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Full Length Research Paper

Characterization and evaluation of *Paulownia elongota* as a raw material for paper production

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***Paulownia elongota*, one of the most fast growing species of the world, was evaluated as raw material for pulp and paper production. The chemical, morphological and anatomical aspects of paulownia wood were determined. The lignin, holocellulose and α-cellulose contents in *P. elongota* wood were comparable to those of some common non-wood and hardwood raw materials. Different chemical pulping procedures were applied to *P. elongota* wood to evaluate its pulping potential. Paper strength properties and acidic group content bound to the cell wall were determined. The alkali solubility, water solubility and alcohol-benzene extractive content were higher than those from wood and most non-woods. The fiber length of 0.83 mm was observed, which is close to low end of the hardwoods but fiber diameter was very wide, similar to that of softwoods. The pulpability of paulownia wood was also studied. The pulp yield and viscosity were very low and the kappa numbers were high. The strength properties were comparable to those of some wood and non-wood pulps. Although, paulownia pulps are considered as low quality materials, it can be used for paper production when mixed with long fibrous materials.**

Key words: *Paulownia elongota*, chemical, morphological, anatomical properties, pulping.

INTRODUCTION

Pulp and paper industry is facing ever-increasing demand of quality paper and paperboard that is causing search for new and hitherto unexploited sources of cellulosic fibers. However, out of nearly 600 known species, less than a dozen are in commercial use for pulp production. These species, most frequently found in plantations in the different regions of the world, may not always be favorable with regard to fiber quality and wood composition as well as natural evolution and ease of hybridization (Khristova et al., 2006).

Paulownia is a genus of about 20 native species in China and South-East Asia and cultivated since as early as 1000 BC. Its characteristics of rot resistance, dimensional stability and a very high ignition point ensure the popularity of this timber in the world market (Bergmann, 1998). Most species of paulownia are extremely fast growing and can be harvested in 15 years for valuable timber. Low quality lumber can easily be produced from 6-7 years old tree. A full grown paulownia can reach a height of 10 to 20 m and grows up to 3 m in one year under ideal conditions. A 10-year old tree can measure 30-40 cm diameter at breast height (DBH) and can have a timber volume of 0.3-0.5 m^3 (Flynn and Holder, 2001). The wood of paulownia is soft, lightweight, ring porous straight grained, and mostly knot free wood with a satiny luster. Average specific gravity of the wood is reported as 0.35 g cm^{-3} (Kalaycioglu et al., 2005).

Paulownia is also known as a fast growing tree. It can be used for several applications; one of them is its use as source for pulp (Virginia et al., 2008; Rai et al., 2000). It can be characterized by a fast development and a uniform and regular growth. Each paulownia tree could produce a cubic meter of wood at the age of 5–7 years; it may grow in intensive plantations with about 2000 trees ha^{-1}. Based on the above one can calculate that an annual production would be 330 ton ha^{-1}, a more conservative number would be about 150 ton ha^{-1} (Caparro et al., 2008).

The main objective of this study was to establish the suitability of *Paulownia elongata* as a potential source of

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lignocellulosic fibers for paper and composites materials. In the present study, anatomical, morphological and chemical characteristics were evaluated in order to obtain more information about their suitability for pulp production.

MATERIALS AND METHODS

Materials

For this study, a wood sample of the hybrid *P. elongota* (2 years-old tree) was harvested from a plantation in the west of Turkey (plantation of Bragfor Fidancılık). Several trees of about 6.0–7.5 m high and 27-33 cm diameter at breast height were felt and the stems were cut into 0.5-2.0 m wood logs that were air-dried and used to make 2–3 cm chips in length for the pulping trials. A representative part of the chips were also ground into 40–60 mesh wood mills, 10 g of which were used for the chemical analyses.

Characterization of raw materials

The raw materials were analyzed for holocellulose, α-cellulose, lignin, ash, alcohol–benzene extractable, cold and hot water and 1% soda soluble, in accordance with the applicable TAPPI standards: T-203-0S-61, T-222, T-221, T-204, T-257 and T-212, respectively. Five replicates were done for each experiment.

Morphological and anatomical properties

For the measurements of fiber length, fiber width, lumen width and cell wall width, *P. elongota* wood (after removing barks) was macerated in a solution containing 1:1 HNO_3 and $KClO_3$. For maceration, wood samples taken from three parts of each *P. elongota* wood were chosen. A drop of macerated sample was taken on a slide and fiber length, fiber width, lumen width and cell wall thickness were measured under a microscope. For measuring fiber length and diameter, 200 fibers were measured from 10 slides and average reading was taken.

