TECHNOLOGICAL PROPERTIES OF IRANIAN CULTIVATED PAULOWNIA WOOD (*PAULOWNIA FORTUNEI*)

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P. fortunei was imported into Iran from China and was planted at different spacings in the forest of the north of Iran, for wood production. In this research, physical, chemical, mechanical properties and morphological characteristics of Iranian cultivated paulownia (*Paulownia fortunei* L.) wood were investigated. Paulownia has acceptable Runkel, flexibility and slenderness coefficients, which are in the same range as those of hardwood and softwood. In general, the results of the chemical and morphological analyses indicate that Iranian cultivated paulownia fibers are a promising fibrous raw material for paper production. The species is not suitable for uses requiring mechanical strength. The values obtained for physical properties were as follows: oven-dry density – 0.261 g cm^{-3}, basic density – 0.242 g cm^{-3}, air-dry density – 0.291 g cm^{-3}, volumetric shrinkage – 7.54%, percentage of cell wall – 17.41%, porosity – 82.59%, fiber saturation point – 31.15%, and maximum moisture content – 349.72%. The means of holocellulose, cellulose, lignin and extractives were of 80.1, 51, 23.5, and 11.8%, respectively. The average values of mechanical properties were the following: modulus of rupture – 41.07 MPa, modulus of elasticity – 3.74 GPa, and compression strength parallel to the grain – 14.61 MPa. The mean value of fiber length was 996 µm, fiber width – 30.55 µm, width of lumen – 25.30 µm, and cell wall thickness – 5.25 µm.

Keywords: *Paulownia fortunei* L., physical properties, chemical properties, mechanical properties, morphology properties

INTRODUCTION

The global demand for fibrous materials in the wood-based industry has been growing, but the production of industrial wood from natural forests continues to decline. The decline in forest resources in developing countries is due to the higher demand for wood due to the increasing population and new application area, and the withdrawal of forest areas from industrial production for other uses, such as recreational areas.[1] In order to meet future demands and overcome a potential wood shortage, studies have been conducted to utilize new or alternative resources in the forest industries as raw material components for pulp and paper production in several countries.[2]

Paulownia is a fast-growing shade tree native to China and South-East Asia, which is grown commercially for the production of hardwood timber.[3] Paulownia wood has also been investigated as a promising raw material for the production of chemical pulp.[4-8] The most suitable species of paulownia for this purpose is *Paulownia fortunei*, with an average fiber length of 1.42 mm.[5] This species is characterized by its fast development and uniform and regular growth.[6,9] In China and some other Asian countries, paulownia wood is used for a variety of applications, such as furniture, construction, musical instrument, ship building, aircraft, packing boxes, coffins, paper, plywood, cabinet making, and molding.

P. fortunei was imported into Iran from China and was planted at different spacings in the forest of the north (Iran) for wood production. This exotic species has shown good adaptation to the Iranian environmental conditions, five-year-old paulownia trees presenting a height and a diameter of 10.24 m and 23.5 cm, respectively.[10]

Wood density is an important wood property for both solid wood and fibre products in both conifers and hardwoods.[11] It is affected by cell wall thickness, cell diameter, the earlywood and latewood ratio and the chemical composition of the wood.[12] Kiaei[13] established that wood density is a measure of the cell wall material per unit volume and, as such, gives a very good indication of the strength properties and expected pulp yields of timber. Basic density is closely related to end-use quality parameters, such as pulp yield and structural timber strength.[14] According to Panshin and de Zeeuw, density is a general indicator of cell size and a good predictor of strength, stiffness, ease of drying, machining, hardness and various paper making properties.[15] Cown stated that the density of wood is recognised as the key factor influencing wood strength.[16] Indeed according to Schniewind[17] much of the variation in wood strength, both between and within species, can be attributed to differences in wood density. Research has shown that higher density species tend to have stronger timber than lower density species.[18] However, there is a limited number of studies on the physical properties of *P. tomentosa*,[19] *P. elongata* and *P. fortunei*.[20]

