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A study of selected features of Shan Tong variety of plantation paulownia and its wood properties

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Abstract: *A study of selected features of Shan Tong variety of plantation paulownia and its wood properties*. The study was conducted on three-year-old and representative paulownia tree of the Shan Tong variety, from a plantation in the Kujawsko-Pomorskie Voivodeship, Poland. The three-year-old paulownia tree was 4.2 m high and its diameter at butt level was of 11 cm. The tree provided material for the study from its three-year-old shoot, which was divided into three parts: leaves, branches and the main trunk. According to calculations, this typical paulownia tree (a three-year-old shoot) from a plantation accumulated 4.664 kg of carbon in the part above the ground level, which corresponds to the absorption of 17.101 kg of CO_2 from the atmosphere. Taking into account the underground part of this plant, it can be estimated that it absorbed over 30 kg of CO_2 (on average, ca. 10 kg CO_2 per year). The density of paulownia wood in absolute dry state was ca. 250 kg/m^3. The width of annual growth rings was ca. 1.5 cm. This kind of wood is highly porous, with porosity of about 85% (good thermal insulation), and at the same time it has favourable resistance properties characterized by the modulus of elasticity of 4.05 GPa.

Key words: annual growth rings, biomass, carbon accumulation, CO_2, density, modulus of elasticity, paulownia, plantation, porosity

INTRODUCTION

Wood plantations are becoming more and more important as an alternative for typical commercial forest stands, and even more so for natural forests, as a source of the much-needed wood biomass (West 2014). Paulownia is one of the kinds of cultivated trees with short rotation time, and with a remarkable capacity to adjust to different climate conditions.

The *Paulownia* genus contains over a dozen species of trees that grow naturally in warmer regions of Asia, mostly in China, as well as in Laos and Vietnam (Icka et al. 2016). Nowadays, they are grown in plantations in many other locations, and they have been crossbred, creating several inter-species hybrids whose growth dynamics is even greater. In Poland, the main varieties that are cultivated are “Oxytree”, “Shan Tong” and “Cotta Vista 2”. The fast growth of paulownia and the resulting high absorption of carbon dioxide from the air constitute an additional advantage.

Thanks to its low density, paulownia wood can be easily processed, both manually and mechanically. Dry wood does not generate any specific smell during processing. The drying process itself is fast and easy, without any major risks of cracking or deformations. After hydro-thermal processing, paulownia wood can be easily cut and bent. It can also be easily connected with the use of nails and screws, glued and finished with paints and lacquers (Kozakiewicz 2013).

Studies have confirmed the usefulness of plantation-grown paulownia for cellulose/paper production (Ashori and Nourbakhsh 2009, Akyildiz and Sahin Kol 2010) and also for power generation (López et al. 2012, Yanorov et al. 2014). Similar conclusions have been drawn by the authors of a meta-analysis of publications on the possibility of cultivation and application of paulownia (Jakubowski et al. 2018). A limitation of the use of paulownia wood grown in short rotation cycles lies in its dimensions, which do not allow for the production of full-sized sawn timber and, consequently, the production of solid wood elements.

Nonetheless, studies on the properties of this juvenile wood are being performed in many different centres (Kaymakci et al. 2013, Kozakiewicz 2013, Vilotić et al. 2015, San et. al. 2016, Koman and Feher 2017, Lachowicz and Giedrowicz 2020). The authors point out the characteristic low density of paulownia wood and its potential applications. Starting from the production of small wooden objects of daily use (wooden accessories) such as pencils (Kaygin et al. 2015), the production of various kinds of wooden materials (Kozakiewicz 2013), as well as packaging and materials for thermal and acoustic insulation (Kozakiewicz 2013, Lachowicz and Giedrowicz. 2020).

It should be pointed out that the wood of older paulownia trees (about fifteen years old) can be used to manufacture furniture and elements of door and window carpentry. Specific applications of paulownia wood include sculptures (easy processing) and musical instruments. An example of this application is koto, a traditional Japanese instrument. This is due to the good acoustic properties of paulownia, related to its low ultrasound wave resistance and high damping of ultrasound radiation (Kozakiewicz 2013).