For anatomical properties, paulownia wood chips of about 1 cm was autoclaved followed by immediate storage in a mixture of equal volume of glycerin, ethyl alcohol and water till sectioning with sliding microtome. Then permanent slide was prepared and analyzed on a microscope. The percentage of vascular bundles was calculated from the vascular bundle area divided by total area.

Pulping

Three different pulping processes were conducted: kraft-antraqhinon (AQ), soda-AQ and ethanol (ALCELL). Pulping experiments were carried out in 15 L electrically heated laboratory type rotary digester and governed with digital temperature control system. At the end of pulping, pressure was relieved to atmospheric pressure then pulps were washed, disintegrated in a laboratory type pulp mixer with 2 L capacity and screened on a Noram type pulp screen with 0.15 mm slotted plate. Pulp yield was determined as dry matter obtained on the basis of oven dried (od) raw material. Kappa number and viscosity were determined in accordance with T 236 cm-85 and T 230 om-94, respectively. Hand sheets of unbleached pulps with a grammage of ~60 g m^{-2} were prepared according to Tappi T 272 om-92. Before the ethanol pulp sample was used in this study, displacement washing was performed with a 70% ethanol solution at 70°C a 10% pulp consistency, a superficial velocity of 100 ml min^{-1} and a dilution factor of 4.5 ml g^{-1}. The kappa number of the washed pulp thus obtained was 42.06.

Acid groups

Paulownia wood sample was mechanically refined, then extracted following TAPPI T-264-88 with the substitution of acetone before determination of acid groups. The extracted sample and three different *P. elongota* pulps were alternately soaked and rinsed two times in 0.1 N HCl for 45 min. The pulp samples were dispersed 450 ml of 0,001 M sodium chloride and titrated with 0.1 M sodium hydroxide. The alkali was added at a rate of 0.5 ml every 5 min so as to allow sufficient time for equilibrium to be reached between readings. Following titration, the pulp was washed and oven-dried at 105°C. All titrations were followed both potentiometrically and conductometrically (Katz et al., 1984).

RESULTS AND DISCUSSION

Table 1 shows the chemical properties of *P. elongota* wood and their comparison with bamboo, eucalyptus, some annual plants, coniferous and deciduous wood which are the main fibrous raw materials. As shown in Table 1, lignin content of *P. elongota* was found as 20.5%, which is comparable with all annual plants and hardwoods (17-26%) especially with eucalyptus (23.3%); it is however, substantially lower than softwoods (25-32%). The average holocellulose content of *P. elongota* was found as 75.74% and it is fairly acceptable ratio when compared with bamboo (70.5%), most annual plant and coniferous (68-74%). The α-cellulose in *P. elongota* wood (43.61%) is higher than wheat straw, corn stalk, tobacco stalk, sunflower stalk and kenaf (38.2, 35.6, 37.5, 37.5 and 37.4%, respectively) When compared with hardwoods and softwoods, *P. elongota* have substantially higher water, alkali and alcohol-benzene solubility, which means lower pulp yield probably higher biological oxygen demand (BOD) load in the effluent. *P. elongota* wood also showed similar solubility with bamboo and eucalyptus and better solubility values than wheat straw and than most annual plants (Table 1).

The anatomical structure of *P. elongota* wood was studied on transverse and tangential sections (Figure 1a,b). The light microscopy observation revealed the prevalence of four distinct tissue systems: vessels, parenchyma, rays and fibers. It can be seen from cross section (Figure 1a) that the difference in vessel size between early and late wood is three or five times. Solitary vessels, simple perforation and tyloses in vessels can be seen. Each vessel was surrounded by a large number of paratracheal. Parenchyma can be seen mostly clear around the vessels of late wood and wide strip-shaped in early wood. Fiber cells are more in late wood than in early wood. Rays are multiseriate, usually homogeneous and 1-40 cells high and 1-5 cells wide (Figure 1b). These anatomical properties are closely similar to *Paulownia fortunei* wood studied by Hua et al. (1986).

The average content of parenchyma cells of *P. elongota* is about 53.8%. The percentage of parenchyma cells for *P. elongota* differs from wood species (7 and 30% for soft and hardwood, respectively) (Rydholm, 1976), but resembles other non-wood like corn stalks, straw etc.

