Empirical investigations on the wood quality assessment of five tropical species for multifarious industrial utility

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Abstract. Four species and one hybrid: *Khaya senegalensis, Melia dubia, Chukrasia tabularis, Toona ciliata*, and an *Acacia* hybrid were assessed for their physical, chemical, and thermo-chemical properties. *Khaya senegalensis* had the highest density (665.74 kg/m³), while *M. dubia* exhibited the highest recovery rate (80%). *Melia dubia* had the highest holocellulose content (75.50%), while lignin content in *K. senegalensis* was 28.60%. Caloric value (4380.20 kcal) was highest in *Chukrasia tabularis* while the fixed carbon (15.87%) content reached a maximum for *K. senegalensis*. The findings suggest that *K. senegalensis* and *M. dubia* are promising species for plywood, pulp, and energy applications.

Keywords: Tropical species, Physical, Chemical and thermo-chemical properties, Veneer recovery

Introduction

Wood has been used for centuries for house construction, furniture, tools for agriculture, transportation and most importantly supplying energy to peri-urban and rural communities. India is the world's largest producer and consumer of timber and timber products (Ramesh et al. 2022). Native forests were the primary source of timber until the 1980s, and forest management continues to revolve around timber production. The 1988 National Forest Policy shifted toward the conservation of forests and their management for maintaining ecological balance and ecosystem services, as well as supplying local community livelihood needs. As a result, the domestic wood supply was drastically reduced from 10 million m^3 in the 1970s to about 4 million m^3 in the 1990s (Gilbert et al. 2014). A Supreme Court 1996 order banned logging in

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all forests unless it aligned with the State Working Plans that the national government had authorized. This led to an even greater decline in timber production. However, the rapid expansion of the economy, urbanization, industrialization, and population growth, have created a steady increase in demand for various kinds of wood and wood products. The exclusive National Agroforestry Policy by the Indian Government in 2014 has encouraged greater involvement from the wood-based industries to promote industry-specific agroforestry. The wood-based industries are attempting to revamp infrastructure and implement better processing technologies to meet the growing consumer demand.

Wood-based industries such as pulp and paper, plywood, and panel rely on a few species, creating competition for resources. *Eucalyptus* and *Casuarina* are the most commonly used pulp wood species in India, but can be problematic due to their variable adaptability and low productivity in marginal areas (Parthiban et al. 2004). The plywood industry also uses a small number of species, primarily poplars and eucalypts (Parthiban et al. 2014). Both of these genera are exotic in origin and have been criticized due to their severe water consumption (Kutnik et al. 2014) Eucalypts, in particular, can suppress the growth of other plants through allelopathy and deplete soil moisture (Desta et al. 2020). Poplar, on the other hand, faces challenges due to its low wood price, which can make it less profitable for farmers. Both species also compete with crops and intercrops for water and nutrients (Kumar et al. 2017).

Globally, high-yielding tree species are being planted to meet increasing demands for pulp and paper manufacture, plywood production, and dendroenergy (Espinoza 2004). However, not all timber species are suitable for commercial production. Density is the most significant and extensively researched wood property, correlating with several other characteristics. The increased demand for wood fiber has created a need to identify alternate species with superior wood quality coupled with high productivity and amenability for agroforestry schemes (Harper et al. 2009). The objective of this study was to assess the properties of four species and one hybrid for various industrial uses.

Materials and methods

Four tree species and one hybrid, viz., *Melia dubia*, *Chukrasia tabularis*, *Khaya senegalensis*, *Toona ciliata,* and Acacia hybrid (*Acacia auriculformis* x *Acacia mangium*) were selected based on their prolific growth, superior morphogenic characteristics, and multi-industrial utility. The three 3- to 5-year-old trees of each species were harvested from research trials established at the Forest College and Research Institute, Mettupalayam, India. The boles and large branches were debarked and chipped (chips of ~7 mm) after shade drying. The selected species along with their geographical distribution and biometric attributes are presented in Tables 1 and 2.

Table 1. Species investigated and their geographical sources.