The purpose of the conducted research is to specify the dendrometric characteristics and other selected properties of the Shan Tong variety of paulownia, and to assess its capacity to absorb the atmospheric CO_2.

MATERIAL AND METHOD

The tree chosen for the study is a typical (representative) individual (Figure 1) acquired in September 2019 from a plantation in the Pilewice locality, the municipality of Stolno, Powiat Chełmiński, Kujawsko-Pomorskie Voivodeship. The plantation is located on slightly undulating terrain composed of poor, sandy soils, and equipped with an artificial irrigation system. It has been established in a place of the former crushed stone pit used for the needs of the A1 highway construction.

Figure 1. Paulownia tree selected for analysis (September 2019 – shortly before logging)

The plantation was created in 2016. One-year-old paulownia saplings obtained with laboratory methods from the Shan Tong variety were planted in July 2016. After one year of growth, in spring 2017, their shoots were removed to strengthen the root system. The growth of new shoots started from the root collar and lasted for three vegetative seasons (2017, 2018 and 2019).

The part acquired for research was the shoot (the part above the ground) of a three-year-old tree. It was roughly divided into three parts: leaves, branches and the main trunk (Figure 2). The accumulation of atmospheric carbon dioxide was calculated according to the methodology described in the EN 16449:2014 standard.

After drying, the main stem was cut into cuboid samples for testing. The longitudinal samples were cut in line with the main anatomical sections, with the cross-section dimensions of 20x20 mm and length of 300 mm (the last dimension parallel to the grain). According to the pertinent standards, the following properties of wood were determined: moisture content (according to ISO 13061-1:2014), density, porosity (according to ISO 13061-2:2014) and annual growth rings (according to EN 1309-3:2018), but the rings were considered on the entire trunk radius, from the circumference to the pith.

Figure 2. The research material divided into three parts: leaves, branches and the main trunk

Selected acoustic properties were determined using the ultrasounds method, with the help of a UMT-1 material tester. On the basis of previous research (Kozakiewicz 2002, Hadinata and Kozakiewicz 2020), appropriate settings of the device (40 kHz frequency, 40 dB gain, repulsion of 12Hz at pulse mode and coupling substance in the form of polyacrylic gel) were adjusted. After running ultrasound waves parallel to the grain, the time of the main echo was read and some acoustic properties of wood were calculate using the following formulas:

$$c_{||} = \frac{L}{t} \tag{1}$$

where: c – velocity of the longitudinal ultrasound waves parallel to the grain [m/s]
L – sample length [m] (assuming that $L > \lambda$)

t = real time of the passing through of the longitudinal wave [s]

$$MOE_d = 0.74286 \cdot c_{\parallel}^2 \cdot d \tag{2}$$

where: MOE_d – dynamic modulus of elasticity parallel to the grain [GPa]
0.74286 – reduced Poisson's ratio for wood
d – density of wood of a known moisture content [kg/m^3]

$$T = \frac{5 \cdot 10^{-8} \cdot c}{g} = \frac{5 \cdot 10^{-8} \sqrt{\frac{E}{g}}}{g} \tag{3}$$

where: T – damping of ultrasound radiation

$$Z = g \cdot c = g \cdot \sqrt{\frac{E}{g}} = \sqrt{g \cdot E} \tag{4}$$

where: Z – ultrasound wave resistant

RESULTS AND DISCUSSION

The three-year-old shoot (paulownia tree) was 4.2 m high and its diameter at butt level was 11 cm. There were over 350 leaves on the tree. In wet state (immediately after logging) the trunk mass was over 11 kg, the mass of the branches to 2.4 kg and the leaves over 4 kg. The total wet mass of the shoot amounted to 17.678 kg. The percentual share has been presented in Figure 3a. The material was dried until achieving the absolute dry state, and later it was weighted again. On this basis, the initial moisture (water content) was determined, which in case of the leaves was over 300%, 100% for branches, and 55% for the main trunk with a dominant share of wood,. After drying to 0%, the percentual share of each element changed significantly. The share of the trunk increased a lot, while the mass share of leaves was significantly reduced (Figure 3b). The total dry mass of the shoot amounted to 9.328 kg.

