (Amidon 1981). Though thicker walls give higher pulp yield and high tear resistance it tends to produce coarse, bulky sheets with poor printing surface, poor burst and tensile strength and inhibits chemical bonding (Joransen 1960; Zobel and van Buijtenen 1989) [23, 73]. Thinner walled cells collapse upon pulping and respond well with chemicals to obtain good chemical bond between fibres and to produce paper with smooth surface. Paper produced from thick walled cells would have low folding endurance (Biermann 1993) [5]. According to (Karlsson 2006) [26], narrow fiber width is desirable for pulp and paper applications because it results in smoother paper and more uniform formation. (Pulkkinen *et al*. 2008) [47] studied the use of fibre wall thickness data to predict handsheet properties of *Eucalyptus* pulp fibres and revealed that fibre wall thickness distribution was found to be the major contributor of handsheet properties studied, such as tensile strength, sheet density and air resistance. He concluded that fibres with low wall thickness and narrow fibre lumen width had higher strength properties, density of the handsheets and air resistance. He reported that the thick-walled fibres with wide wall thickness distribution have a wide stress distribution with a different amount of fibre shrinkage between adjacent fibres, resulting in a higher change in sheet dimensions and producing relatively loose fibre network. Cell wall thickness governs fibre flexibility. Thick walled fibre adversely affects the bursting strength, tensile strength and folding endurance of paper. The paper manufactured from thick walled fibres was bulky, coarse surfaced, and containing a large amount of void volume. But the paper from the thin walled fibres was dense and well formed. Fibre lumen width affects the beating of pulp. Larger the fibre lumen better will be the beating of pulp because of the penetration of the liquids into the fibre lumen.

In the present study, *Casuarina equisetifolia* can be considered as an alternative pulpwood species because of its higher fibre length and comparable fibre diameter with *Eucalyptus*. Though *Melia dubia* has low fibre length and fibre wall thickness, it can be effectively used for making different grades of paper having low bursting and tearing strength and higher flexibility. Higher lumen width will increase flexibility of paper. Higher lumen width preferable for pulp and paper making in the case of *Casuarina* also. (Guha and Nadan 1963) [16] reported that *Casuarina equisetifolia* have high pulp yield with good satisfactory strength properties. *Eucalyptus globulus* had tensile, tear, bending, freeness, and pulp yield that were positively correlated to fiber length (O'Neill 1999; Wimmer *et al*. 2002) [43, 70].

Table 4: Indices derived from fibre morphological parameters of three species, *viz. Eucalyptus*, *Melia dubia*, *Casuarina equisetifolia*.

Indices	*Eucalyptus*	*Melia dubia*	*Casuarina equisetifolia*
Runkel ratio	1.396	0.269	2.468
Slenderness ratio	73.609	33.779	66.799
Flexibility coefficient	41.744	78.781	28.832
Rigidity coefficient	58.256	21.219	71.168
Luce′s shape factor	0.703	0.234	0.847

Indices derived from wood fiber characteristics have often been associated with paper strength-in particular, paper made from hardwoods. Indices derived from fibre morphological parameters of three species, viz. *Eucalyptus*, *Melia dubia*, and *Casuarina equisetifolia* has given in table 4. Runkel ratio is a measure of the suitability of fibre for paper production. The Runkel Ratio is a microscopic extension of the wood density in that wall thickness and lumen width are the basic factors used in their determination. Fibres with high Runkel, i.e. more than one, is considered as thick walled fibres which are stiffer, less flexible and form bulky paper sheet of lower bonded area (Dutt *et al*. 2009) [14]. Thick walled fibres with narrow lumen retain its tubular structure on pressing and thus offer less surface contact for fibre bonding (Dutt *et al*. 2004) [13]. A number of researchers suggested an approximate range of runkel ratio applicable to pulp and paper production; 0.25 to 1.5 by (Singh, Rai, and Dhawan 1991) [56]; less than 1 by (Dadswell and Wardrop 1959) [9] and less than or equal to 1 by (Okereke 1962) [40] and (Rydholm 1965) [50]. In this study, *Eucalyptus* and *Melia dubia* are within the acceptable range of Runkel ratio (0.25-1.5) proposed in previous studies.

