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Research Article
Anatomical Features, Fiber Morphological, Physical and Mechanical Properties of Three Years Old New Hybrid *Paulownia*: Green *Paulownia*

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Abstract

Objective: Green *Paulownia* (hybridization of *Paulownia elongata*×*Paulownia fotunei* and tropical *Paulownia* spp.) is new hybrid claimed as one of the fast-growing woody plants with the high potential as a fiber material or lignocellulosic material. The material for this study originates from the area of Nanning in China. **Methodology:** Cell morphology and anatomical appearances were observed and evaluated under the image analysis system (Leica DMLS). Physical and mechanical properties were evaluated based on the American Society for Testing and Materials (ASTM) standards. **Results:** From the results, average value of the mean fiber length was 0.905 mm, mean fiber length 34.59 μm, lumen thickness 26.80 μm and cell wall thickness 3.89 μm. Fiber dimensions of green *Paulownia* are in the normal range for hardwoods. The physical and mechanical properties of 3 years old green *Paulownia* have similar properties than those 7-11 years old *Paulownia* published in China. **Conclusion:** The 3 years old green *Paulownia* timbers can be used as materials for furniture.

Key words: *Paulownia*, fiber length, lumen thickness, cell wall thickness

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

According to forest products statistics published by Food and Agriculture Organization of the United Nations[1], tree planting to provide wood for the world timber industries has become a big business[1]. The tremendous growth of timber plantation in the world is highly related with increasing demand of international trade in wood products such as wood-fiber panels and paper. Consequently, this has led to an intensive study to explore and create new fast growing tree species for wood supply to timber industries. Particularly, people tends to find new species that have short rotation and produces light colour timber for the wood and furniture industries. Recently, attention has been focused on growing *Paulownia* trees due to their unique characteristics. *Paulownia* is a plant genus contains 6-17 species and classified under family Paulowniaceae, related to and sometimes included in the Scrophulariaceae[2].

Paulownia tree is a fast-growing deciduous tree that can be grown on differing soil types and tolerate to broader range of climatic conditions[3]. This tree is initially from China and also discover in tropical area where receiving rainfall from 500-2000 mm per annum[4]. It is widely used in Japan, China, South Korea and Australia for multiple uses including surfboards, boats, pallets and household furniture as well as plywood, prefabricated houses, moldings and internal construction panels, handicraft items, chests, coffins, doors and moulding. The success of *Paulownia* as raw material in timber industries may lie on its wood characteristics and the highest strength to weight ratios as compare to other commercial available woods[5]. Mechanically, the high strength to weight ratio makes the *Paulownia* timber unique for ship building, decoration panel in aviation, surfboards and caravans but not limited to those mentioned products.

The good physical properties and unique fiber morphology makes *Paulownia* timber to avoid warp, crack or deform during drying. Further, moisture penetrates negligently little in comparison to other popular timber[6]. With such mentioned characteristics, the *Paulownia* timber benefits for wood processing and saves energy resources during drying. *Paulownia* timber also characterized with good insulation, very good acoustics, good sound conductivity, rot resistance and easy processing[7]. The amazing resonance makes it highly valued and sought for musical instrument[8].

Nonetheless, the wood structure, mechanical properties and anatomy, including cell biometry and cell type proportion that have been shown to vary between species, tree and age[9,10]. This study presented the properties of newly hybrid green *Paulownia* (hybridization of *Paulownia elongata*× *Paulownia fotunei* and tropical *Paulownia* spp.) towards the quality of timber properties as those 7-11 years old commercially available *Paulownia* species. The green *Paulownia* is the new hybrid of *Paulownia* tree Obtained/supplied to the Nanning Lv Tong Forestry Technology Limited Company. In this study, anatomical features, fiber morphological, physical and mechanical properties of 3 years old *Paulownia*, grown in the area of Nanning, China were studied. The results were compared with those commercial *Paulownia* species.

MATERIALS AND METHODS

Raw material preparation: In 2012, an experimental plot was established in the area of Nanning in China, in which green *Paulownia* were grown. In June of 2015, 6 representative trees of green *Paulownia* with diameter at breast height (DBH) of 30 cm and height of 12 m were cut in order to obtain samples for testing. From all cut trees of green *Paulownia*, 3 cm thick disks were taken at breast height for anatomical features analysis and fiber morphological. The sample discs softening was done in an autoclave at temperature of 121°C for 30 min prior to sectioning and maceration process. The remaining of the tree trunks were cut into lumber for physical and mechanical tests. The tree trunks were cut into size of 2" thick and 2" wide irrespective of length and subjected to kiln drying to achieve 12-16% moisture content.

