Measuring Wood Quality of *Paulownia Tomentosa* Harvested in West Delta of Egypt for Effective Utilization and Potentiality for Afforestation

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ABSTRACT

The objective of this study was to investigate different properties of *paulownia* (*Paulownia tomentosa*) wood so that decision makers in Egypt could use such information in relation to effective decision making for afforestation projects. *Paulownia* trees with an average age of 7 years old in West Delta, Egypt (30°16'14.94' N 30°52'6.85" E) harvested for the experiments. Properties of various imported and local species including beech (*Fagus sylvatica*) and Scots pine (*Pinus sylvestris*), white she-oak (*Casuarina glauca*) and black poplar (*Populus nigra*) were tested for comparative purposes. Physical, chemical and mechanical properties of samples were evaluated based on the international standards. The results showed that *paulownia* wood had a low-density 266 kg.m^{-3}, with a total volumetric shrinkage of 8.73%, having cellulose and hemicellulose contents of 51.2% and 25.1%, respectively. It appears that *paulownia* samples had relatively low mechanical properties in bending strength of 49.8 MPa, and compressive strength of 21.6 MPa. Janka hardness values of the samples were 1.08% and 1.33% in radial and tangential grain orientations, respectively. Based the findings in this work it seems that *paulownia* wood has a great potential with accepted properties to be used for different applications as well as having significant potential for afforestation in Egypt.

Keywords: Paulownia- Afforestation- Mechanical properties- Janka hardness- Wood quality.

INTRODUCTION

It is a fact that climate changes have become a tangible reality threating all systems in the world, which greatly affecting the global economy, livelihoods, and the abundance of natural resources (Kreidenweis et al., 2016). The agriculture in many regions of the world including Egypt is also significantly affected by climate change. The option of mitigating climate changes has become a major challenge facing humans to live in peace and security in the world (Reyer et al., 2009). It has become imperative for the international community to cooperate together to adapt and mitigate climate changes by working to reduce carbon dioxide emission and even remove carbon from the atmosphere and store it in the depths of the soil and oceans (Jakubowski, 2022). The main objective of afforestation and reforestation programs is to maximize volume of wood produced from forest plantations (Adi et al., 2014) to reduce the gap between demand and supply which can be achieved through the use of fast-growing species. At the same time, afforestation projects aim to maximize the wood yield during the harvesting cycle while preserving the quality of the produced wood, as there is an inverse relationship between the growth rate and the quality of wood (Fundov, 2012 and Garcia-Morote et al., 2014). With the exception of the Gebel Elba forests and the mangrove forests on the red sea coasts, Egypt has a very limited forestland, as it does not have natural forests due to the scarcity of rain (El-Baha, 2012) as well as due to high rate of urbanization (El-Kateb et al., 2015). Egypt relies heavily on imported wood, including lumber, timber or different wood products such as particle board, veneer, plywood, fiberboard, pulp and paper (Nasser et al., 2015).

Egypt has pursued, since the beginning of the twenty-first century, the policy of afforestation by planting thousands of hectares of species on treated wastewater in many districts (El-Kateb et al., 2022). More than 24 forest plantations have been established and planted with a large number of tree species (Zalesny et al., 2011). After the 27th Climate Conference hosted by Egypt in Sharm El-

Sheikh, Egypt is striving to expand afforestation operations on treated wastewater, and the demand has become great for fast-growing species such as *Corymbia citriodora* and *Casuarina* sp. as local species which can be grown successfully with having short harvesting cycles in Egyptian climate (El-Kateb et al., 2022). Globally with increasing attention to the issue of climate change and striving towards reducing forest cutting, and with the increase in wood demand and the gap between wood demand and supplies as a result of the increase in population, there was an urgent need to search for alternative wood species, including underutilized and fast-growing species, in an attempt to bridge this gap (Gungor et al., 2007). It is preferable to use fast-growing species for afforestation and reforestation purposes. This is ideal in the case of commercial forestry since substantial demand of wood can be effectively satisfied. In addition to its role for mitigation the climate changes through reducing carbon dioxide from the atmosphere as bio-traps for carbon storage (Qi et al., 2016). The overall quality of wood including mechanical, physical, chemical, and anatomical, characteristics plays a significant role for determining its efficient utilization for many applications (Kask et al., 2021).

Paulownia trees (*Paulownia tomentosa*) family Paulowniaceae, are very fast-growing deciduous trees, especially under suitable conditions (Yadav et al., 2013), it is native to China and spreads in various temperate zones worldwide. The tree gives valuable wood at a harvesting cycle of 15 years or more, and its wood is low quality between 5-7 years due to the increased of juvenile wood and the lack of mature wood (Olson and Carpenter, 1985). One tree gives between 0.3-0.5 m^3 of wood, and a hectare planted with a density of 2000 trees gives about 330 tons of wood (Caparros et al., 2008). Various previous studies carried out have shown that *paulownia* wood is resistant to rot having high dimensional stability (Koman and Feher, 2020). It is also mostly free of knots with satiny luster (Akyildiz and Kol, 2010). In general, it has very low thermal conductivity (Kaymakci et al., 2013), and does not easily warp or crack (Silvestre et al., 2005), with a high specific strength ratio, *Paulownia* wood has been used as a raw material for many applications, including particleboard (Kalaycioglu et al., 2005 and Nelis and Mai, 2021), pulp and paper (Ates et al., 2008), bioenergy (Qi et al., 2016), and veneer and plywood production (Nelis et al., 2019). Previous conducted studies showed that *paulownia* has a high ability to capture carbon dioxide from the air, 10 times more than that of other species, so that it removes greenhouse gases and releases more oxygen at a high rate (Nair, 2012). Therefore, paulownia trees could play a major role in mitigating climate changes if it is used extensively in afforestation programs. *Paulownia* as one of the most important fast growing tree species, which makes it a strong candidate for use in afforestation projects in Egypt. (Kandeel et al.,1990) reported that the Egyptian Ministry of Agriculture introduced paulownia trees from China as a potential species for afforestation. (Kandeel and Aly, 1991) used the thinning of *paulownia* trees as raw materials for pulp paper, while (Aly and Krahmer**,** 1993) investigated the anatomical structure of one-year old paulownia wood. As mentioned above the paulownia tree is considered one of the extremely fast-growing species therefore it has a great potential for afforestation and reforestation.