Table 1. Chemical analysis of *Paulownia elongota* wood

Raw material	Holocellulose (%)	α-cellulose (%)	Lignin (%)	Ash (%)	Alcohol benzene (%)	1 % NaOH (%)	Cold water (%)	Hot water (%)	Literature
Paulownia (S.d.)	75.74 (0.42)	43.61 (0.28)	20.5 (0.28)	0.21 (0.01)	3.76 (0.04)	24.5 (0.71)	8.50 (0.69)	10,05 (0.96)	Determination
Eucalyptus	80.42	50.17	23.30	0.47	3.29	23.56	5.62	9.91	Ayata 2008
Bamboo	70.5	43.3	24.5	1.35	3.94	25.1	-	6.47	Deniz,and Ates 2002
Wheat straw	74.5	38.2	15.3	4.7	7.8	40.59	10.75	13.99	Deniz et al.2004
Rye straw	74.1	44.4	15.4	3.2	9.2	39.2	10.2	13.0	Usta and Eroglu 1987
Corn stalk	64.8	35.6	17.4	7.5	9.5	47.1	-	14.8	Usta et al. 1990
Tobacco stalk	67.6	37.5	19.5	7.3	6.5	42.9	15.8	19.1	
Sunflower stalk	74.9	37.5	18.2	8.2	7.0	29.8	15.5	16.5	Eroğlu et al. 1992
Cotton stalk	77.6	-	21.4	4.2	3.0	21.9	-	-	
Reed	77.9	47.5	18.7	3.9	4.0	28.3	3.3	3.8	Kirci et al. 1998
Kenaf	81.2	37.4	14.5	4.1	5.0	34.9	11.7	12.8	Atchison 1993
Hemp	86.77	63.77	6.59	-	4.23	29.55	7.75	9.06	Gumuskaya and Usta 2006
Coniferous	68-74	40-45	25-32	<1	-	-	2-6	2-5	Eroglu 1998
Deciduous	70-81	38-49	17-26	<1	-	-	3-6	3-6	

S.d. Standart deviation.

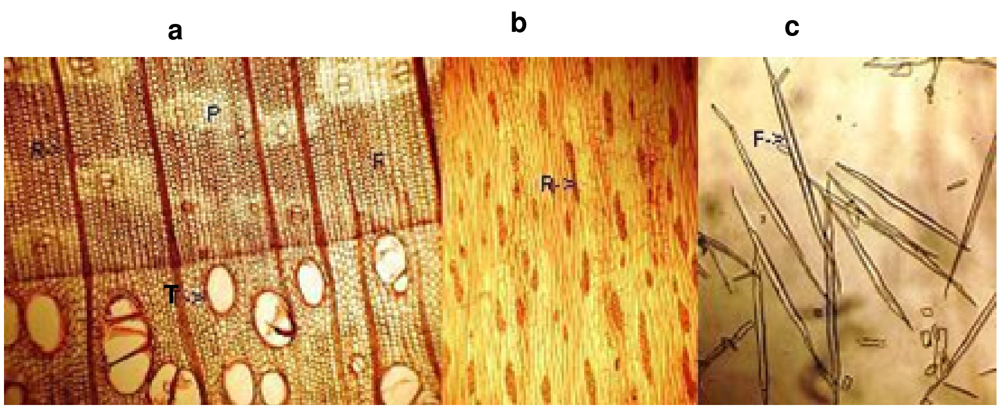

Figure 1. Transversal (a) and tangential (b) sections and macerated sample (c) of *Paulownia elongota* wood. F: Fibers, P: parenchyma, R: rays, and T: trachea cells.

(Atchison, 1993). The similar ratio of tissue systems was found by Jahan et al. (2006) for golpata fronds (*Nypa fruticans*). The proportion of vascular tissues and fibers in *P. elongota* (9.71 and 39.04%, respectively) are also different from woods (30 and 50%), but close to other materials like wheat straw (13.5 and 37.5%) and bamboo (11 and 38%) (Shatalov and Pereira, 2006). When compared with woody materials, *P. elongota* wood has lower amount of fiber and higher content of short parenchyma cells.

