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Assessment of Physical and Mechanical Properties Considering the Stem Height and Cross-Section of *Paulownia tomentosa* (Thunb.) Steud. *x elongata* (S.Y.Hu) Wood

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Abstract: The aim of this study is to analyze the properties of *Paulownia tomentosa x elongata* plantation wood from Serbia, considering the influence of the stem height (0 to 1 m and 4.5 to 6 m above soil level—height spot) and radial position from the pith to bark (in the core, near the bark, and in between these zones—cross-section spot). The results show that most properties are improved when the samples were taken from upper parts of the tree (height spot) and from the near bark spot (cross-section spot). The mean density measured 275 kg/m^3 at the stem height between 4.5–6 m and 245 kg/m^3 for the samples collected from 0–1 m trunk height. The density had the highest value on the spot near bark (290 kg/m^3), for the mature wood at a height of 4.5–6 m, and near pith had a mean density of 230 kg/m^3. The Brinell hardness exhibited highest values in the axial direction (23 N/mm^2) and near bark (28 N/mm^2). The bending strength was 41 N/mm^2 for the trunk's height range of 4.5–6 m and 45 N/mm^2 in the cross-section, close to cambium. The three-point modulus of elasticity (MOR) of the samples taken at a stem height of 4.5 to 6 m was up to 5000 N/mm^2, and on the spot near bark, the MOR measured 5250 N/mm^2. Regarding compressive strength, in the cross-section, near the pith, the mean value was the highest with 23 N/mm^2 (4.5–6 m), whilst it was 19 N/mm^2 near bark. The tensile strength was, on average, 40 N/mm^2 for both 0–1 m and 4.5–6 m trunk height levels and 49 N/mm^2 between bark and pith. The screw withdrawal resistance measured 58 N/mm for the samples extracted at a stem height of 4.5 to 6 m and 92 N/mm for the specimens collected near pith. This study stresses the influence, in short-rotation Paulownia timber, of indicators, such as juvenile and mature wood (difference emphasized after the fifth year of growth) and height variation, on the physical and mechanical properties of sawn wood. This study will help utilize more efficient sustainable resources, such as Paulownia plantation wood. This fast-growing hardwood species from Europe is adequate as a core material in sandwich applications for furniture, transport, sport articles, and lightweight composites, being considered the European Balsa.

Keywords: Paulownia; wood properties; position in stem; plantation wood; Balsa

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1. Introduction

Paulownia is a fast growing tree that originates in Asia, having at least nine species within the family [1]; *Paulownia tomentosa* (Thunb.), *Paulownia elongata* (S. Y. Hu), and *Paulownia fortunei* (Seem.) Hemsl. are intensely used and studied [2–4]. Paulownia hybrids can combine, for example, *Paulownia tomentosa x elongata* [5] or *Paulownia elongata x Paulownia fortunei* [6,7]. In Europe, the most studied clones are Paulownia in vitro 112—Oxytree [1,8,9], BIO 125 [10], or Cotevisa 2 [11].

In the last decades, interest for agroforestry plantations of Paulownia for industrial use has risen in Europe. As a result, the ecological footprint of Paulownia lumber from Asia is diminished due to elimination of oversea transport costs. Paulownia plantations contribute to the scaling down of soil hazards by tree intercropping in farmlands [7] and crop fields. For example, when intercropped with wheat, the production rate was increased, similar to the increase in ginger production [12]. It is recommended to intercrop Paulownia with winter crops and vegetables, considering that the trees in the dormant season will not compete for water and nutrients during the cold season [13]. Paulownia protects systems against erosion, flooding, or wind damages [14], reduces soil degradation (by absorbing heavy metals), diminishes air pollution (by cleaning the air of harmful gases due to its huge leaves), and improves the microclimate [15].

Paulownia's bark is commonly processed with its wood because the bark is thin, difficult to remove, and accounts for less than 1% of the overall volume [16].

This species arrived in Europe over a century ago as a decorative tree. Paulownia and its hybrids were naturalized in Europe after an adjustment process dependent on climatic zones and soils. Literature on the properties of Paulownia wood sourced from European plantations is in continuous development, yet still scarce [1], considering that studies on its properties commenced a decade ago on the old continent [7].

This tree is renowned due to it being fast growing with a low density of 260 to 300 kg/m^3 [5], gaining in the last period the nickname of "European Balsa" [3] or the aluminum of wood. The density correlates sharply with other physical and mechanical properties and influences the woodworking and drying processes. The maximum moisture content of this wood species measures 350% [17]; therefore, kiln-drying schedules should be attentively selected and controlled. Paulownia air-dried wood is normally without drying defects [18].