Currently there is very little or no information on the quality and properties of wood from paulownia grown in Egypt as well as how it can possibly be utilized for reforestation. Therefore, the objective of this study was to determine the quality and physical, chemical and mechanical properties of locally grown *paulownia* wood so that such species can be suggested as raw materials for different wood products manufacture including particleboard, fiberboard and pulp and paper. Data from this study would also be beneficial for decision makers to consider *paulownia* for afforestation programs, as function of wood quality.

MATERIALS AND METHODS

Samples preparation:

Randomly selected plantation grown three *paulownia* trees harvested in Abou Ghalib region, west Delta in Giza district of Egypt were used in this study. This study was carried out during 2022, at age of 7 years. Initially seedlings were planted in an open field in 2015 at spacing of 2.5 by 2.5 m and irrigated with drip irrigation system. The environmental conditions of the west Delta region during study were less than 250 mm average annual rainfall, most of which is received from October to April. In summer, the temperature rises as high as 28°C, and in winter it falls to 25°C. Average age of the trees was 7 years and with diameter outside bark ranging from 11 to 13 cm.at DBH.

For each tree and before felling, north direction of log was marked. After felling, 0.50-m-long bolt logs at breast height was removed along the grain and the ends of each log were coated with a moist cloth to reduce moisture loss and transported to the Wood Testing Laboratory, Faculty of Agriculture, Alexandria University, Alexandria, Egypt for further analysis. According to ASTM D-1037(1989) and from each bolt, two adjacent diametric strips (3 by 3 cm) were removed and re-sawn longitudinally into different samples. The samples were stacked and conditioned in the laboratory until they reached to equilibrium moisture content (Pometti et al., 2009).

Comparison purpose four wood species, including two local wood i.e., black poplar (*Populus nigra*), and white she-oak (*Casuarina glauca*), and two imported ones i.e., beech (*Fagus sylvatica*) and Scots pine (*Pinus sylvestris*). The local wood species were obtained from trees grown in the farm of the Faculty of Agriculture in Alexandria, while the imported wood was supplied by a local company in Alexandria. Physical, chemical and mechanical properties of the five wood species were determined using the same standard methods used for paulownia samples.

Biomass aspect of the samples:

After felling trees and using a balance, the green weight of the above-ground portion including stem, branches and foliage was recorded. Samples of each component were taken and covered with moist cloth to reduce moisture losses and transferred to the Wood Technology Laboratory at the Department of Forestry and Wood Technology, Faculty of Agriculture, Alexandria University for further analysis. The samples of stem, branches and foliage were weighed in the green state and oven-dried at a temperature of 70°C for foliage and 103 ± 2˚C for stem and branches until they reached to a constant weight. The ratio of oven-dried to green weight was calculated for each component. To calculate the oven-dry weight of each component, dry matter biomass, the ratio of oven-dried/green weight was multiplied by the actual green weight of each component. For biomass allocation, the percentages of each biomass component were calculated based on the total above-ground biomass in oven-dried states. Stem dry weight biomass per hectare was estimated as the average stem dry biomass multiplied by 1600 based on 2.5x2.5 m spacing. Biomass production and biomass allocation were determined based on the process described by (Aref et al., 2003).

For each tree, certain physical, chemical and mechanical properties were determined to evaluate the wood quality of paulownia. For chemical analysis, wood samples were ground individually in a laboratory hammer mill, and screened to pass through a 40-mesh screen and retained on a 60-mesh screen.

Physical properties of the samples:

For each tree, total volumetric shrinkage, wood density at green, air-dried and oven-dried conditions, fiber saturation point (FSP), and maximum moisture content (MMC) were determined based on the methods described by (Akyildiz &Kol 2010 and Nasser et al. 2012) using the following equations:

$D_g = W_o/V_g$, $M_f = \beta_v/D_g$, and $M_{max} = (1.5-D_g)/(1.5 \times D_g)$,

Where D_g is basic specific gravity, W_o is the oven-dry weight, V_g is the green volume, M_f is the FSP and β_v is the total volume of shrinkage.

Mechanical properties of samples:

Mechanical properties of samples were determined based on British Standard BS 373 (1957), conditioned small clear specimens free from any visible defects with 2-cm cross-section were used for the experiments. Static bending, compression parallel-to-grain, impact bending and Janka hardness tests were carried out as mechanical tests. The modulus of rupture (MOR), maximum crushing strength (C_{max}), impact strength as well as Janka hardness number (JHN) in radial and tangential directions were calculated. The mechanical tests were carried out employing Amsyler Universal Testing Machine equipped with a load cell having 4,000 kg capacity. The mechanical tests and the specifications of specimens as well as the calculated strength parameters are listed in **Table (1)**.

Table (1). Mechanical tests and small clear specimen specifications of *Paulownia tomentosa* wood.

Mechanical test	Specimen dimensions (cm)		Loading	Calculated
	Cross Section	Length	Rate	strength parameters
Static bending	2 x 2	30	6.6	MOR= $(1.5 \times L \times P_{max})/(b \times h^2)$.
Impact bending	2 x 2	30	-	Impact strength.
Compression parallel to grain	2 x 2	3	0.63	$C_{max}=P_{max}/(b \times h)$.
Janka hardness	2 x 2	6	6.3	JHN in radial and tangential.

P_{max}: maximum load, b & h: width and depth of specimen, L: specimen span, 28 cm.
MOR: Modulus of Rupture, C_{max}: Maximum crushing strength, JHN: Janka hardness number.
Loading rate is the rate of load applied in mm/min.

The moisture content and density of wood based on oven-dry weight and volume at test were determined based on ASTM D 2395-84 (1989). According to (Akyildiz & Kol 2010), the static quality value (I_s) was calculated as a ratio of crushing strength parallel to grain and air-dry density of samples using the following equation:

$I_s = [C_{max}/(D_{12}*100)] *10.2$

Where: C_{max} is the compression strength parallel to grain ($kg.cm^{-2}$) at about 12% MC, D_{12} is the air-dry density ($g.cm^{-3}$).

Chemical analysis of samples:

Tested bending samples were cut into small chips and ground using a hammer mill to 40-60 mesh size material. The extractive content of the samples was determined according to ASTM D-II05-84 (1989) using Soxhlet apparatus in three stages i.e., benzene-ethanol (2:1 v/v) for 4 hrs, 95% ethanol for 4 hrs and boiling water for 3 hrs with changing water every hour. The percentage of total extractives was calculated based on oven-dry weight of the samples. Extractive-free particle was used to determine the contents of the three main chemical components, namely cellulose, hemicelluloses and lignin according to the methods described by (Nikitin 1960, Rozmarin and Simionescu 1973 and ASTM D 1106-84, 1989), respectively. Ash content of the samples as a secondary chemical wood component was determined by ignition the wood sample in manful at 575 ± 25°C to burn off all the carbon in the sample ASTM D-1037(1989).