Table 2. Morphological analyses of *Paulownia elongota* wood

	Fiber length (mm)	Fiber width (µm)	Lumen width (µm)	Cell wall thickness (µm)	Literature
Paulownia (Std. dev.)	0.82 (0.13)	36.3 (0.006)	19.2 (0.006)	8,6 (0.003)	Determination
Eucalyptus *(E. globulus)*	1.28	18.0	-	7.0	Teresa et al. 2000
Bamboo	2.30	15.1	6.9	4.17	Deniz,and Ates 2002
Wheat straw *(T. durum L)*	0.74	13.2	4.0	4.6	Deniz et al.2004
Rye straw	1.15	14.7	4.2	1.1	Usta and Eroglu 1987
Corn stalk	1.32	24.3	10.7	6.8	Usta et al. 1990
Cotton stalk	I.32	29.3	23.0	3.6	
Tobacco straw	1.07	26.8	16..3	5.3	Eroğlu et al. 1992
Sunflower stalk	128	22.1	15.6	3.3	
Reed	1.39	13.5	7.0	3.2	Kirci et al. 1998
Kenaf	2.60	20.0			Atchison 1993
Coniferous	2.7-4.6	32-43	-	-	Atchison 1987
Deciduous	0.7-1.6	20-40	-	-	

Table 2 shows the morphological characteristics of *P. elongota* and its comparison with other fibrous materials. The image of the fibers can be shown in Figure 1c. The average fiber length of *P. elongota* wood is 0.82 mm, which is shorter than softwoods (2.7-4.6 mm) and close to minimum value of hardwood fibers (0.7- 1.6 mm) and almost the same with wheat straw fibers (0.74 mm). However, the fiber lengths of eucalyptus, rye, and tobacco stalk are 1.28, 1.15 and 1.07, mm respectively (Table 2). The fiber width of *P. elongota* was found as about 36.3 µm which was in normal range when compared to hardwoods fiber (approximately 20.0–40.0 µm) (Atchison, 1987). The fiber wall thickness of *P. elongota* is also higher than the other fibrous materials. The physical properties of a pulp sheet are closely related to morphological properties of pulp fiber (Young, 1981).

The strength properties of the papers were found to positively correlate with the felting coefficient (fiber length/fiber diameter). It is stated that if felting coefficient of a fibrous material is lower than 70, it is invaluable for quality pulp and paper production (Young, 1981; Bektas et al., 1999). The felting coefficient of *P. elongota* fibers was found as 22.7. Whatsoever high felting coefficient means lower strength properties. Some authors have a different opinion because not only strength properties depend on felting coefficient, but also cell wall thickness (Eroğlu, 1998). As depend on the cell-wall thickness, rigidity coefficient (cell wall thickness x 100/fiber width) is one of the important parameter. Rigidity coefficient was calculated as 23.7 for *P. elongota* wood. Higher rigidity ratio gives lower paper strength properties especially lower burst, tear and tensile indexes (Bektas et al., 1999). Strength properties of *P. elongota* obtained from three different chemical pulping processes confirms these results (Table 3).

Related with this expression, another criterion is elasticity coefficient (Istas et al., 1954) for evaluating fiber quality (lumen width x 100/fiber width). We calculated the elasticity coefficient as 52.9 for *P. elongota* fibers. According to Istas et al. (1954), if the elasticity coefficient is between 50 and 70, this kind of fibers easily can be flat and give good paper with high strength properties. So, *P. elongota* fibers with short fiber length, thick cell wall and large lumen width can be used for paper production after mixing with long fibrous materials.

P. elongota wood was cooked by kraft-AQ, soda-AQ and ethanol processes. Pulping conditions and results of the characterization of unbleached pulp samples obtained using three different methods, and of paper sheets made from them are presented in Table 3. The conditions were selected a series of pre-trial, just to evaluate *P. elongota* wood as pulping raw material.

Table 3. Operation conditions used in the pulping of *Paulownia elongota* and results of the characterization of unbleached pulp samples using three different methods and of paper sheets made from them.