The chemical composition of wood varies broadly between 40 and 50% cellulose, 20 and 30% hemicelluloses, 20 and 35% lignin, 0 and 10% extractives. The variation of chemical composition is high among different species and, to a more limited extent, within the same species, as a result of environmental and genetic factors. Besides, age, growth conditions and stress factors may also influence the chemical composition and make it vary from tree to tree. Although the structural components may vary in quantity and, in some cases, in composition (e.g. lignin and hemicelluloses), most of the chemical variability both in structure and concentration is found in extractives.[21] There is little information about the chemical properties of paulownia wood reported by Kalaycioglu *et al*. (2005, *P. fortunei*),[22]Ashori and Nourbakhsh (2009, *P. fortunei*)[23] and Ates *et al*. (2008, *P. elongata*).[24]

Modulus of rupture (MOR) and modulus of elasticity (MOE) are important properties for the use of wood as a structural material. MOR is an indication of the bending strength of a board or structural member, and MOE is an indication of the stiffness. The correlation of MOR and MOE with specific gravity is typically very strong, as reported by Zhang for hardwood and softwood.[25] The importance of natural material fiber dimensions and their derived values (Runkel ratio, slenderness ratio and flexibility coefficient) on pulp and paper mechanical strength is well documented.[2,8,23]

Ashori and Nourbakhsh[23] studied the chemical and morphological properties of *Paulownia fortunei* grown in Chamestan-Noor region (Mazandran province). In this study, we will focus on the properties of *Paulownia* grown in a different region of Iran, specifically, in Guilan. Therefore, our objectives are to examine the physical, chemical, mechanical and morphological characteristics of Iranian cultivated *Paulownia fortunei* and, using various indices, to assess its potential as a raw material for paper production by comparing its examined properties with those of softwoods and hardwoods.

EXPERIMENTAL

Materials

Six trees of *Paulownia fortunei* L. were harvested from a plantation in the north of Iran (Fakhrabad Experimental Forest, Lashtnesha, Guilan province). The experimental area is located at an average altitude of 20 m. The mean annual precipitation of the experimental area is of about 1347 mm/year; the yearly average temperature is 17 ºC. The age, height and diameter of the trees were: 5 years old, 7.2 m and 41 cm. All climatic data were obtained from the Iranian meteorology station located very near the research area. Logs were cut between 2 and 4 m of tree height to obtain samples for different wood properties. The north direction of the logs was marked.

Methods

Physical properties

A 5 cm thick disk was obtained from each log for the evaluation of the physical properties. Lumber boards with 25 mm thickness were radially sawn in the four cardinal directions of radius. Then, test specimens were cut from these boards with the dimensions of 20 × 20 × 20 mm, according to ASTM D143-94[26] and used for measuring the oven-dry density, basic density, air-dry density (12%), volumetric shrinkage, fiber saturation point, percentage of cell wall, porosity and maximum moisture humidity content. 45 samples were used for each test.

The oven-dry density (D_0) was calculated as follows:

$$D_0 = M_0 / V_0$$

where M_0 and V_0 are the oven-dry mass (g) of the specimen and volume (cm^3) of specimen, respectively.

The basic density (D_b) was determined by the gravimetric method:[27]

$$D_b = M_0 / V_g \text{ (g cm}^{-3}\text{)}$$

where Vg is the green volume of the specimen (cm^3) and M_0 is the oven-dry mass of the specimen (g).

Volumetric shrinkage (βv) was determined as follows:

$\beta v = (V_s - V_0) / V_s$ (%)
where V_s is saturated volume and V_0 is oven-dry volume.

Fiber saturation point (FSP) was calculated by the following equation:[19,28]

FSP = β_v / D_b (%)
where β_v is volumetric shrinkage (%) and D_b is basic density (g cm^{-3}).

The percentage of the cell wall and porosity were calculated by the following equations:[28]

$V_c = D_0 / D_C \times 100$ (%)
$V_H = 100 - V_c$ (%)
where V_c is the percentage of the cell wall (%), D_0 is oven-dry density (g cm^3), D_c is oven-dry density of the cell wall (1.5 g cm^{-3}) and V_H is the percentage of porosity (%).