Comparison of *Paulownia* with other species:

The five wood species used in this study including paulownia and four wood species for comparison (Poplar, white she-oak, China berry, European redwood and American beech) were rated based on the positive and/or negative impacts on the wood quality; the property was assigned a value between 1 and 6, with 1 being the best and 6 being the worst. The rating was calculated as the sum of all values divided by the number of measured properties (Σ/9). Rating value refers to the mechanical properties of wood as well as wood static quality value of each wood species to understand completely the quality of the species.

Statistical analysis:

Descriptive statistical analysis was used for the results of physical, chemical and mechanical properties of paulownia samples. The analysis of variance (ANOVA) with a complete randomized design (CRD), was employed to detect the differences among the samples of *paulownia* and other species. LSD at 0.05 level of probability was used to detect the differences among the average properties. The relation between the bending strength and wood density was also determined by using the correlation analysis (Snedecor and Cochran, 1967).

RESULTS AND DISCUSSION

Biometric characteristics of *Paulownia* Trees:

Biometric characteristics of *paulownia* trees used in the current study are shown in **Table (2)**. It can be seen from this table that the age of the trees used in the study was 7 years, the average total height and diameter at breast height were 11.4 m and 16.3 cm, respectively, and the annual growth rate in diameter was 2.3 cm per year.

The growth parameters in this study are somewhat lower than those obtained by other researchers with different *paulownia* varieties and other fast-growing species growing in other soil and climate conditions in several countries around the world (Akyildiz and Kol ,2010, Fos et al., 2023 and Alaejos et al., 2023). Our results differ from Fos et al. (2023) on 7year-old *paulownia* trees grown in Spain, as the DBH of trees ranged between 25.9 and 30.86 cm, and the radial growth rate ranged between 3.44 and 4.77 cm per year. In Turkey, 6-years-old of *P. tomentosa* gave a diameter of 30 to 40 cm at breast height with a total tree height 6.0 to 7.5 m (Akyildiz & Kol 2010). On the other hand, these results of the biometric properties of the paulownia trees under study are in agreement with the results of (Olson and Carpenter, 1985), where the DBH of the paulownia trees grown in Southeastern Kentucky, USA at the age of 7 years ranged between 13.8 and 16.0 cm, and the radial growth rate was ranged between 1.97 and 2.29 cm per year. It is a known fact that for most of tropical hardwoods, the minimum diameter is 45 cm Kewilaa (2007), however, Avery (1975) stated that the logs used for veneer production should be 35 cm at least. Accordingly, these results show that the paulownia trees at the age of 7 years did not produce the minimum diameter needed for the production of veneer and plywood in sawmill. This is in contrast to that reported by Fos et al. (2023), where trees at the age less than 7 years gave the minimum diameter (30.2 cm) required for this industry.

Table (2). Biometric properties of *Paulownia tomentosa* trees used in the study.

Tree no.	Age (year)	Height (m)	DBH_{OB} (cm)	Growth rate in DBH (cm/year)
1	7	11.50	15.44	2.21
2	7	11.00	15.60	2.23
3	7	11.70	17.83	2.55
Mean	**7**	**11.40**	**16.29**	**2.33**
SD	-	**0.36**	**1.34**	**0.19**

DBH_{OB} is diameter at breast height outside bark.
SD is the standard deviation.

Biomass yield of *Paulownia*:

The amount of dry matter produced by trees during their lifetime, or what is known as biomass, which is usually expressed in units of tons per hectare per year ($t.ha^{-1}.year^{-1}$), and plays very important role as raw material for different wood industries including pulp and paper industry, particleboard and fiberboard industry and energy production. The above-ground green biomass (kg) of whole *paulownia* tree and its allocation (%) based on oven-dry basis at age of 7 years planted at 2.5x2.5 m spacing and the annual dry biomass of the stem of each tree (kg) as well as the annual biomass productivity per hectare ($t.ha^{-1}.y^{-1}$) based on oven-dry basis are shown in Table (3). It can be seen from these data that the proportion oven-dry weight of *paulownia* stem was the highest (79.66%) among the other tree parts. Such results are in agreement with those determined by Alaejos et al. (2023), on twelve fast-growing species including *Paulownia fortunei* growing in short rotation under Mediterranean climate. In this study, the above-ground biomass of the whole *paulownia* tree and the total dry matter biomass of paulownia were 7.87 kg per tree and 12.59 $t.ha^{-1}.y^{-1}$, respectively.

The results also agree with those of Wang and Macfarlane, (2012), on poplar and willow trees, where the dry biomass yield ranged between 2.7 and 22.7 $t.ha^{-1}.y^{-1}$, although the yield differed between the three studied sites. These results showed that *paulownia* gave dry biomass higher than the amount of dry matter produced by poplar grown in China (Zhang et al., 2009), where it was produced 43.16 t. ha^{-1} during five year rotation cycle (about 8.63 t. $ha^{-1}.y^{-1}$) and the results of Wang & Macfarlane (2012) where they yielded an amount of dry biomass ranged between 2.9 and 9.4 $t.ha^{-1}.y^{-1}$ on coppiced poplar and willow clones at three locations in Michigan, USA under short rotation coppice system (SRC).

Comparing the biomass production of *paulownia* to other species, it can be concluded that the productivity of *paulownia* as dry matter (12.6 t. $ha^{-1}.y^{-1}$) closed to biomass production from beach poplar plantation 11.74 $t.ha^{-1}.y^{-1}$(Zhang et al., 2009), was higher than other wood species i.e., milkweed tree 5.41 $t.ha^{-1}.y^{-1}$ (Nasser et al., 2012), and lower than dry matter produced from hybrid poplar 15 $t.ha^{-1}.y^{-1}$, (Youngquist et al., 1994).

Table (3). Above-ground biomass and allocation of whole *Paulownia tomentosa* tree and dry biomass production of hectare based on 2.5 x 2.5 m spacing at age 7 years.