Flexibility coefficient, which determines the degree of fibre bonding in paper sheet is one of the important derived indices to determine strength properties of paper like tensile strength and busting strength (Ona *et al*. 2001) [42]. Flexibility coefficient values for hardwood and softwoods are 0.55-0.70 and 0.75 respectively (Smook 1997) [57]. The fibres having flexibility coefficient more than 0.75 and between 0.50-0.75 are considered as 'highly elastic' and 'elastic fibres' (Bektas, Tutus, and Eroglu 1999) [4]. So *Melia dubia* alone can be considered for paper in this aspect. Rigidity coefficient is a measure of physical resistance properties of paper. Higher values for this coefficient affect tensile, tear, burst and double fold resistance of paper negatively (Hus, Tank, and Goksal 1975) [19]. *Casuarina equisetifolia* (71.168) and *Eucalyptus* (58.256) have moderately high rigidity s compared to *Melia dubia* (21.219).

Slenderness ratio is a measure of tearing property of paper. Higher the slenderness ratio, greater will be the expected flexibility that will give better tensile and tear property. Slenderness ratio is also related with resistance to tearing (Rydholm 1965) [50]. The fibres with a high slenderness ratio are long, thin and have high tearing resistance, where as short and thick fibres have less slenderness ratio and tearing resistance. It is reported that slenderness ratio of fibrous material more than 33 is considered good for pulp and paper production (Xu *et al*. 2006) [72]. So *Casuarina equisetifolia* and *Eucalyptus* with slenderness ratio 66.799 and 73.609 are suitable in this regard.

Luce's shape factor, an important fibre index derived from fibre diameter and lumen diameter is directly related to paper sheet density and is significantly correlated to breaking length of paper (Sharma, Sharma, and Kumar 2013) [55]. Fibers with lower values of shape factor will give better strength to paper and lower tensile stiffness (Page and Seth 1980) [44]. So species with lower shape factor is suitable as a raw material for pulping and paper making. Shape factor and solid factor were found to be related to the paper sheet density and could significantly be correlated to breaking length of paper in *Eucalyptus* (Ona *et al*. 2001) [42]. According to (Page and Seth 1980) [44], lower the value of shape factor, higher will be the paper strength. Since lower value of shape factor was obtained for *Melia dubia* (0.234) and moderate values for *Casuarina equisetifolia* (0.847) and *Eucalyptus* (0.703) these species can be considered for pulp and paper making. Luce's shape factor of fibres extracted from various species was as follows; 0.29 for, *Gmelina arborea*, 0.25 for *Ficus mucuso*, and 0.16 for *F. exasperate* (Ogunkunle 2010) [38]; 0.20 for *Gmelina arborea*, 0.47 for *Afzelia Africana* and 0.73 for *Detarium senegalense* (Ojo 2003) [39]; and 0.41 for *Leucaena lencocephala* (Oluwadare and Sotannde 2007) [41].

Conclusion

Understanding of physical, chemical and fibre morphological characteristics of pulpwood will help judicial utilization of the raw material in pulp and paper industry. Suitability of wood of three species namely *Eucalyptus*, *Melia dubia* and *Casuarina equisetifolia* for pulp and paper making was studied. Parameters like basic density, holocellulose content (%), lignin content (%), fibre length, fibre diameter, fibre wall thickness, fibre lumen width and fibre derived indices like Runkel ratio, slenderness ratio, flexibility coefficient, rigidity coefficient and Luce′s shape factor were considered. Basic density was highest for *Casuarina equisetifolia* followed by *Eucalyptus* and then *Melia dubia*. Since basic density affects yield of the pulp obtained from wood, *Casuarina equisetifolia* and *Eucalyptus* were superior in this regard. Fibre length and fibre wall thickness are two important fibre morphological parameters considered for pulp and paper making. High fibre length was obtained for *Casuarina equisetifolia* followed by *Eucalyptus* and *Melia dubia*. Fibre wall thickness was obtained maximum for *Eucalyptus* followed by *Casuarina equisetifolia* and *Melia dubia*. In the present study, *Casuarina equisetifolia* can be considered as an alternative pulpwood species because of its higher fibre length and comparable fibre diameter with *Eucalyptus*. Though *Melia dubia* has low fibre length and fibre wall thickness, it can be effectively used for making different grades of paper having low bursting and tearing strength and higher flexibility. All the three species showed almost same chemical composition, *i.e.*, ≈73% holocellulose and ≈23% lignin. Though *Eucalyptus* is widely used for pulp and paper making, fibre derived indices showed that *Melia dubia* is better than *Eucalyptus* for paper making. Based on fibre derived indices *Casuarina equisetifolia* was least preferred over other species. However these three species differed in physical, chemical and fibre morphological parameters, the judicial mixing of pulp obtained from these species can be done to meet the growing demand of pulp for paper production.

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