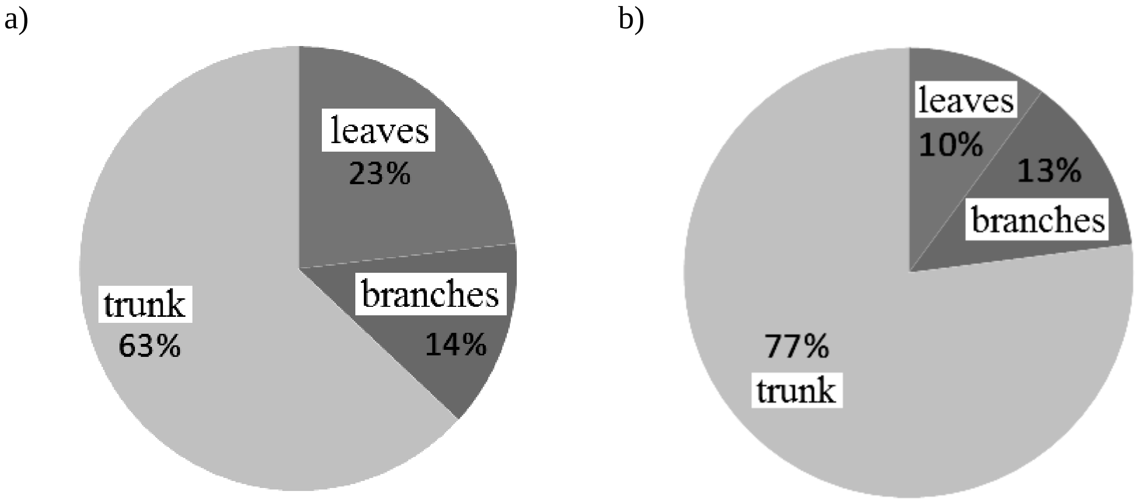

Figure 3. Percentual mass share of each part of the paulownia tree shoot: a) in wet state (green), b) in absolute dry state (after drying)

According to the indications included in the PN 16449:2014 standard, it was assumed that carbon corresponds to 50% of the tree in the absolute dry state. Similar proportions were assumed for the remaining kinds of tissue: leaves, phloem and bark. Therefore, the content of elemental carbon in the shoot was estimated to be 4.664 kg. On the basis of the estimated mass of elemental carbon in the (absolute dry) biomass of the shoot, the amount of carbon dioxide absorbed from the atmosphere by the paulownia tree during its three vegetative seasons was calculated according to EN 16449:2014. The result was 17.101 kg of CO_2. The actual amount of the absorbed CO_2 is much higher. We can assume that the mass of the underground part (the extensive root system) is similar to the mass of the shoot. Therefore, the amount of the absorbed carbon dioxide should be doubled, and a careful estimation would be 30 kg of CO_2 per year, which translates into about 10 kg of CO_2 absorbed every year (during each vegetative season). The quoted average value is lower during the first two years of tree growth. With age, paulownia trees grow dynamically and absorb more CO_2 from the atmosphere (multiplied photosynthesis processes in a growing assimilation apparatus of the tree).

On the basis of data related to the typical dimensions of different tree species depending on their age (Jaworski 2004) and data concerning the density of the acquired wood (Wagenführ 2007) (and, at the same time, a similar amount of accumulated biomass), the amount of CO_2 absorbed from the atmosphere can be roughly estimated. A quickly growing, individual paulownia tree, during the first three years of its growth, can absorb the same amount of CO_2 from the atmosphere as a tree of Scots pine or European beech after they have been growing for 15-20 years.

Figure 4. Cross-section of the paulownia trunk in the butt part

At the base, the trunk was not perfectly circular (Figure 4), but 0.5 m higher it already had a regular, cylindrical shape. The empty pith present in the middle of the trunk was over 15 mm in diameter, and the width of annual growth rings was, on average, 13.3 (±1,9) mm. The tree under research produced juvenile wood, in only the first three rings around the pith. The density of paulownia wood in wet state, that is ca. 60% moisture content, was 386 kg/m^3 on average, with a low coefficient of variation of 5.4%, which confirms that this characteristic is quite stable in the trunk under research. The average speed of ultrasounds wave through paulownia wood parallel to the grain was 3850 m/s, while the modulus of elasticity was 4.05 GPa. In the absolute dry state (with moisture content of 0%) the density of paulownia wood was 246 (±13) kg/m^3.