Species	Age (years)	Location	Location
Melia dubia	5	11.2592°N, 77.0345°E	Pogalur
Chukrasia tabularis	5	11.3241°N, 76.9370°E	FC &RI
Khaya senegalensis	5	11.3241°N, 76.9365°E	FC &RI
Toona ciliata	3	11.3231°N, 76.9386°E	FC &RI
Acacia hybrid	5	11.3237°N, 76.9386°E	FC &RI

Table 2. Characteristics of trees assessed for wood properties.[a]

Species	Height (m)	GBH (cm)	Volume (m^3)
Melia dubia	15.75	99.75	0.685
Toona ciliata	10.75	52.50	0.129
Chukrasia tabularis	19.00	76.30	0.483
Khaya senegalensis	15.40	55.50	0.206
Acacia hybrid	15.00	56.50	0.209

a. Values represent means of three trees per species.

Estimation of physical properties of wood

Bulk density

The bulk density of the wood was calculated based on procedures described by Haygreen and Bowyer (1996). Chips were taken, and their volume was calculated by placing them into a suitable graduated container, then the chips were oven dried (103°C) and weighed. Bulk density was calculated based on the following formula:

$$\text{Bulk density (kg/m}^3\text{)} = \frac{m}{v} \tag{1}$$

Where, m = Oven-dry weight of chips at 100°C; and v = Volume.

Basic density

The basic density of each wood sample was calculated by using the following formula:

$$\text{Basic density (kg / m}^3\text{)} = \frac{E2}{F+G} \tag{2}$$

Where, E_2 = Green weight (after soaking in water for 48 hours); F = Oven dry weight of chips; and G = Deflection of the needle in cm due to water displacement.

Moisture content

One hundred g of wood chips were weighed, dried at 105°C for 8 hours, and weighed. Moisture content at the time of chipping was calculated using the following formula:

$$\text{Moisture content (\%)} = \frac{\boldsymbol{Initial\ weight - Final\ weight}}{\boldsymbol{Initial\ weight}} \times 100 \quad (3)$$

Estimation of chemical properties of wood

Billets of each tree species were chipped, air dried, and then ground to pass a 40-mesh screen using a Wiley mill (Secon India). The milled wood was passed through a 60-mesh screen and measured for moisture, ash content, hot water solubles, 1% NaOH solubility, ethanol/benzene extractives, acid insoluble lignin, and holocellulose, as per TAPPI methods (TAPPI 1980).

Ash content

One g of oven-dry sample was placed on a tared porcelain crucible and heated in a muffle furnace at 840 ± 5°C for 1 hour. The crucible was cooled inside a desiccator and weighed. The ash content was calculated from the observed mass difference:

$$\text{Ash content (\%)} = \frac{\boldsymbol{W3 - W1}}{\boldsymbol{W2 - W1}} \times 100 \quad (4)$$

Where, W1 = weight of empty crucible, g; W2 = weight of empty crucible + original sample, g; and W3 = weight of empty crucible + ash sample, g.

Hot water extractives

Two g of sample was placed in conical flask with 300 ml distilled water and boiled for 2 hours. The contents were then filtered through tared Whatman filter paper, which was washed and oven-dried at 105 ± 2°C for 24 hr. The filter paper was cooled in a desiccator and weighed (W_2). The hot water solubles were calculated using the following formula:

$$\text{Hot water solubles} = \left[\frac{\boldsymbol{W2 - W1}}{\boldsymbol{W2}}\right] \times 100 \quad (5)$$

1% NaOH extractives

Two g of sample was placed in conical flask with 100 ml of 1% sodium hydroxide (NaOH). The sample was refluxed for 4 hours then the contents were filtered through a tared G_2 crucible (W_1). The crucible was oven-dried at 105 ± 2°C overnight and cooled in a desiccator before being weighed (W_2). Each material was tested in duplicate. NaOH solubility was calculated using the following formula:

$$\text{1\% NaOH solubility} = \left[\frac{\boldsymbol{W2 - W1}}{\boldsymbol{OD\ weight\ of\ the\ sample}}\right] \times 100 \quad (6)$$