Anatomical analysis: For the anatomical features evaluation, the *Paulownia* sample discs were cut into small strips with the dimension of 2 cm in length and 0.5-1 cm in width. Cross sections of *Paulownia* with the thickness of 20-30 μm were sliced from the strips using the sliding microtome. The first stage of anatomical feature analysis involves dehydration process by immersing and washing the sliced sections for 2 min in an increasing series of alcohol concentration (from 30, 50-70% concentration alcohol). The staining process was carried out by using 1% of safranine-o in 70% of ethanol. Later, the sliced sections were subjected to 2nd stage dehydration process carried out through 70 and 95% series of ethanol concentration. The sliced sections were cleaned with clove oil before mounting onto the slide glass with one drop of D.P.X. (Neutral mounting medium). The samples were then dried for 7 days. The sections with permanent slides were observed through the Leica image analysis system (Leitz DMRB) to ascertain vessel, fiber as well as ray distribution. The detailed examinations of the sections were carried out using the microscopic magnification of 100X.

Fiber morphological analysis: A small piece from the side of samples were cut and prepared for macerations according to the modified Franklin method[11]. Maceration solution consisted of 30% hydrogen peroxide and glacial acetic acid in a 1:1 ratio. The prepared reagent was applied to wood samples (fragmented to the size of the matches) in the glass tubes, after which the tubes were corked. The material in test tubes was transformed into pulp in the oven at a temperature of 65°C for the period of 24 h. After rinsing with distilled water and shaking individual cells of xylem tissue suitable for measuring were obtained. Macerated wood fragments are transported to the glass slide with a dissecting needle and they are observed under microscope. Fiber length, thickness of cell walls and lumen diameters were measured using the system consisting of Leica DMLS microscope and a camera: Leica DC 300 supported by Leica IM 1000 software which enabled digital recording of prepared preparations and very precise electronic measurement of the mentioned anatomical elements. A total of 800 fibers were measured to achieve the accuracy of properties evaluated. From the data, the average fiber dimensions were calculated and then the following derived indexes were determined:

$$\text{Runkel ratio} = \frac{2\times\text{wall thickness}}{\text{Lumen width}}$$

$$\text{Flexibility ratio} = \frac{\text{Lumen width of fiber}}{\text{Diameter of fiber}}\times 100$$

$$\text{Slenderness ratio} = \frac{\text{Length of fiber}}{\text{Diameter of fiber}}$$

Physical and mechanical properties: The physical and mechanical properties of 3 years old green *Paulownia* were evaluated using standard testing method of series of ISO 13016 standard. All the samples were subjected to condition of 65% relative humidity and 25°C prior to testing. The density and moisture content of the lumber were tested from the small cut of bending samples. The mechanical properties evaluated include bending, hardness and compression parallel to the grain. The Modulus Of Rupture (MOR) and Modulus Of Elasticity (MOE) were calculated using the center point loading formula after the bending test. The impact property was tested according to ISO 3348: 1975 standard.

Statistical analysis: Descriptive statistical analysis was conducted to obtain the means, standard deviations, minimum and maximum values of fiber morphological, physical and mechanical properties of 3 years old green *Paulownia*.

RESULTS AND DISCUSSION

Wood fibers are usually cellulosic elements that are extracted from trees and used in the manufacture of pulp and paper or fiberboard. The fiber morphological characteristics are important because it determine the suitability of the lignocellulosic material before proceeding to production. The anatomical properties of 3 years old green *Paulownia* are presented in Table 1. The measured values of mean fiber length, 0.905 mm, which is slightly lower than the values around 1.0 mm for the *Paulownia* genus (Table 2) and are slightly higher than for *P. elogata*[12] 0.82 mm. As expected, the fiber length of green *Paulownia* is shorter than softwoods (2.7-4.6 mm) and close to fiber length of its own hardwood which range from 0.7-1.6 mm. The fiber width of green *Paulownia* was found as about 34.59 μm which was in normal range when compared to hardwoods fiber (approximately 20.0-40.0 μm)[13]. The fiber width of green *Paulownia* with mean 34.59 μm which was very close to other

Table 1: Anatomical and morphological properties of green *Paulownia* wood

Properties	Mean	Standard deviation	Maximum	Minimum
Fiber length (mm)	0.905	0.143	0.1218	0.659
Fiber width (μm)	34.590	8.690	55.1500	24.360
Lumen thickness (μm)	26.800	9.260	50.0100	16.260
Cell wall thickness (μm)	3.890	1.360	6.3250	2.170
Runkel ratio	0.350	0.260	1.3500	0.100
Slenderness ratio	27.580	7.240	43.0500	18.220
Flexibility ratio (%)	75.960	10.780	90.6800	42.610