Maximum moisture content (M_{max}) was calculated by the following equation:

$M_{max} = (1.5 - D_b) / (1.5 \times D_b)$ (%)

Chemical properties

A 5 cm thick disk was obtained from each log for the evaluation of chemical properties. The chemical composition of paulownia was determined following the standards outlined in TAPPI test methods (2002).[29] Holocellulose was determined following the procedure of Wise and Karl,[30] and alpha-cellulose based on Tappi T 203 cm-99. Acid-insoluble (Klason) lignin content was determined by hydrolyzing the carbohydrates with 72% sulfuric acid as per T 222 om-02. The solubility properties were determined based on hot water (Tappi T 207 cm-99) methods. Four replicates were analyzed for each experiment.

Fiber properties and morphological characteristics

A 3 cm thick disk was obtained from each log for the evaluation of morphological properties. The samples for fiber maceration and fiber measurements were obtained from the middle sections of the stalks. The samples were macerated according to the modified Franklin method.[31] Firstly, they were boiled in a beaker containing water to remove all the air from the raw material. Air-free pieces were placed in test tubes containing an equal amount of glacial acetic acid and 35% hydrogen peroxide. The test tubes were uniformly white. The pieces were washed thoroughly with distilled water, then placed in separate test tubes and shaken in an ethanol and distilled water mixture.

For this study, 600 undamaged/unbroken fibers were measured in terms of their length (L), fiber width (d), lumen diameter (c) and cell wall thickness (p), using a Quantimeter Image Analyzer equipped with a Leica microscope and Hipad digitizer. The fiber length was expressed as arithmetic average length. The calculations of Runkel ratio (2 p/c), coefficient of flexibility (c/d × 100), and slenderness ratio (L/d) were carried out using the measured data. The values were compared to those of softwoods and hardwoods to assess the suitability of the plant raw materials for paper production.

Mechanical properties

8 cm wide lumber boards were cut from logs, according to ISO 3129. Sawdust was removed from the surface and the boards were stored under uncontrolled conditions in an unheated room for air-drying. Following the air-drying process, small and clear specimens were cut from the boards, according to ISO standards, to determine compression strength parallel to the grain,[32] bending strength (MOR),[33] and modulus of elasticity in bending (MOE).[34] Then, the specimens were conditioned at 20 ± 2 ºC and 65±5% relative humidity to reach equilibrium moisture content throughout 8 weeks, according to ISO 554.[35] After acclimatization, the mechanical properties of the paulownia wood were determined. At the end of the experiments, the moisture contents of the specimens were measured according to ISO 3130[36] and the specimens whose moisture content deviated from 12% were determined. 30 samples were used for each test. Then, strength values were corrected (transformed to 12% moisture content) by using the following strength conversion equation:

$\delta_{12} = \delta_m \times [1 + \alpha (M_2 - 12)]$
where δ_{12} – strength at 12% moisture content, δ_m – strength at moisture content deviated from 12%, α – constant value showing the relationship between strength and moisture content (α = 0.05, 0.04, 0.02 for compression strength parallel to the grain, modulus of rupture and modulus of elasticity, respectively), M_2 – moisture content during the test. In addition, p value (the ratio of static bending strength and compression strength parallel to the grain), and static quality (the ratio of compression strength parallel to the grain and 100 × density at 12% moisture content) were calculated for evaluating the properties and potential use of paulownia wood.

RESULTS AND DISCUSSION

Physical properties

All descriptive statistics for air-dry density (12%), oven-dry density, basic density, volumetric shrinkage, fiber saturation point and maximum moisture content of paulownia wood are given in Table 1. The percentage of the cell wall and porosity was calculated as 17.41% and 82.59%, respectively.

The results obtained for the physical properties of Iranian paulownia (the studied species) were compared to the values for *P. tomentosa*,[19] *P. elongata*[20] and *P. fortunei*[20] reported by other authors. According to Table 2, the volumetric shrinkage value of Iranian paulownia is lower than those of *P. tomentosa*, *P. elongata* and *P. fortunei*, while its oven-dry density is lower than that of *P. tomentosa* (grown in Turkey) and higher than those of *P. elongata* (China) and *P. fortunei* (China).