Tree No.	Green biomass production (kg/tree per 7 years)			Biomass Allocation, od (%)			Annual biomass, od per	
	Foliage	**Branches**	**Stem**	**Foliage**	**Branches**	**Stem**	**Tree (kg)**	**Hectare* (ton)**
1	2.00	14.0	65.0	2.46	19.72	77.82	7.32	11.72
2	1.50	11.5	65.0	1.83	16.18	81.99	6.97	11.15
3	1.48	17.0	83.5	1.39	Chart Area	79.17	9.32	14.91
Mean	**1.66**	**14.17**	**71.2**	**1.89**	**18.45**	**79.66**	**7.87**	**12.59**
SD	**0.29**	**2.75**	**10.7**	**0.54**	**1.97**	**2.13**	**1.27**	**2.02**

od is oven-dry basis. * Based on 2.5x2.5 m spacing. SD is the standard deviation.

Physical properties of *Paulownia* samples:

The physical properties of a species including density, specific gravity, shrinkage, swelling and fiber saturation point (FSP), play very important role on determination of its suitability for different utilization and need to be determined for an effective utilization of any species (Dinwoodie, 2000).

Descriptive statistical data i.e., mean values, minimum and maximum values, standard error and coefficient of variation (CV) of the physical properties of *paulownia* wood produced from 7 years-old paulownia trees are shown in **Table (4)**. The physical properties included wood density based on oven-dry volume (ρ_{od}, $kg.m^{-3}$) and air-dried volume (ρ_{ad} at 10.6% MC, $kg.m^{-3}$), basic specific gravity (SG_{basic}), fiber saturation point (FSP, %), maximum moisture content (MMC, %) and total volumetric shrinkage (β_V, %). The density of the wood expresses the weight of the wood for a specific size and it is affected by the moisture content of the wood. With weight constant, the increase in the moisture content in the wood decreased its density. **Table (4)** displays values of oven-dry density of paulownia samples based on weight and volume at oven-dry ranging between 252 and 338 $kg.m^{-3}$, with an average of 291.5 $kg.m^{-3}$. These values are consistent with the results of Akyildiz and Kol (2010) and Koman et al. (2017), on 7 years-old *Paulownia tomentosa* trees grown in Turkey. The aid-dry density of *paulownia* wood was ranged from 239 to 298 $kg.m^{-3}$ with an average of 266 $kg.m^{-3}$. These values are 11.5% lower than the values published by the same previous studies. The coefficient variation values for all the studied properties ranged from 6.7 to 11.7%. By comparing the air-density values of *paulownia* wood (at 12% MC) with other wood species determined in this study including some local and imported woods to Egypt as well as published results **(Fig. 1),** it can be concluded that the density values of *paulownia* are always lower than those of European redwood as imported softwood (*Pinus sylvestris*, 454.2 $kg.m^{-3}$), American beech as imported hardwood (*Fagus* *sylvetica*, 679.1 kg.m^{-3}) and white she-oak (*Casuarina glauca*) as local fast-growing hardwood species (803.8 kg.m^{-3}) and black poplar (*Populus nigra*; 378.8 kg.m^{-3}), but they are close to *Erythrina humeana* wood (Nasser et al., 2015) 303.0 kg.m^{-3} and higher than the density of balsa wood (*Ochroma pyramidales*, 80-220 kg.m^{-3}) Midgley et al. (2010). These results in this study showed that *paulownia* wood is very light weight wood (266 kg.m^{-3}), which is less than that of poplar and willow wood according to Klasnja et al. (2013), where they are 341 and 336 kg.m^{-3}, respectively. However, the density of *paulownia* wood was higher than that of the three group densities of balsa (*Ochroma pyramidale*) according to the Midgley et al. (2010), where the density of balsa wood ranged from 80 to 220 kg.m^{-3}.

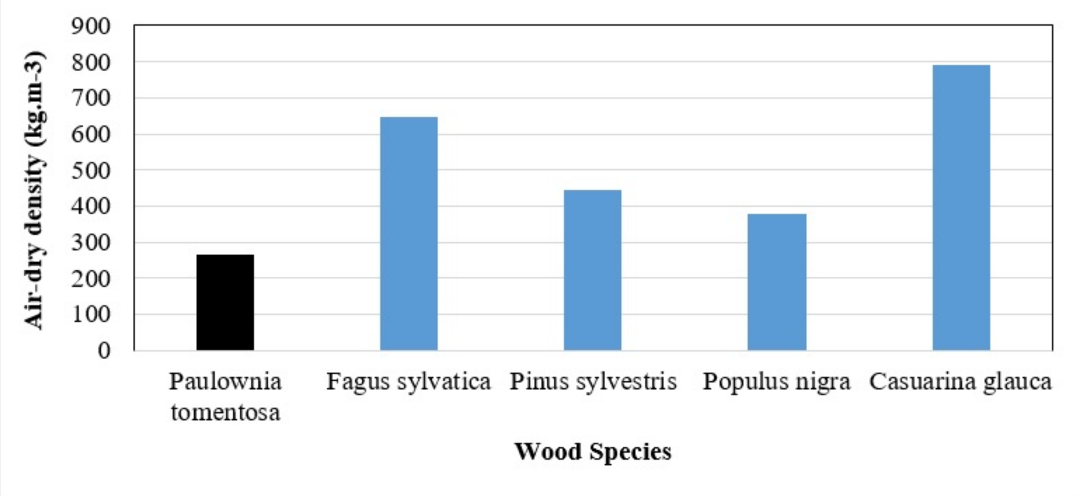

Fig. (1). Air-dry density of paulownia compared with other species.

The basic density of wood, SG_{basic} based on oven-dry weight and green volume is considered important element in the manufacture of veneer, pulp and paper, charcoal and particleboard (Koman and Feher, 2020 and Zhang et al., 2009), as it predicts the value of the yield resulting from the logs before production, as it means the amount of oven-dried wood by weight from a certain volume of green wood, and its increase means an increase in the yield resulting from a unit volume in the green state. As seen in Table 4, the SG_{basic} of *paulownia* wood ranged from 0.28 to 0.31 with an average of 0.27, very low density. This result is in agreement with the values of basic specific gravity of *paulownia* wood obtained by Koman et al. (2017) 0.26 and Akyildiz and Kol (2010) 0.27, however, this value is less than that of poplar wood, 0.38 (Bozkurt and Erdin 1997) and *Pterocarya fraxinifolia* wood, 0.35 (Gungor et al., 2007). Panshin and DeZeeuw (1980) classified wood based on the basic specific gravity (SG_{basic}) into three classes, namely light wood with SG_{basic} of 0.36 or less, moderately light to moderately heavy with SG_{basic} of 0.36 to 0.50 and heavy wood with SG_{basic} above 0.50. According to this classification, *paulownia* classified as "light wood" with SG_{basic} is 0.27. Light wood such as *paulownia* wood, is preferred by packaging and particleboard industries (Koman and Feher, 2020 and Kalaycioglu et al. 2005), as well as for sound and thermal insulation purposes (Kotlarewski et al., 2014 and Bertolini et al., 2019).