The fiber saturation point is 31.15% for *Paulownia fortune* and 29% for *Paulownia tomentosa*. The chemical composition of the cell wall is as follows: 51% cellulose, 30% hemicellulose, 23.5% lignin, and 11.8% extractives [17]. Depending on the species, the porosity of Paulownia ranges between 75 and 88% [19].

Since the end of the last century, several countries, such as Austria, Italy, France, Serbia, Spain, Romania, Bulgaria, Hungary, Israel, and Ukraine, are experimenting with Paulownia plantations [4,7,20]. Paulownia was gradually introduced in South America (Argentina, Brazil, Paraguay) and Australia and is used for timber production [2]. Paulownia exhibits facile processability [21], acceptable fire resistance, and high rate of carbon absorption [22]. Magar et al. [12] calculated a rate of 33 t CO_2 per hectare per year for Paulownia. Paulownia implemented in agroforestry systems can help to reduce the greenhouse emissions in cities and neighborhoods of farmhouses, highlighting the carbon storage potential, which is about 50 fold, 30 fold, and 20 fold higher compared to oak, beech, and lime trees, respectively [23], and at least 10 times more than any other tree species [24].

An adult Paulownia tree has a trunk of 10 to 20 m, with an increment of about 3 m/year and a 40 cm diameter [25]. Harvesting of 15-year-old Paulownia trees from plantations with about 2000 trees per hectare results in valuable timber [26]. Paulownia wood is used for furniture construction [26], packaging, plywood, solid wood products (single-layered), and pulp production [27]. The increased content of holo-cellulose (81%) determines a higher pulp yield and acceptable strength properties [17]. Paulownia wood is also interesting because it does not crack or warp and is not susceptible to decay [28]. It is light-colored, soft, easy to carve, dimensionally stable, generally knot free and straight-grained [18], uniform texture, and clear after plaining [4]. The absence of knots and fibers that run parallel to the longitudinal axes are due to appropriate Paulownia plantation management, considering the orientation (southern facing exposure with wind protection) and well-drained soil (pH-value of 5–8). The tree should be irrigated until the root system is robust [29]. The Paulownia is a light-loving tree and even slight shade can cause deformation in saplings. At 70% shade, the younger trees can be completely damaged. Paulownia trees are coppiced (the sapling is cut back to ground level, to determine the formation of a new shoot) during the second year of life (technical cut, maintaining 2 cm of plant) [30]. Only the best buds will be selected to fully grow [29]. When the saplings are 2 or 3 years old, the pruning should be done during the growing season, when new branches develop. The purpose of the pruning is to raise the value of the timber by gaining much cleaner roundwood (without knots). Unnecessary lateral branches should be removed; the branches of the crown, however, should not be cut during the year of their emergence, since they will constitute the sympodial monochasium of the trunk [29]. The condition is to keep the first 6–7 m of the stem clear of branches (75%) for a stem height of 7–8 m; after this height, the canopy can be allowed to reach its natural shape [30].

Lower quality Paulownia trunks can serve as raw materials for biomass and biofuels [5], with potential for second generation bioethanol production [31]. The phenolic compounds in Paulownia have antioxidant properties; therefore, can be used for medical purposes [12]. In Asia, different elements as leaves, flowers, fruits, and barks were used for centuries and served as traditional medicines [31].

Paulownia could be considered invasive according to [3,32,33]. Invasive tree species are able to survive, to reproduce, and to spread over the landscape, sometimes at disturbing quotes [34], aggressively competing with native plants. As reported by [35], the spreading of this tree species can be considered as high or wide-ranging. Paulownia is not included in the updated list of invasive alien species of the European Union [36].

To analyze the potential of Paulownia timber, is important to scrutinize the properties of the length and cross-section of the tree stem. In this way, the influence of juvenile and mature wood on the physical and mechanical properties of Paulownia plantation wood can be studies. In most species, juvenile wood has a low density [37], not only in plantation, but also in naturally grown trees. This can be attributed to the shorter tracheids (for softwood) and fibers (for hardwood) with thinner cell walls. Transverse shrinkage is lower in a vast majority of wood species. Juvenile wood has a significantly lower modulus of rupture, modulus of elasticity, and reduced compressive and tensile strength [37]. Wood properties of short-rotation plantation Paulownia trees can be controlled competently through forest management. In general, the longer the rotation age, the more mature wood is harvested; therefore, the better the mechanical properties for productive purposes. Estevez et al. [6] estimated a minimum of 5 years for felling of Paulownia for its use as solid fuel (pellets) and as solid wood

This research is a follow-up study of [5]. The aim of this study is to assess the properties of *Paulownia tomentosa x elongata* plantation wood from Serbia, cut from different trunk heights, namely 0–1 m and 4.5–6 m, and from three cross-section sites (near to bark, near to the pith, and in between.