Table 2: Comparison of anatomical properties of green *Paulownia* with other *Paulownia* species

Properties	Green *Paulownia*	*Paulownia fortunei*[a]	*Paulownia fortunei*[b]	*Paulownia elongata*[c]	Softwood[d]	Hardwood[d]
Fiber length (mm)	0.905	0.996	1.002	0.82	2.7-4.6	0.7-1.6
Fiber width (μm)	34.590	30.550	35.440	36.30	32.0- 43	20.0-40
Lumen thickness (μm)	26.800	25.300	26.490	19.20	-	-
Cell wall thickness (μm)	3.890	5.250	6.470	8.60	-	-

a: Rafat[23], b: Ashori and Nourbakhsh[24], c: Ates *et al.*[12] and d: Atchison[13]

Paulownia species and falls within the range of softwood(approximately 32-43 m). The value of lumen thickness of green *Paulownia* was higher than *P. fortunei* but much lower than *P. elongate* with value 19.2 µm. Besides, fiber cell wall thickness of green *Paulownia* is lower than other fibrous materials. However, its cell wall thickness was very close to trunk of *Ailanthus altissima* (3.34 µm)[14]. The thickness of cell wall was important in pulp refining process. The strength properties of cell wall was directly affected by cell wall thickness. The thicker the cell wall, the more flexibility of fibers in pulp refining process.

Runkel ratio is usually used to determine the suitability of a fibrous material for pulp and paper production. If a wood species has a runkel ratio more than 1, its fiber will be stiff, less flexible and poor bonding ability. Whereas, fibers with low ratio (<1) produce good quality pulp and paper[15]. Jang and Seth[16] reported that materials having a runkel value less than 1 would be suitable for papermaking, because they collapse (become ribbon like) and provide a large surface area for bonding. Therefore, the calculated runkel ratio for green *Paulownia* (0.35) was suitable for papermaking. A high value of slenderness ratio provides better forming and well-bonded paper. Generally, the acceptable value for slenderness ratio of papermaking is more than 33[15]. The slenderness ratio for green *Paulownia* which was 27.58 was slight lower than the standard performed by Xu *et al.*[15].

Coefficient of flexibility gives the bonding strength of individual fiber and by extension the tensile strength and bursting properties. The flexibility coefficient of green *Paulownia* fibers was 75.96%. According to flexibility ratio there are 4 groups of fibers[17]: (i) High elastic fibers having elasticity coefficient greater than 75. (ii) Elastic fibers having elasticity ratio between 50-75: (iii) Rigid fibers having elasticity ratio between 30-50: (iv) Highly rigid fibers having elasticity ratio less than 30. According to this classification, the flexibility coefficient of green *Paulownia* fibers was included in the high elastic fibers group.

The cross sections of 3 years old green *Paulownia* observed under microscopic magnification of 100X were shown from Fig. 1a-d and Fig. 2a, b showed vessel and radial section of green *Paulownia* wood. The light microscopy observation revealed the prevalence of four distinct tissue systems: Vessels, parenchyma, rays and fibers. Solitary and in multiples of two or three vessels and simple perforation in vessels can be seen. Each vessel was surrounded by a large clear around the vessels which is parenchyma.