The fiber saturation point (FSP) is an important concept in wood technology because, although it is a point, it is a turning point for many wood properties, especially with regard to dimensional stability and mechanical properties (Zhang et al. 2009). The mean value of the FSP of *paulownia* wood in this study (**Table 4)** was 31.3% and ranged from 25.5 to 38.2%. These values of paulownia wood were close to, but slightly higher than, the published values for paulownia wood (23.1 and 24.5% for *P. tomentiosa* by Koman and Feher (2020) and Akyildiz and Kol (2010), respectively) and other wood species (28.4%) Bozkurt and Erdin, 1997 on poplar. The total volumetric shrinkage of wood is the decrease in the wood volume when dried from the green state (above the FSP) to the oven-dried state (at zero MC, %) (Hygreen and Bowyer 1996). In this study, paulownia wood had a low total volumetric shrinkage (7.73%) and ranged from 7.3 to 10.0% compared to other hardwood species. The total volumetric shrinkage of *paulownia* in this study (7.73%) is in agreement with the volumetric shrinkage of 9 years old Paulownia Clone in vitro 112 hybrid (8.47%). Also, these values in the current study were close to, but slightly higher than, the published values for *paulownia* wood (6.9% for Koman et al. (2017) and 7.8% for Akyildiz and Kol (2010).

The results of this study showed that the mean values of physical properties of *paulownia* wood at the age of 7 years-old are very similar to the published values of same species grown in different parts of the world. The results indicated that *paulownia* wood is characterized as a lightweight with low total volumetric shrinkage. These results showed that *paulownia* wood can be a good raw material for manufacture of particleboard, aircraft, packing boxes, table tennis bats, boats building and for uses that require high acoustic, thermal and electrical insulation. The results of density and shrinkage of paulownia in this study also showed that it can be used as a substitute for balsa wood in different uses.

Table (4). Some physical properties of *paulownia* wood from trees grown in West Delta of Egypt at age 7 years compare to some local and imported wood species as well as compared to literature results.

Tree No.	ρ_{od} (kg.m^{-3})	ρ_{ad} (kg.m^{-3})	SG_{Basic}	FSP (%)	M_{max} (%)	β_V (%)
1	302.5	268.9	0.277	29.34	297.7	8.48
2	299.4	262.3	0.273	31.13	301.7	8.78
3	272.7	265.6	0.247	33.54	339.1	8.92
Average	**291.5**	**265.6^E**	**0.267**	**31.34**	**312.8**	**8.73**
Min. value	251.9	238.9	0.282	25.51	256.9	7.30
Max. value	338.2	298.0	0.309	38.16	371.4	10.04
Standard error	6.41	4.12	0.006	0.87	8.56	0.16
CV (%)	9.50	6.69	9.52	11.74	11.61	7.93
E. redwood	489.8	454.2^C	-	-	-	-
Beech	727.4	679.1^B	-	-	-	-
White she-oak	889.7	803.8^A	-	-	-	-
Black poplar	394.6	378.8^D	-	-	-	-
***P. tomentosa*[1]**	275.5	300.2	0.264	**23.12**	**266.4**	6.94
***P. tomentosa*[2]**	294.0	317.0	0.272	**24.54**	**248.8**	7.78
***Populus tremula*[3]**	420.0	450.0	0.380	**28.44**	-	12.80

* Each value is an average of 18 specimens (6 per tree).
Means with the same letters in the same column are not significantly different at 0.05 level of probability according to LSD test.
[1]Koman and Vityi (2017), FSP and MMC were calculated. [2]Akyildiz and Kol. (2010), FSP and MMC were calculated.
[3]Bozkurt and Erdin (1997), FSP was calculated. FSP: Fiber saturation point; M_{max}: maximum moisture content.
ρ_{od} is based on oven-dried weight and volume. ρ_{ad} is based on oven-dried weight and air-dried volume at MC of 10.6±0.3%. SG_{basic} is calculated based on oven-dry weight and green volume.

Chemical analysis of samples:

The chemical composition of wood is one of the most important properties It also determines the suitability of wood for use as a raw material in wood industries, especially the production of pulp and paper, the production of chemicals from wood, and the production of energy in its various forms from wood (Hygreen & Bowyer, 1996). **Table (5)** showed the descriptive data of paulownia wood including the mean values, minimum and maximum values, standard error and the coefficient of variation for the primary elements, namely cellulose, hemicelluloses and lignin and secondary materials such as ash and extractives chemical components compared to some local wood species (White she-oak: *Casuarina glauca* and black poplar: *Populus nigra*) and imported woods (European redwood: *Pinus sylvestris* and American beech: *Fagus sylvatica*), in addition to compare the values with some published values for paulownia wood, hardwoods, and others wood species. The results indicated that total extractives of *paulownia* wood ranged from 11.6 to 12.9%, with an average value of 12.2% and a coefficient of difference of 4.5%. Comparing these results **(Table 5)** with local and imported woods, it can be seen that the total extractives of paulownia wood is higher than that of hardwood species (2-6%), while it falls within the range of hardwood species growing in Egypt reported by Nasser et al. (2015),