Alcohol benzene (AB) extractives

Around 7 g of oven-dried sample was placed in a tared thimble that was covered with cotton and placed in Soxhlet apparatus. The sample was then extracted in 300 ml of a 1:2 mixture of ethanol and benzene (AB extractives) for 6 hours at 70–85°C. The extracted thimble was oven-dried at 100°C and weighed (W_2). The AB extractives were calculated using the formula:

$$\text{AB Extractive \%} = \left[\frac{\boldsymbol{W2 - W1}}{\boldsymbol{OD\ weight\ of\ the\ sample}}\right] \times 100 \quad (7)$$

Holocellulose (ash corrected)

Five ($\pm$ 0.01) g of oven-dried sample were placed in a 250 ml conical flask and wetted thoroughly with 10 ml of distilled water. Then 150 ml of distilled water, 1.5 g of sodium chlorite, and 0.5 ml of acetic acid (glacial) were added and a smaller flask was used to cap the flask. The contents were heated in a water bath at 70°C for 1 hour, and then the supernatant was transferred to a tared crucible (W_1). The treatment was repeated with water, sodium chlorite, and acetic acid. The contents were then filtered through Whatman # 1 filter paper into a conical flask, and the filtered residue was washed with acetone. The filter paper with residues was oven-dried at 105°C overnight and weighed (W_2). The holocellulose percentage was calculated using the formula:

$$\text{Holocellulose \%} = \left[\frac{\boldsymbol{W2 - W1}}{\boldsymbol{OD\ weight\ of\ the\ sample}}\right] \times 100 \quad (8)$$

Estimation of Thermochemical properties of wood

Volatile matter

The volatile content of the sample was determined using ASTM D3172 (ASTM 2002). One g of dried, powdered sample was placed in a pre-weighed crucible and heated in a muffle furnace at 600°C for 6 min. The volatile matter was calculated using the following formula:

$$\text{Volatile matter (\%)} = \frac{(\text{W1} - \text{W2})}{(\text{W1} - \text{W3})} \times 100 \quad (9)$$

Where, W_1 = Weight of the crucible + Sample; W_2 = Weight of the final ash present in the crucible + crucible; and W_3 = Weight of the empty crucible.

Fixed carbon

Fixed carbon in the sample was derived by subtracting ash content and volatile matter from the original sample mass. The fixed carbon was calculated by using ASTM D3172-84 (ASTM 2002), which follows:

$$\text{Fixed carbon (\%)} = 100 - (\text{ash content} + \text{volatile matter}) \quad (10)$$

Caloric value

The caloric value was determined using a digital bomb calorimeter (Model B.C.M – A217014, Mfg. by Advance Research Instrument Co.). A one gram sample was pelleted and fed into the calorimeter. This oxygen driven instrument burned the pellets and subsequently gave the calorific values of the samples. The amount of energy chemically bound in biomass was indicated by its caloric value, which was transformed into heat energy during combustion. Caloric value of biomass fuel significantly impacts the design of a biomass combustor (Erol et al. 2010).

Estimation of veneer recovery

The logs were transported to a nearby industrial facility and debarked. They were then fed into a 1.2 m capacity rotary lathe to produce 1.8-mm-thick veneer (Jamuna Engineering, Yamunanagar). Recovery was based upon the length of veneer produced from each log vs. the original tree diameter.

Results and discussion

Physical properties

A better understanding of how wood interacts with the environment is expected to improve processing optimization and the design of wood-based products (Avramidis 2016). In the present investigation, the wood samples collected from four species and one hybrid exhibited significant variation in physical properties (Table 3). Similarly, Izekor and Alufohai (2010) reported the mean density values of 480, 556, and 650 kg m^3 for 15-, 20-, and 25-year-old *Tectona grandis* wood, indicating that density increased with age. Similar results were reported among various *Eucalyptus* species for basic density, which ranged between 425 kg per m^3 and 542 kg per m^3 (Vennila 2009). Wood density is important for production of quality pulp and paper. The amount of wood needed to produce 1 ton of air-dried pulp is calculated from the density and pulp yield (Storebraten 1990). Therefore, the high density recorded for *Chukrasia tabularis* would make it an attractive alternate species for pulp production.