Paulownia fortunei grown in Iran has a quite low density because of its fast growth and low percentage of the cell wall. So, it has a quite high percentage of porosity. Consequently, the maximum moisture content was determined to be 349.72%, which can be considered as a high value (due to the low density). Density closely correlates with physical and mechanical properties, with transportation, hardness and heat values of wood, with abrasion resistance, machining, electrical, acoustical and drying properties. Simpson reported that the maximum moisture content in lumber is important because of its influence in controlling kiln-drying schedules.[37] In addition, porosity is linearly and inversely related to wood maximum moisture content and wood density, respectively.

Water exists in wood either as bound water (in the cell wall) or as free water (in the cell cavity). As bound water, it is bonded (via secondary or hydrogen bonds) within the wood cell walls. As free water, it is simply present in the cell cavities. When wood dries, most free water separates at a faster rate than bound water, because of accessibility and the absence of secondary bonding. The moisture content at which the cell walls are still saturated, but virtually no water exists in the cell cavities, is called the fiber saturation point.[38-39] In the present study, the fiber saturation point (FSP) value for paulownia wood was determined to be 31.15%, which is higher than that for *Paulownia tomentosa* (28.79%).[20]

Chemical composition

Lignocellulosic materials contain cellulose, hemicelluloses, lignin, and extractives in various amounts. The chemical properties and behavior of wood components during pulping are very important. A brief review of their characteristics is, therefore, necessary as a background to this study. The results of the chemical analyses of paulownia wood are presented in Table 3. The average holocellulose content of the samples was found to be 80.1%, which is higher than that of hardwood (68-74%).[40] The higher content of holocellulose for Iranian grown paulownia fiber provides a higher pulp yield and probably strength properties, compared with hardwood. The holocellulose content found in this study agrees with the content of 78.8% reported by Kalaycioglu *et al.*[22]

Paper strength depends on the cellulose content of raw wood materials. Wood materials with 40% and over of α-cellulose content are characterized as promising for pulp and paper manufacture, from chemical composition point of view.[41] The cellulose content of paulownia was found as 51%, which is satisfactory, but well below the values for hardwood and softwood.

Table 1
Basic statistics for physical properties of paulownia wood

Properties	N	Mean	Max. and min.	SD
Oven-dry density (g cm^{-3})	45	0.261	0.228 – 0.297	0.027
Basic density (g cm^{-3})	45	0.242	0.215 – 0.283	0.025
Air-dry density (12%, g cm^{-3})	45	0.291	0.249 – 0.335	0.030
Volumetric shrinkage (%)	45	7.45	6.59 – 8.65	0.75
Percentage of cell wall (%)	45	17.41	15.2 – 19.8	1.78
Porosity (%)	45	82.59	80.20 – 84.8	1.78
Fiber saturation point (FSP)	45	31.15	29.82 – 32.97	0.91
Maximum moisture content (%)	45	349.72	286.69 – 398.45	41.71

SD: Standard deviation

Table 2
Comparison of physical properties of Iranian paulownia and other tree species

Species	a	b	c	d	e	Reference
P. fortunei	0.261	0.242	0.291	7.45	31.15	This study
P. tomentosa	0.294	0.272	0.317	7.78	28.79	19
P. elongata	0.209	-	0.264	8.12	-	20
P. fortunei	0.258	-	0.309	8.96	-	20

a: Oven-dry density (g cm^{-3}); b: basic density (g cm^{-3}); c: air-dry density (12%, g cm^{-3}); d: volumetric shrinkage (%); e: fiber saturation point (%)

Table 3
Chemical properties of paulownia wood

Properties (%)	Method	*P. fortunei*[b]	Hardwood[c]	Softwood[c]
Holocellulose	Wise and Karl	80.1	68 – 74	70 – 81
α-cellulose	T 203cm-99	51	58 – 64	55 – 61
Lignin[a]	T 203cm-99	23.5	17 – 26	25 – 32
Extractive (hot water)	T 207 CM-99	11.8	2 – 5	3 – 6

a: Klason lignin; b: This study; c: TAPPI Test Methods (2002)

Table 4
Mechanical properties of *Paulownia* wood

Properties	MOR (MPa)	MOE (GPa)	Compression parallel to the grain (MPa)
N	30	30	30
Mean	41.07	3.74	14.61
Max.	50.68	4.76	16.87
Min.	34.06	2.63	11.45
St. dev.	6.19	0.78	1.77