On 7 hardwood species growing in Egypt (3-16%). No significant differences were detected between the total extracts of *paulownia*, European redwood (12.0%), and white she-oak wood (11.3%), while the total extractive values of *paulownia* were significantly higher than American beech wood as imported wood (4.3%) and black poplar wood as local wood species (4.5%). The ash content of *paulownia* wood was 0.32% and ranging from 0.21% to 0.29%. The ash content of *paulownia* is within the range of hardwoods (0.2-0.5%), and is higher than the European redwood and American beech (0.27 and 0.29%, respectively), however, the ash content of *paulownia* is lower than white she-oak wood (0.84%), and the differences between them were significant. As it is displayed in Table (5) paulownia wood grown in Egypt gave a high content of cellulose (51.2%) and a low content of both hemicellulose (25.1%) and lignin (23.6%) compared to white she-oak, black poplar and European redwood determined in the current study and hardwood species in the literatures, but it was lower than cellulose of American beech in this study. The cellulose content of paulownia wood did not differ significantly from the cellulose content of beech wood (52.3%), while paulownia wood was significantly higher than European redwood (41.7%) and White she-oak (45.4%) in cellulose content. The cellulose content of *paulownia* growing in Egypt (51.2%) was lower by 17.5% than the cellulose content of *Paulownia elongata* growing in Turkey at 2 years-old (Ates et al., 2008), and 6% than the cellulose content of *P. tomentosa* (Kalaycioglu et al., 2005), while the hemicellulose content is higher by 21.9%. These results may be due to the species, age of the trees and the climatic conditions in which they grow. The results of the chemical analysis of *paulownia* wood show that it is characterized by a high content of cellulose and hemicellulose with a low content of lignin. Therefore, it is expected that *paulownia* wood will be a good raw material for the production of pulp and bioenergy. These expected results are consistent with the results of Ates et al. (2008**)**, where it was found that *paulownia* wood, although its low fiber quality, can be used as a raw material for the production of pulp paper, particleboard (Kalaycioglu et al., 2005) and bioenergy (Qi et al,. 2016).

Table (5). Chemical constitutes* of *paulownia* wood from trees grown in West Delta of Egypt at age 7 years compared to some local and imported wood species as well as compared to literature results.

Wood species	% content of				
	Total extractives	**Cellulose[1]**	**Hemicelluloses[1]**	**Lignin[1]**	**Ash[2]**
***Paulownia tomentosa* (This study)**					
Average (X)	**12.19**^{A}	**51.22**^{A}	**25.14**^{C}	**23.64**^{C}	**0.319**^{B}
Minimum value (Min.)	11.63	48.06	21.90	19.97	0.212
Maximum Value (Max.)	12.89	54.87	28.38	27.03	0.363
Standard Deviation (SD)	0.49	2.86	2.10	2.35	0.045
Coefficient of variation (CV)	4.02	5.58	8.36	9.94	14.11
E. redwood	12.01^{A}	41.73^{C}	26.05^{B}	32.22^{A}	0.274^{C}
Amer. Beech	4.25^{B}	52.32^{A}	25.16^{C}	22.51^{D}	0.287^{C}
White she-oak	11.30^{A}	45.40^{C}	27.50^{A}	27.07^{B}	0.843^{A}
Black poplar	4.48^{B}	49.02^{B}	21.68^{D}	28.70^{B}	1.235
Hardwood[3]	**2-6**	**45-50**	**15-35**	**18-25**	**0.2-0.5**
Nasser *et al.* (2016)	**3-16**	**33-44**	**23-35**	**18-28**	**0.4-8.5**
Ates *et al.* (2008) *P. elongota*	-	**43.61**	**32.13**	**20.50**	**0.210**

*Each value is an average of three trees and 9 samples.
[1]As a percentage of free-extractive oven-dry weigh.
[2]As a percentage of oven-dry weigh.
[3]Data from Fengel &Wegener (1989).

Mechanical properties of samples:

Table (6) displays the average values of mechanical properties, range, standard error, and the coefficient of variation (CV) of the samples, with a comparison with the values determined in this study for two types of the most important wood imported to Egypt i.e., European redwood and American beech, as well as two local fast-growing hardwood species growing in Egypt i.e., White she-oak and black poplar. The table also gave a comparison to the published values of the same species or other species that grow in different places of the world, as well as compared to some values published for some hardwoods growing in Egypt.

The modulus of rupture of wood, abbreviated as MOR or called bending strength, measures the ultimate resistance of wood in a static bending test and determines the load a beam will carry (Hygreen and Bowyer, 1996). It is one of the important mechanical parameters that determine the use of timber as beams. The results in Table 6 show that *paulownia* wood has the lowest mechanical properties compared to all wood species in the table for the purpose of comparison, which is due to, of course, the lower density of the wood. It was found that the bending strength (MOR) ranged from 38.4 to 63.5 MPa, with an average of 49.5 MPa with high coefficient of variation (12%). These values were higher by 35% than the values obtained by Koman & Feher (2020) for *Paulownia tomentosa* grown in Hungary at 9 years-old, and higher by about 16% than the value obtained by Koman et al. (2017**)** on the same species. **Table (6)** has the values indicating that the differences were significant between the mean values of the bending strength of *paulownia* wood and each of imported wood such as European redwood and American beech (92.5 and 134.3 MPa, respectively), and local wood species growing in Egypt such as black poplar and White she-oak (62.9 and 122.4 MPa, respectively). Regarding to the compressive strength parallel to grain, *paulownia* samples had a low compressive strength of 21.6 MPa and ranged between 17.4 and 25.5 MPa with high coefficient of variation (11.9%), which is due to the low wood density. The statistical analysis showed that the value of C_{max} of *paulownia* was significantly less than beech (51.6 MPa), white she-oak (51.8 MPa) and black poplar (26.7 MPa), although it approached poplar. The values of *paulownia* in this study were less than the values published for the same species grown in Turkey, where it gave 25.5 MPa (Akyildiz and Kol 2010) and 35.6 MPa for *Paulownia elongata* (Kaymakci et al. 2013) grown in Turkey. The value falls of the values published for the 7 hardwood species grown in Egypt than (Nasser et al. 2015) and much higher than the balsa wood (Kotlarewski et al., 2016).