Chemical properties

The proximate chemical analysis gives an idea of potential for papermaking (Rao et al. 1999). In the present study, *T. ciliata* had lowest solubility in alcohol benzene extractive, cold water, hot water, and 1% NaOH, while *C. tabularis* had the highest alcohol benzene extractive and 1% NaOH solubility. *Melia dubia* had the highest hot water solubility when compared to other species (Table 3). Lal et al. (2010) reported low cold-water solubility (2.3%), higher hot water (5.0%), and alcohol benzene (2.4%) solubility than *E. tereticornis* (2.9%, 7.8%, and 1.4%, respectively). The lower extractives content results in fewer pitch problems and produces more homogeneous paper (Kasiviswanathan 1998). *Melia dubia, Acacia hybrid, and C. tabularis* wood will create fewer pitch problems and produce more homogeneous paper sheets. The 1% NaOH solubility measures low molecular weight carbohydrates, which were lower in *T. ciliata* when compared to the Acacia hybrid. Lower 1% NaOH solubility indicates that pulp will be less resist to UV degradation, heat and fungal decay. Hence pulp degradation will be greater in *Toona* spp. when compared to the other species. Saravanan et al. (2013) also reported similar results in 1- to 5-year-old *M. dubia* and recommended longer rotations. Holocellulose content is important for assessing the suitability of raw material for papermaking (Ona et al. 2001). Holocellulose represents the total content of carbohydrate materials and therefore, high holocellulose content is desirable for pulp and paper production because it is correlated with a higher pulp yield (Mabilangan and Estudillo 1996). *Melia dubia* was rich in holocellulose content (75.50%) when compared to the other species. This result shows that *Melia dubia* is suitable for the pulp and paper industry at early rotation.

Table 3. Physicochemical properties of wood from five different wood species.

Analysis	*Melia dubia*	*Chukrasia tabularis*	*Khaya senegalensis*	*Toona ciliata*	*Acacia* hybrid
Moisture content (%)	20.80	33.04	27.04	25.30	20.8
Bulk density (kg/m^3)	510.46	600.30	559.37	450.61	510.46
Basic density (kg/m^3)	555.14	656.43	665.74	464.45	555.84
1% NaOH solubility	6.38	6.81	5.88	3.05	9.43
Hot water solubility (%)	4.47	3.98	3.71	2.15	3.79
Alcohol-Benzene (AB) Extractive (%)	1.86	4.55	3.26	1.53	3.91
Holocellulose (%)	75.50	66.52	64.41	66.56	64.83
Acid insoluble lignin (%)	22.18	24.52	28.60	27.70	25.8
Ash content (%)	6.65	3.80	3.52	2.98	5.35

Similar results were observed in *M. dubia* and *Pinus taeda* at different ages (Saravanan et al. 2013; Mcdonough et al. 2011). Acid insoluble lignin varied from 22.18% to 28.60%. Low lignin content of a lignocellulosic material reduces pulping time and chemical consumption (López et al. 2008; Diaz et al. 2007). Furthermore, higher lignin content consumes more chemicals (Khristova et al. 2005) and results in lower pulp yield (Haygreen and Bowyer 1996) and lower pulp strength (Fengel and Wegener 1989) and requires more bleaching chemicals (Ona et al. 2001). Lignin content was lower for *M. dubia* in the current study, and similar results were obtained with *M. dubia* at different ages (Saravanan et al. 2013).

The highest ash content was found with *M. dubia* (6.65%). A high content of ash negatively impacts the chemical recovery process and, therefore, could constitute a serious drawback (Khiari et al. 2010). Similar results were reported by Saravanan et al. (2013) in *M. dubia,* with ash content decreasing with increased age.