The lignin content obtained for paulownia wood was 23.5%, which is comparable with the values for hardwood and softwood. Higher lignin content in paulownia indicates the need for more chemicals during chemical pulping. The extractives content (hot water) of this species was 11.8%, which is higher than those for hardwood and softwood. The chemical properties of paulownia wood were also reported by Kalaycioglu *et al.*[22] and Ashori and Nourbakhshi.[23]

Mechanical properties

In Table 4, all descriptive statistics are given for modulus of rupture (MOR), modulus of elasticity (MOE), and compression strength parallel to the grain of paulownia wood. The values obtained for MO), MOE and compression strength parallel to the grain were the following: 41.07 MPa, 3.74 GPa, and 14.61 MPa, respectively.

The results of the mechanical properties of Iranian-grown paulownia wood were compared to the values for *P. tomentosa*,[19] *P. elongata*[20] and *P. fortunei*[20] reported by other authors. According to Table 5, the modulus of elasticity (MOE) and compression strength parallel to the grain of Iranian paulownia wood are lower than those for the other species. The modulus of rupture (MOR) determined in this study is higher than those reported for *P. elongata* and *P. fortunei*, while it is lower than that for *P. tomentosa.*

The static quality and p values of the studied species and other tree species are shown in Table 5. Hardwoods can be classified as having low (below 6), fair (between 6 and 7) and good (above 7) static quality value (I_S). The limit values for the classification change depending on the density and hardness of the species.[38] According to this classification, *Paulownia fortunei* (I_S = 5.01) has low static quality wood, its value being lower than that of the other species discussed here. Generally, the p value, the ratio between static bending strength and compression strength, is considered to be 1.75.[42] In the present study, the p value was determined as 2.85, which is higher than the p values for *Paulownia* grown in Turkey and China.

Wood density is one of the most important wood properties,[43] and it is a commonly used indicator of wood quality and cell size, since it is a good predictor of timber strength, stiffness, ease of drying, hardness and it is related to fiber properties, pulp yield and various paper making properties.[15,44] Blair *et al.*[45] established that high-density wood is preferred for construction and furniture uses and it has generally been assumed to be preferred for pulping too. However, if the main purpose is the conversion to sawn lumber, then high density will confer the best strength properties and high density should be the criterion when selecting for this feature. Research has shown that higher density species tend to have stronger timber than lower density species.[18] In the present study, it was determined that *Paulownia* wood has low density.

Table 5
Comparison of mechanical properties of Iranian *Paulownia* and other tree species

Species	a	b	c	d	e	Reference
P. fortunei	41.07	3.74	14.61	5.01	2.85	This study
P. tomentosa	43.56	4.28	25.55	8.10	1.70	19
P. elongata	28.34	4.11	15.59	5.98	1.81	20
P. fortunei	39.72	6.17	18.44	6.04	2.15	20

a: modulus of rupture (MPa); b: modulus of elasticity (GPa); c: compression strength parallel to the grain (MPa); d: static quality (I_s); e: p value

Table 6
Anatomical and morphological properties of *Paulownia* wood

Properties	N[a]	Mean	Max and Min	SD
Fiber length (mm)	30	0.996	0.801 – 1.33	0.181
Fiber width (µm)	30	30.55	25.12 – 37.09	4.55
Cell wall thickness (µm)	30	5.25	3.54 – 7.54	1.16
Lumen width (µm)	30	25.30	19.18 – 31.05	4.33
Slenderness ratio	30	33.10	21.59 – 41.66	6.48
Flexibility ratio	30	82.61	75.69 – 87.65	4.02
Runkel ratio	30	0.426	0.282 – 0.642	0.121

a: From each of the samples 30 fibers were selected (total: 600 fibers)

Table 7
Comparison of anatomical properties of Iranian P*aulownia* and other tree species

Properties	*P. fortunei*[a]	*P. fortunei*[b]	*P. elongata*[c]	Softwood[d]	Hardwood[d]
Fiber length	0.996	1.002	0.82	2.7 – 4.6	0.7 – 1.6
Fiber width	30.55	35.44	36.3	32 – 43	20 – 40
Cell wall thickness	5.25	6.47	8.6	-	-
Lumen width	25.30	26.49	19.2	-	-

a: present study; b: Ashori and Nourbakhsh[23], c: Ates [24], d: Atchison[46]