The Janka hardness is one of the important mechanical tests for wood that determines the suitability of wood for use in floor industry. It expresses the wiping of the wooden material and the extent of its resistance to scratching or a change in its shape and measured by stitching a small ball with a diameter of 11.28 mm in the surface of the wood and recording the value of the force needed for that. The results in Table 6 showed the same mechanical behavior in MOR and C_{max} due to the low wood density, as we find that the values of Janka hardness number (JHN) are very low in the radial direction (1.08 KN) and the tangential direction (1.33 KN). Comparing these values with imported wood species such as beech and European redwood, we find that the values of *paulownia* are low significantly than imported woods as well as the values are lower than the values of local timber growing in Egypt such as white she-oak (4.0 and 4.2 KN, in radial and tangential directions respectively) and poplar (1.9 and 2.3 KN, respectively). The relative hardness comparison is usually used to indicate the hardness of a wood as a percentage of the Northern red oak (5.74 KN based on the Forest Products Laboratory (2010). In this study, it was found that the relative hardness of *paulownia* wood lower by 76.8% and 81.2% in the tangential and radial directions, respectively, than the Northern red oak. This indicated that *paulownia* wood is 77% softer than the Northern red oak. The Janka hardness numbers of *paulownia* wood are far from the wood commonly used for wood flooring, such as teak (3.4-5.8 KN), mahogany (3.8-4.8 KN), and beech (3.8-4.2 KN) according to Oduor (2013). Accordingly, it can be said that *paulownia* wood is not suitable for manufacture of floor parquets. It could be concluded that paulownia wood is not suitable for use as a floor wood, and it cannot be considered an alternative to beech wood, nor a substitute for white she-oak and black poplar. **Fig. (2)** showed a significant strong direct relationship between the density of *paulownia* wood and the bending strength (MOR) as one of the mechanical properties (R^2= 0.82). This result consistent with the data published by the Forest Products Laboratory (2010) and with many researchers (Nasser et al., 2015, Pometti et al., 2009 and Izekor et al., 2010) where they found that increasing density of wood increases the values of mechanical properties of wood, because density of wood measures the amount of wood cell wall that is subjected to loads and then resists them (Nasser et al., 2015).

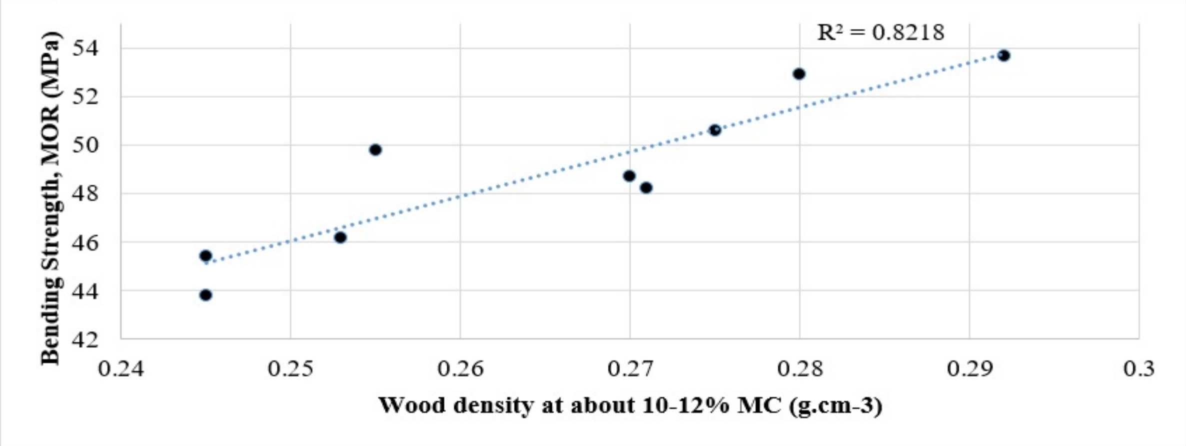

Fig. (2). Relationship between the bending strength and wood density of *Paulownia tomentosa* at 7 years-old grown in Egypt

The expression specific strength or strength-to-weight ratio is usually used in wood technology, which is the strength of wood relative to its weight or density. Wood with high specific strength, which means it has high mechanical properties compared to its weight, is preferred for many uses. This characteristic is usually used to compare the strength of wood with the strength of other building materials such as iron, copper, concrete, etc. It is known that the specific strength of wood is higher than that of other building materials (Tsoumis 1999). In this context, and based on Kollman and Cote (1968), and many researchers (Nasser et al,. 2015, Bektas et al., 2002 and Kiaei, 2013), hardwoods are divided into three categories according to static quality index (I_s), which is calculated from dividing the compressive strength of wood by the wood density as an indicator to the specific strength of wood. These three categories are low quality (I_s <7), fair quality (7<I_s<8.5) and good quality (I_s >8.5). According to the results of this study and the observed classification of hardwoods with the viewpoint of the mechanical properties, *paulownia* wood is considered a fair quality (I_s is 8.34; between 7 and 8.5), which means that it has medium mechanical properties in relation to its density.

The results indicated that *paulownia* samples had rather low mechanical properties which are in agreement with those found in previous studies (Jakubowski ,2022, Koman and Feher ,2020, Kaymakci et al., 2013, Fos et al., 2023, Koman et al., 2017 and Kiaei, 2013). It cannot be compared to beech wood or the locally grown white she-oak, but it can be an alternative to black poplar wood, although the poplar is outperforming it in the density and mechanical properties.

The results of this study are also in agreement with the findings of Barrette *et al.* (2023), they concluded that wood produced from fast-growing species usually contains a high percentage of juvenile wood, which produced wood with low mechanical properties that make it unsuitable for use in specific uses.

Table (6). Mechanical Properties* of *paulownia* wood from trees grown in West Delta of Egypt Compared to Other local and imported wood Species as well as other wood species in the literatures.

Wood species	MC (%)	SG	Bending strength[1] (MPa)	Crushing strength[2] (MPa)	Hardness strength[3] (kN) Tangential	Hardness strength[3] (kN) Radial	Value, I[4]
Paulownia							
Average (X)	**10.63[A]**	**0.264[D]**	**49.79[D]**	**21.58[D]**	**1.33[C]**	**1.08[D]**	**8.34**
Min. value	10.10	0.239	38.40	17.40	0.82	0.81	
Max. value	11.33	0.298	63.46	25.50	1.74	1.56	
SD	0.26	0.02	6.03	2.56	0.25	0.22	
CV	2.44	6.69	12.1	11.9	18.8	20.4	
N	30	30	15	15	15	15	
E. redwood	10.50[A]	0.443[C]	92.49[C]	40.37[B]	2.42[B]	2.36[C]	9.30
Beech	11.35[A]	0.645[B]	134.33[A]	51.63[A]	4.15[A]	3.79[B]	8.16
White she-oak	11.15[A]	0.791[A]	122.38[B]	51.77[A]	4.22[A]	4.02[A]	6.68
Black poplar	12-14	0.379	62.91	26.70[C]	2.26[B]	1.92[C]	7.19
Hardwood[5]	**12**	**0.34-0.88**	**46-139**	**28-70**	**2.8-7.5**	**1.6-5.9**	-
***P. tomentosa*[6]**	-	**0.32**	**43.6**	**25.53**	-	-	**8.14**
***P. elongate*[7]**	-	**0.28**	**35.8**	**35.56**	-	-	**12.9**
Seven hardwoods[8]	**11-13**	**0.30-0.58**	**41-93**	**18-55**	**3.0-6.7**	**2.8-6.0**	**7.2-10.1**
Ochroma *pyramidal*[9]	-	**0.15**	**19.6**	**11.60**	**0.30**	-	-