The volume of wood can be expressed as the sum of volume occupied by cell walls (the wood substance) plus the volume occupied by empty spaces (pores). On the basis of calculations in absolute dry state, and on the basis of the proportions described in reference literature (Bowyer et al. 2007, Shukla and Kamdem 2010), the wood porosity was determined to be as much as 84%. This means that almost 85% of paulownia wood in absolute dry state is made up of air. Such highly porous material has good thermal insulation properties.

The analyses that were carried out also confirm a favourable relation between the mechanical properties and density of paulownia wood (Kozakiewicz 2013). Some time ago it was even considered as a raw material that could potentially be used in the aviation industry (Wanin 1953).

The analysed juvenile paulownia wood was characterised by high damping of ultrasound radiation equal to 52.4×10^{-8} $m^4/s{\cdot}kg$ and low ultrasound wave resistance at the level of 1416 kN s/m^3, which confirms its usefulness as a material for the production of musical instruments (Kozakiewicz 2013). Thanks to its above-mentioned properties, Paulownia wood can be used in the cores of skis snowboards and surfboards, as well as elements of table tennis paddles.

CONCLUSIONS

Based on the selected features and properties of paulownia plantation wood, the following conclusions have been drawn:

1. A typical paulownia tree (three-year-old shoot) of the Shan Tong variety from a plantation located in the Pilewice locality, Stolno municipality, Powiat Chełmiński, Kujawsko-Pomorskie Voivodeship, accumulated 4.664 kg of carbon in its shoot (part above the ground), which corresponds to the absorption of 17.101 kg of CO_2 from the atmosphere. Taking into account the underground part of this plant, it can be estimated that it absorbed over 30 kg of CO_2 (on average, ca. 10 kg CO_2 per year).
2. Plantation-grown paulownia wood has absolute dry state density of about 250 kg/m^3 and extremely wide annual growth rings, with an average width of almost 1.5 cm. This kind of wood is highly porous, with porosity of about 85% (good thermal insulation), while also having favourable mechanical properties characterized by the modulus of elasticity of 4.05 GPa. Moreover, it has favourable acoustic properties indicating that it is a good material to be used in the production of musical instruments.
3. The analyses of paulownia wood properties clearly indicate that this material has important potential and many possible applications. The main limitation for three-year-old trunks lies in their dimensions, which are still too small to obtain full-sized sawn timber that could be used in carpentry (this limitation gradually disappears in trees that are more than 10 years old).

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Streszczenie: *Badanie wybranych cech paulowni odmiany Shan Tong i właściwości drewna.* Plantacje szybko rosnących drzew uprawianych w krótkim cyklu zyskują na znaczeniu również w Polsce. Do badań pozyskano typowe drzewo paulowni (trzyletni odrost) odmiany Shan Tong z uprawy plantacyjnej w miejscowości Pilewice w woj. kujawsko-pomorskim. Drzewo to zakumulowało w części nadziemnej, w ciągu trzech lat wzrostu ponad 4,6 kg węgla, co odpowiada pochłonięciu ponad 17 tysięcy kg CO_2 z atmosfery. Przeprowadzone analizy cech drewna paulowni jednoznacznie wskazują, że jest to materiał o znaczącym potencjale i możliwych zastosowaniach. Plantacyjne drewno juwenilne paulowni charakteryzuje się gęstością wynoszącą w stanie absolutnie suchym około 250 kg/m^3 i wybitnie szerokimi przyrostami rocznymi o średniej szerokości wynoszącej prawie 1,5 cm. Jest to drewno o wysokiej porowatości rzędu 85% (dobrej izolacyjności termicznej), a przy tym o korzystnych, jak na niską gęstość, cechach wytrzymałościowych charakteryzowanych przez moduł sprężystości równy 4,05 GPa. Drewno to wykazuje też korzystne cechy akustyczne, predestynujące do użycia w instrumentach muzycznych. Ograniczeniem w potencjalnym zastosowaniu jest przede wszystkim nadal niewielka średnica trzyletniego pnia. Ograniczenie to, zakładając utrzymującą się dynamikę przyrostową na grubość, powinno zaniknąć po kilkunastu latach uprawy.

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