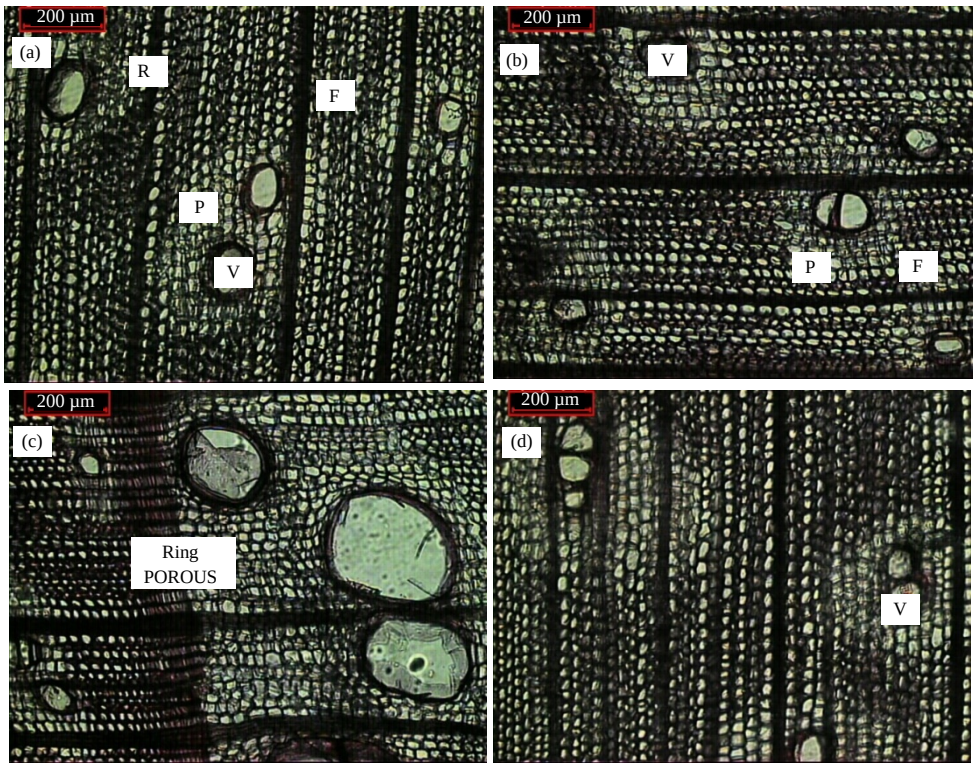

Fig. 1(a-d): Cross section of *Paulownia* wood under microscopic magnification of 100X (a and b) Simple perforation, (c) Compress fiber showed wood ring, winter season and (d) Multiple vessel, F: Fibers, P: Parenchyma, R: Rays and V: Vessel

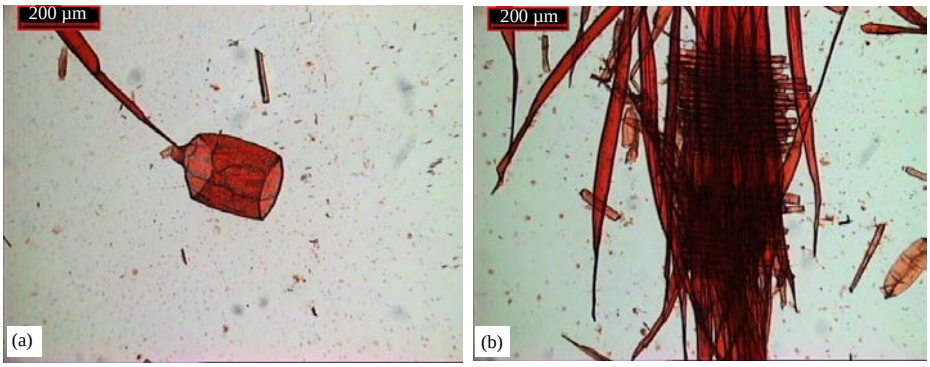

Fig. 2(a-b): (a) Vessel macerated sample and (b) Radial section, F: Fibers and R: Rays

Table 3: Physical and mechanical properties of 3 years old green *Paulownia*

Properties	Direction	Values	Coefficient of variation (%)
Density		214 kg m^{-3}	11.3
Moisture content		11.9 %	5.0
MOR		29.4 MPa	9.1
MOE		3970 MPa	12.2
Compressive stress parallel to the grain		17.4 MPa	10.5
Hardness (Maximum force)	Longitudinal	1310 N	6.7
	Radial	780 N	6.5
	Tangential	580 N	4.4
Impact strength		6 KJ m^{-2}	11.4

These anatomical properties are closely similar to *Paulownia fortunei* wood studied by Hua *et al.*[18]. Figure 2 showed vessels appearances are almost round shape.

The physical and mechanical properties of 3 years old green *Paulownia* are given in Table 3. As shown in the Table, the density of the 3 years old green *Paulownia* is less than those commercially available *Paulownia* in the market, which range[5] from 270-450 kg m^{-3}. Nonetheless, as being mentioned by numerous researchers, *Paulownia* exhibit high strength to weight ratio[19,20]. The high strength to weight ratio was observed for green *Paulownia* with the value of 0.137 for MOR and 17.14 for MOE. All the properties presented in the Table 3 are comparable to those 7-11 years old *Paulownia* timber[21,22].

CONCLUSION

Fiber dimensions of *Paulownia* are in the normal range for hardwoods. The morphology of fibers and its fiber indices from the *Paulownia* wood is reasonably good for the purpose of paper manufacturing. The 3 years old green *Paulownia* with the size of DBH 30 cm and height of 12 m perform similarly with those matured 7-11 years old commercial *Paulownia*.

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