* Each value is an average of three trees and 15 samples (mean value ± standard deviation).
Means with the same letters in column are not significantly differences at 5% level of probability according LSD Test.
[1]In static bending test. [2]In compression parallel to grain test. [3]In Janka hardness test.
[4]According to Bektas *et al.* (2002). L (I_s<7), F (7<I_s<8.5) and G (8.5< I_s) are low, fair and good quality, respectively.
[5]Data from Bendtsen and Ethington (1975). [6]Akyildiz & Kol (2010). [7]Kaymakci *et al.* (2013).
[8]Nasser *et al.* (2015) on seven hardwood species grown in Egypt. [9]Midgley *et al.* (2010).
SG is based on oven-dry weight and volume at test and MC is moisture content of the samples at test (means of 30 samples).

Rating of *Paulownia* wood:

To best understand of the evaluation of the quality of *paulownia* the four wood species, rating was used according to Nasser et al. (2015). Rating was based on the positive and/or negative impacts on the wood quality including some physical, chemical and mechanical properties. For ranking of a wood species by rating, the selected property was assigned a value between 1 and 5, with 1 being the best and 5 being the worst. The rating was calculated as the sum of all values divided by the number of measured properties (**Σ**/9).Wood species that has low rating value refers that it has wood quality and vice versa. The rating of *paulownia* wood among other wood species including two imported wood species to Egypt (American beech, *Fagus sylvatica* and European redwood, *Pinus sylvestris*) and two fast-growing wood species grown in Egypt (Black poplar, *Populus nigra* and white she-oak, *Casuarina glauca*) based on the measured most important technological properties of wood estimated in this study is presented in **Table (6).** The results indicated that *Poplulus nigra* showed the poorest rating value (3.78) with the last one order followed, while American beech (*Fagus sylvatica*) showed a preferable order (1.56) with the first one order followed by the *Casuarina glauca* (2.44) and *Pinus sylvestris* (2.78) and *Populous nigra* (3.78). On the basis of their wood quality and rating, the five wood species in the current study including paulownia wood showed the following order: *Fagus sylvatica* > *Casuarina glauca* > *Pinus sylvestris* > *Paulownia tomentosa* > *Populus nigra*. This order was done, in general, from the view of point of the properties determined the wood quality and may be change in certain uses, for example the most preferable wood species for flooring is *F. sylvatica* followed by *C. glauca* and *P. sylvetris* and *P. nigra* and *P. tomentosa* according to hardness strength. These results showed that the quality of *paulownia* wood is not the worst among the local and imported species used in this study. *Paulownia* wood can be a substitute for poplar wood, but it cannot be a substitute for American beech, European redwood or Casuarina wood in Egypt.

Table (7). Rating of *paulownia* wood among five wood species regarding the most important technological properties determined in the current study.

Technological property	This study *P. tomentosa*	*P. nigra*	*C. glauca*	*F. sylvatica*	*P. sylvetris*
Wood density	5	4	1	2	3
Cellulose content	2	3	4	1	5
Lignin content	2	4	3	1	5
Ash content	3	5	4	2	1
Bending strength, MOR	5	4	2	1	3
Crushing strength, C_{max}	4	3	1	1	2
JHN in radial	5	4	1	2	3
JHN in tangential	4	3	1	1	2
Static quality wood	2	4	5	3	1
Rating value	**3.56**	**3.78**	**2.44**	**1.56**	**2.78**
Rating order	**4**	**5**	**2**	**1**	**3**

CONCLUSIONS

The objective of the study was to determine the quality of paulownia wood produced from *paulownia* trees grown under Egyptian conditions and to suggest the most important uses of wood to provide technical information to decision makers for expand the cultivation of paulownia trees in Egypt. *Paulownia* can be used to produce non-decorative veneers, and it is not a substitute for beech which produces decorative veneers, with cutting cycle 10 years at least. Among the uses in which *paulownia* wood can be used for the manufacture of packing boxes, some pieces of furniture that are not subject to loads, the manufacture of block board, the production of utility veneers used for plywood, aircraft, surfboards, match, drawing tools and knickknack.

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الملخص العربي

قياس جودة خشب البولونيا (*Paulownia tomentosa*)المحصودة في غرب الدلتا بمصر للاستفادة منها بفاعلية في التشجير

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هدفت هذه الدراسة إلى دراسة خصائص مختلفة لخشب شجرة البولونيا (*Paulownia tomentosa*) لتمكين صانعي القرار في مصر من الاستفادة من هذه المعلومات لاتخاذ قرارات فعّالة بشأن مشاريع التشجير. جُمعت أشجار البولونيا، بمتوسط عمر 7 سنوات، في غرب الدلتا، مصر (30°16'14.94' شمالًا 30°52'6.85" شرقًا) للتجارب. واختُبرت خصائص أنواع مختلفة من الأشجار المستوردة والمحلية، بما في ذلك الزان (*Fagus sylvatica*) والصنوبر الاسكتلندي (*Pinus sylvestris*)، والبلوط الأبيض (*Casuarina glauca*)، والحور الأسود (*Populus nigra*)، لأغراض المقارنة. وقُيّمت الخصائص الفيزيائية والكيميائية والميكانيكية للعينات وفقًا للمعايير الدولية. أظهرت النتائج أن خشب الباولونيا يتميز بكثافة منخفضة تبلغ 266 كجم/م^3، مع انكماش حجمي كلي بنسبة 8.78%، ومحتوى من السليلوز والهيميسليلوز بنسبة 51.2 % و25.2% على التوالي. ويبدو أن عينات الباولونيا تتميز بخصائص ميكانيكية منخفضة نسبيًا في مقاومة الانحناء (49.8 ميجا باسكال)، ومقاومة الضغط (21.6 ميجا باسكال). وبلغت قيم صلابة جانكا للعينات 1.08% و1.33% في اتجاهي الحبيبات الشعاعي والمماسي، على التوالي. وبناءً على نتائج هذا العمل، يبدو أن خشب الباولونيا يتمتع بإمكانيات كبيرة، بخصائص مقبولة، لاستخدامه في تطبيقات مختلفة، بالإضافة إلى إمكاناته الكبيرة في مجال التشجير في مصر.