Fiber properties and morphological characteristics

Fiber is the basic component material in paper manufacturing, which affects paper properties. Fiber morphological characteristics play a key role in determining the suitability of any lignocellulosic raw material for pulp and paper manufacturing. Table 6 provides all descriptive statistics for the anatomical and morphological properties of *P. fortunei* and Table 7 compares the results obtained with those reported for other fibrous materials. The average fiber length of paulownia wood is 0.996 mm, which is shorter than that of softwoods[46] (2.7-4.6 mm), close to the minimum value of hardwood[46] fibers (0.7-1.6 mm), similar to that of *P. fortunei* (Chamestan Experimental Forest, Nour, Iran) and greater than that of *P. elongata*[24] (Turkey).

The fiber width of *P. elongata* averaged 30.55 µm, which lies in the normal range of hardwood fiber (approximately 20-40 μm), but is lower than the values for *P. fortunei* (Chamestan Experimental Forest, Nour, Iran) and *P. elongata* (Turkey). The fiber cell wall thickness of *P. fortunei* found in the present study (5.25 μm) is lower than those of *P. fortunei* grown in Mazandran province (6.47 μm)[23] and *P. elongata* (8.60 μm).[24] In addition, the values for lumen width obtained in the present study is lower than that for *P. fortunei* from the Chamestan Experimental Forest (Nour, Iran) and is higher than that for *P. elongata*[24] (Turkey).

Overall, the physical properties of a pulp sheet are closely related to morphological properties of pulp fiber.[47] When Runkel's value is greater than 1, the fibers have thick walls and the cellulose obtained from this type of fiber is least suitable for paper production. When the rate is less than 1, the cell wall is thin and the cellulose obtained is most suitable for paper production. There are positive relationships between Runkel's value and burst and tensile strength and also between fiber length and tear resistance.[23,40] Jang and Seth[48] stated that materials having a Runkel value less than 1 would be suitable for papermaking, because they collapse (become ribbonlike) and provide a large surface area for bonding. Fibers having Runkel's proportion less than 1 are included in the flexible fiber category, they are easily flattened during paper production and give stronger interfibrous connections.[49] According to this classification, the Runkel ratio of paulownia wood is 0.426 and it is included in the thick wall fiber group. Generally, sheets made from short and thin-walled fibers of paulownia may be expected to give relatively dense papers, which are weak in tearing strength, but are superior in burst and tensile properties. Therefore, from this point of view, the fibers under study are suitable for papermaking.

The flexibility coefficient is the percentage of lumen width over fiber width. It expresses the potential of fiber to collapse during beating, or during drying of the paper. Collapsed fibers provide more bonding area and subsequently stronger paper is produced. On the other hand, the strength properties of paper, such as tensile strength, bursting strength and folding endurance, are affected mainly by the way in which individual fibers are bonded together in paper sheets. The degree of fiber bonding depends largely on the flexibility of individual fibers. According to the flexibility rate, there are 4 groups of fibers:[50] 1) highly elastic fibers having a flexibility coefficient greater than 75, 2) elastic fibers having a flexibility ratio between 50-75, 3) rigid fibers having a flexibility ratio between 30-50, and 4) highly rigid fibers having an elasticity below 30. The flexibility coefficient measured for paulownia wood fibers in this study is 82.61, which includes them into the highly elastic fiber group.

Slenderness coefficient is the ratio of fiber length to fiber width. A high value of this ratio provides better forming and well-bonded paper. Generally, the acceptable value for the slenderness ratio of papermaking fibers is above 33.[51] Considering this, the species of paulownia under study has a good slenderness coefficient with a value of 33.1.