Parameter		Kraft-AQ	Soda-AQ	Ethanol
Active alkali charge (%)		18	18	-
Sulphidity charge (%)		20	-	-
Ethanol charge (%)		-	-	50
AQ (%)		0.1	0.1	-
Liquor to wood		6/1	6/1	8/1
Pulping time (Min.)		90	90	120
Pulping temp (^oC)		160	160	180
Yield (%)		38.3	37.8	38.4
Kappa no		28.2	27.8	42.06
Viscosity (cP)		12.08	10.38	13.92
CSF		670	665	725
Bulk ($cm^3 \cdot g^{-1}$)		2.15	2.13	1.90
Breaking length (km)		1.66	1.53	2.59
Brightness (%ISO)		21.83	24.03	32.86
Burst ($kPa \cdot m^2 \cdot g^{-1}$)		1.15	1.09	0.90
Tear ($mN \cdot m^2 \cdot g^{-1}$)		2.10	1.96	3.36
Coarseness (mg $100m^{-1}$)		10.5	10.5	14.6
Percent fines (0-0.2mm)		17.45	25.00	16.62
Curl Index		0.059	0.052	0.044
Kink Index		0.83	0.74	0.75
Fiber Length (mm)		0.450	0.427	0.508
	Uncooked wood	**Kraft and Soda pulps**		**E-OH Pulp**
Strong acid ($mmol \cdot kg^{-1}$)	370.1	356.7		333.3
Weak acid ($mmol \cdot kg^{-1}$)	170.0	173.3		106.7
Total acid ($mmol \cdot kg^{-1}$)	540.1	530.0		440.0

Table 3 showed that pulp yield in three processes were lower for kraft-AQ, soda-AQ and ethanol pulps as 38.3, 37.8 and 38.4%, respectively, and kappa numbers were little higher than other non-wood fibers. It can be explained with high amount of water and alkali solubility of *P. elongota* wood (Table 1). At similar cooking conditions, golpata fronds showed similar pulp yield and kappa number (Jahan et al., 2006). Viscosity values were found for kraft-AQ, soda-AQ and ethanol pulps as 12.08, 10.38 and 13.92 cp, respectively. The strength properties of *P. elongota* wood for unbleached alkaline pulps are also given in Table 3. The breaking length was higher than that of pine and olive pulps (Jimenez et al., 1992). Burst index for the kraft-AQ, soda-AQ and ethanol *P. elongota* pulps (1.15, 1.09 and 0.90 kPa·m² g^{-1} respectively) are comparable with the giant reed pulps obtained from ethanol soda, ASAM, organacell and kraft pulping process (1.42, 1.31, 1.08 and 0.96 kPa m^2g^{-1} respectively). Similar results for optimum *P. fortunei* organosolv pulp were obtained by Caparro et al. (2008) as 38.4% yield, 46.9 kappa number, 27.4% ISO brightness, 28.87 Nm g^{-1} tensile index, 1.22 kPa $m^2 g^{-1}$ burst index and 1.23 kN m^2 g^{-1} tear index.

Due to its higher content of fines and shorter average fiber length, the soda-AQ pulp had lower breaking length and tear index than the ethanol pulp. The reason is probably the carbohydrates are being protected more effectively against hydrolysis reactions in high alcoholic environment (Akgul and Kirci, 2002) coupled with the effect of the alkali in white liquor. Kraft-AQ pulp showed similar characteristics with soda-AQ pulp. There is no significant difference between the two alkaline pulps.

Table 3 also shows the acid groups bound to cell wall of the *P. elongota* wood. The amount of acid groups on pulp samples decreased after pulping process, decreasing values for both soda-AQ and kraft-AQ pulps (from 540.1 to 530.0 mmol kg^{-1}) obtained were the same. But in ethanol pulping, the acid groups reduced rapidly after pulping (from 540.1 to 440). The freeness (CSF) values of the samples correct it. Acid groups in *P. elongota* wood and pulp samples are extremely higher than wood (Hunt et al., 2002). It can be concluded that, high amount of total acid groups for *P. elongota* pulps do not significantly affect the strength properties.

Conclusions

The following conclusions may be drawn from this investigation: The lignin, holocellulose and α-cellulose in *P. elongota* wood are comparable to hardwood and common non-wood. *P. elongota* have substantially higher water, alkali and alcohol-benzene solubility than that of softwoods and hardwoods, which caused lower pulp yield. *P. elongota* wood has lower amount of fiber and higher content of short parenchyma cells. The pulp yields and viscosities are lower and kappa numbers are higher than some common wood and non wood raw materials. The acid groups bound to cell wall decreased with chemical pulping process. Ethanol process caused maximum decrease on acid groups. *P. elongota* fibers have lower felting coefficient and elasticity coefficient. Although these kinds of fibers are considered as low quality materials, it can be used for paper production when mixed with long fibrous materials.

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