Thermochemical properties

The energy content of wood is significantly influenced by its calorific value and is commonly considered a crucial factor for comparing different fuel types (Haygreen and Boyer 1996). Understanding the qualities of fuelwood is best achieved through assessing its calorific value, which is influenced by the chemical composition of the species (Sofer and Zaborsky 1981). The highest caloric value recorded was 4380.20 kcal (*C. tabularis*), followed by 4034.42 kcal (*K. senegalensis* and Acacia hybrid), 3974.04 kcal (*T. ciliata*), and 3745.67 kcal (*M. dubia*) (Table 4). The recent findings were more favorable than those of Mithilasri et al. (2024) who found that values in four mulberry clones ranged from 6.99 MJ Kg^{-1} to 14.13 MJ Kg^{-1}. Baqir et al. (2017) reported that the caloric value varied between 17.32 MJ Kg^{-1} and 22.56 MJ Kg^{-1} for different wood species.

Volatile matter is the biomass proportion emitted as short and long-chain hydrocarbon gases at temperatures between 400°C and 500°C (Koppejan and van Loo 2012). Fuel wood with higher quantities of volatile matter such as waxes, resins, and lignin generate more heat during combustion (Kataki and Konwer 2002). The volatile matter content in the current study ranged between 84.60% (*C. tabularis*) and 80.48% (*K. senegalensis* and Acacia hybrid). Dai et al. (2015) reported that an ideal range for volatile matter in woody biomass fuel falls between 70% and 90%. Our results are consistent with those of Baqir et al. (2019), where volatile matter of 12 wood species ranged from 76.89% (*Eucalyptus* spp.) to 85.64% (*Pithecellobium dulce*).

Table 4. Thermochemical properties of five different wood species.

Species	Caloric value (Kcal/kg)	Volatile content (%)	Fixed carbon (%)	Total biomass (Mg/ha)
Melia dubia	3745.67	83.54	9.56	303.90
Chukrasia tabularis	4380.20	84.60	11.60	171.38
Khaya senegalensis	4034.42	80.48	15.87	213.28
Toona ciliata	3974.04	82.25	14.48	90.31
Acacia hybrid	4034.42	80.48	13.31	217.27

Fixed carbon content refers to the mass remaining after volatile chemicals, ash, and moisture are removed from biomass (Marques et al. 2020). During combustion, when biomass is heated, volatile matter escapes initially and burns as gas, while fixed carbon remains as char, later burning as a solid. Increased fixed carbon content corresponds to higher energy value in plant materials (Kumar et al. 2010). Fixed carbon is also required for gasification because it is the primary source of carbon used to produce syngas. The highest fixed-carbon content was observed in *K. senegalensis* (15.87%) followed by *T. ciliata* (14.48%), Acacia hybrid (13.31%), *C. tabularis* (11.60%), and *M. dubia* (9.56%). The current findings support those of Desta and Ambaye (2020), who reported that fixed-carbon content of five wood species ranged from 5.96% to 22.39%.

Veneer recovery for plywood production

The suitability of species for plywood production is determined by their economic veneer recovery. *Eucalyptus* are the primary species used in plywood production in India, with veneer recovery ranging between 48% and 54% (McGavin et al. 2014). The recovery of veneer from the identified species (Table 5) varied from 80% (*M. dubia*) to 67% (*T. ciliata*). Kapadi (2020) reported 64% veneer recovery in *Grewia tiliaefolia*. The recovery percentage was higher than similar studies, Parthiban et al. (2019), Rahaman et al. (2012), Tenorio et al. (2011), and Rahaman et al. (2014).

Table 5. Veneer recovery (as a % of total volume for five wood species.

Species	Veneer recovery (%)	CFT	Veneer size (ft)	Sq.m
Melia dubia	80	0.5	8×27	12
Toona ciliata	67	0.3	4×27	5.7
Chukrasia tabularis	76	0.6	9×27	1.2
Khaya senegalensis	76	0.6	9×27	1.2
Acacia hybrid	76	0.4	6×27	8.6

Conclusion

Khaya senegalensis and *Melia dubia* have the best properties for plywood and pulp production based on their density and recovery rate, whereas *Chukrasia tabularis* could be used for fuel production.

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