CONCLUSION

In this study, the physical, chemical and mechanical properties of paulownia wood (*Paulownia fortunei*) from Guilan region were determined, and the results were compared with those reported for other sites or other species grown in different regions of the world. The following conclusions were drawn from this research:

1- Based on the findings of this study, the average alpha-cellulose and lignin contents were determined as 51 and 23.5%, respectively. These values are comparable with the values of typical hardwoods. With regard to chemical components, it is expected for paulownia fibers to exhibit a number of properties that would fulfill the requirements of a good raw material for papermaking, such as being relatively easy to delignify during pulping, giving dense paper with high pulp yield and high strength properties. However, the content of extractive compounds is much higher compared to those of hardwoods and softwoods, which causes some problems in papermaking.

2- Paulownia wood from the trees grown on the site under study, due to its low density, mechanical properties, and static quality, is not suitable for structural applications, compared to the wood from other sites and other paulownia species.

3- *P. fortunei* has short fiber length, but can be used for paper production after mixing with long fibrous materials (from softwood fibers). The species has very good biometric coefficients, which is an important advantage in industrial papermaking. Therefore, it is suitable for this industry in this regard.

4- The variations in the wood properties of the same species are due to different factors, such as growth conditions and ecological factors. In particular, exposure, altitude, soil and climate conditions can affect wood properties. Sample size and properties (e.g. ring orientation), and the test procedure can also affect the test results.

REFERENCES

[1] A. Ashori, *Polym.-Plast. Technol. Eng.*, **45**(**10**), 1133 (2006).
[2] A. Ashori, *Fiber Polym.*, **7**(**1**), 26 (2006).
[3] B. A. Bergmann, *New Forest.*, **16**, 251 (1998).
[4] J. R. Olson and S. B. Carpenter, *Wood Fiber Sci.*, **17**, 428 (1985).
[5] A. K. Rai, S. P. Singh, C. Luxmi and G. Savita, *Ind. J. Pulp Pap. Tech.*, **12**, 51 (2000).
[6] L. Jiménez, A. Rodriguez, J. L. Ferrer, A. Pérez and V. Angulo, *Afinidad*, **62**, 100 (2005).
[7] S. Caparrós, J. Ariza, G. Garrote, F. López and M. J. Díaz, *Ind. Eng. Chem. Res.*, **46**, 623 (2007).
[8] S. Caparrós, M. J. Díaz, J. Ariza, F. López and L. Jiménez, *Bioresource Technol.*, **99**, 741 (2008).
[9] F. J. Ede, M. Auger and T. G. A. Green, *J. Hortic Sci.*, **72**, 179 (1997).
[10] H. Abbasi, *Procs. National Conference on Management of Northern Forest on Sustainable Development*, Ramasar, Iran, 2000, p. 97.
[11] E. B. De Guth, *Procs. IUFRO Conference*, Oxford, England, 1980, p. 1 (Summary).
[12] I. D. Cave and J. C. F. Walker, *Forest Prod. J.*, **44**(**5**), 43 (1994).
[13] M. Kiaei, *Cellulose Chem. Technol.*, **47** (**5-6**), 339 (2013).
[14] C. Harvald and P. O. Olesen, *Scand. J. Forest Res.*, **2**, 525 (1987).
[15] A. J. Panshin and C. De Zeeuw, "Textbook of Wood Technology", 4th ed., McGraw-Hill, New York, 1980.
[16] D. J. Cown, *New Zeal. J. For. Sci.*, **22**(**1**), 87 (1992).
[17] A. P. Schniewind, "Concise Encyclopaedia of Wood and Wood-Based Materials", Pergamon Press, 1989, 248 pp.
[18] J. C. F. Walker and B. G. Butterfield, *New Zeal. J. For. Sci.*, **40**(**4**), 34 (1996).
[19] M. Akyildiz, H. S. Kol, *J. Environ. Biol.*, **31**, 351 (2010).
[20] Asian Network for Biological Science, Chinese Academy of Forestry, "Paulownia in China: Cultivation and Utilization", Beijing, China, 1986, 65 pp.
[21] R. M. Rowell, "The Chemistry of Solid Wood", Advances in Chemistry Series, 207, Am. Chem. Society, Washington, DC, 1984, 614 pp.
[22] H. Kalaycioglu, I. Deniz and S. Hiziroglu, *J. Wood Sci.*, **51**(**4**), 410 (2005).
[23] A. Ashori and A. Nourbakhsh, *Eur. J. Wood Prod.*, **67**, 323 (2009).
[24] S. Ates, N. Yonghao, M. Akgul and A. Tozluoglu, *Afr. J. Biotechnol.*, **7**(**22**), 4153 (2008).
[25] S. Y. Zhang, *Wood Sci. Technol.*, **31**, 181 (1997).
[26] ASTM D 143-94, American Society for Testing and Materials, "Test Methods for Small Clear Specimens of Timber", Volume 04/10, ASTM, Philadelphia, 2003.
[27] J. G. Haygreen and J. L. Bowyer, "Forest Products and Wood Science", 3rd edition, Iowa State University Press, USA, ISBN 0-81382-256-4, 1996, 331 pp.
[28] S. Korkut and B. Guller, *Bioresource Technol.*, **99**, 4780 (2008).
[29] TAPPI Test Methods, Tappi Press, Atlanta, GA, USA, 2000.
[30] L. E. Wise and H. L. Karl, in "Cellulose and Hemicelluloses in Pulp and Paper Science and Technology", edited by Earl L. C., Vol. 1, McGraw Hill Book Co, New York, 1962.
[31] F. L. Franklin, *Tropical Woods*, **88**, 35 (1964).
[32] ISO 3787, International Standard Organization, "Wood-determination of ultimate stress in compression parallel to grain", Switzerland, 1975.
[33] ISO 3133, International Standard Organization, "Wood-determination of ultimate strength in static bending", Switzerland, 1975.
[34] ISO 3349, International Standard Organization, "Determination of modulus of elasticity in static bending", Switzerland, 1975.
[35] ISO 554, International Standard Organization, "Standard atmospheres for conditioning and/or testing specifications", Switzerland, 1976.
[36] ISO 3130, International Standard Organization, "Wood-determination of moisture content for physical and mechanical tests", Switzerland, 1975.
[37] W. T. Simpson, "Dry Kiln Operators Manual", USDA For. Ser. Agric. Handb., WI, U.S. Department of Agriculture, Forest Service, Forest Product Laboratory, 1971, 174 pp.
[38] F. F. P. Kollman and J. R. Côté, "Principles of Wood Science and Technology. I. Solid Wood", Springer-Verlag, New York, 1968, 592 pp.
[39] B. J. Zobel and J. P. Van Buijtenen, "Wood Variation: Its Causes and Control", Springer-Verlag, Berlin, Heidelberg, New York, 1989, 363 pp.
[40] H. Eroglu, "Fiberboard Industry", Karadeniz Technical University, Publication No. 304, Trabzon, Turkey, 1998, 30 pp.
[41] A. Enayati, Y. Hamzeh, S. A. Mirshokraie and M. Molaii, *Bioresources*, **4**(**1**), 245 (2009).
[42] I. Bektas, Ph.D. Dissertation, The Scientific Institute of Istanbul University, Istanbul, 1997, 200 pp.
[43] J. D. Brazier, J. D. and R. S. Howell, *Forestry*, **52**(**2**), 177 (1979).
[44] T. Jyske, H. Makinen, P. Saranpaa, *Silva Fenn.*, **42**(**3**), 439 (2008).
[45] R. L. Blair, B. J. Zobel and J. A. Barker *Tappi J.*, **58**(**1**), 89 (1995).

[46] J. E. Atchison, in "The Secondary Fibers and Non-Wood Pulping", edited by F. Hamilton, third edition, Tappi Press, Atlanta, USA, 1987, 232 pp.
[47] S. Caparro, M. J. Diaz, J. Ariza, F. Lopez and L. Jimenez, *Bioresource Technol.*, **99**, 741 (2008).
[48] H. F. Jang and R. S. Seth, *Tappi J.*, **81**(**5**), 167 (1998).
[49] H. Kirci, "Wood Pulp Industry Lecture Notes", Karadeniz Technical University, Forest Faculty Publication, Trabzon, 2000.
[50] I. Bektas, A. Tutus and H. Eroglu, *Turk. J. Agric. For.*, **23**, 589 (1999).
[51] F. Xu, X. C. Zhong, R. C. Sun and Q. Lu, *Ind. Crop. Prod.*, **24**, 186 (2006).