2. Materials and Methods

The raw material was provided by Glendor Holding GmbH Company (Kilb, Austria) from a Paulownia plantation in Serbia (Figure 1). It consisted of two *Paulownia tomentosa x elongata* trees (7 years old) cut at different stem heights (0–1 m and 4.5–6 m), resulting in 4 logs (Figure 2).

The logs were labelled 1–4, with log 1 and 2 belonging to the first tree and log 3 and 4 to the second tree (Figure 2).

The logs 1 to 4 were processed to sawn wood (Figure 3). Stem 1 and 3 were extracted, at 0–1 m height, arising from the ground. Stem 2 and 4 were cut from the tree trunk at a height of 4.5–6 m (Figure 4). These two stem height levels were chosen due to log cleanliness and knots-free areas without growth defects.

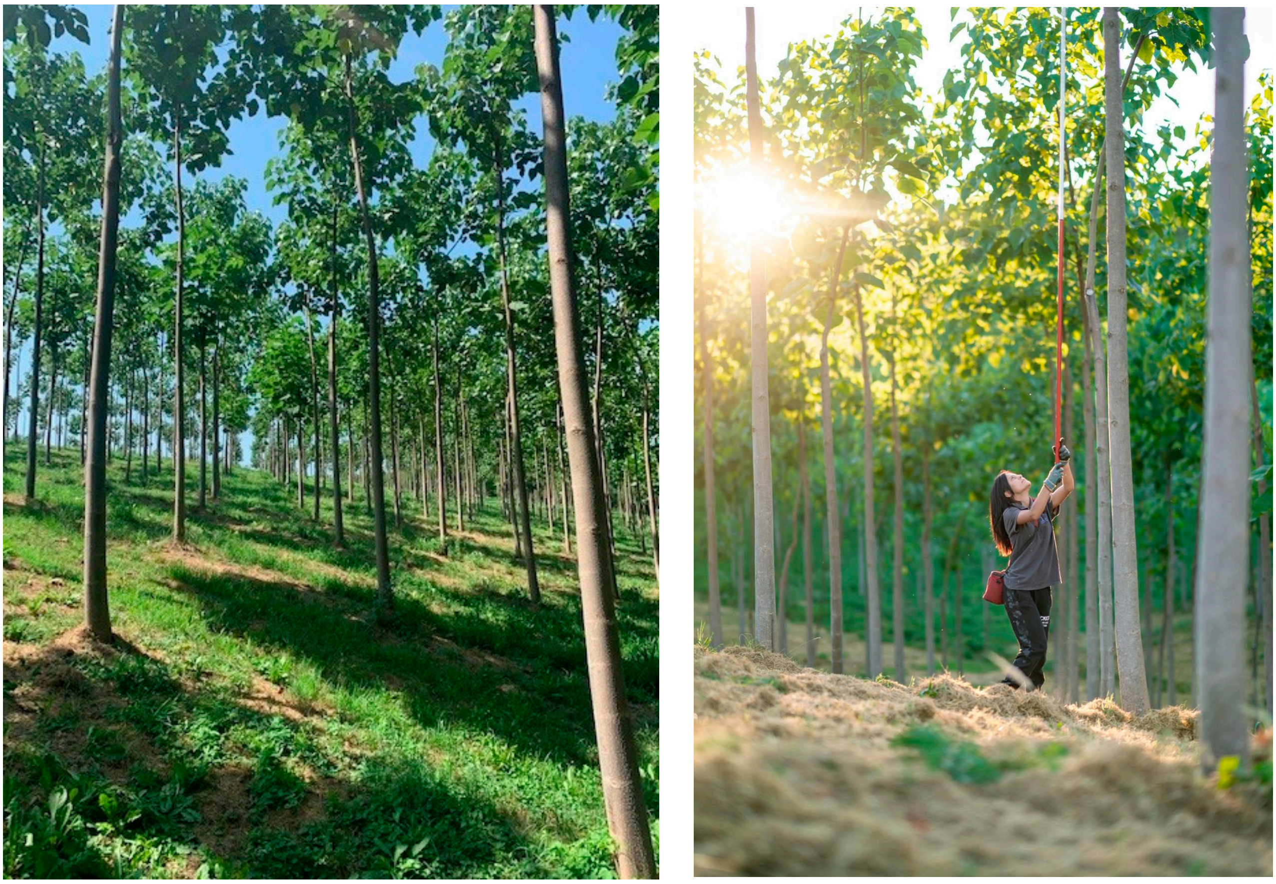

Figure 1. Paulownia plantation managed by Glendor GmbH with 7-year-old trees.

Figure 2. Four Paulownia logs extracted from two trees at different heights (0–1 m, 4.5–6 m).

Figure 3. Marking of Paulownia sawn wood in the cross-section prior to the preparation of testing specimens.

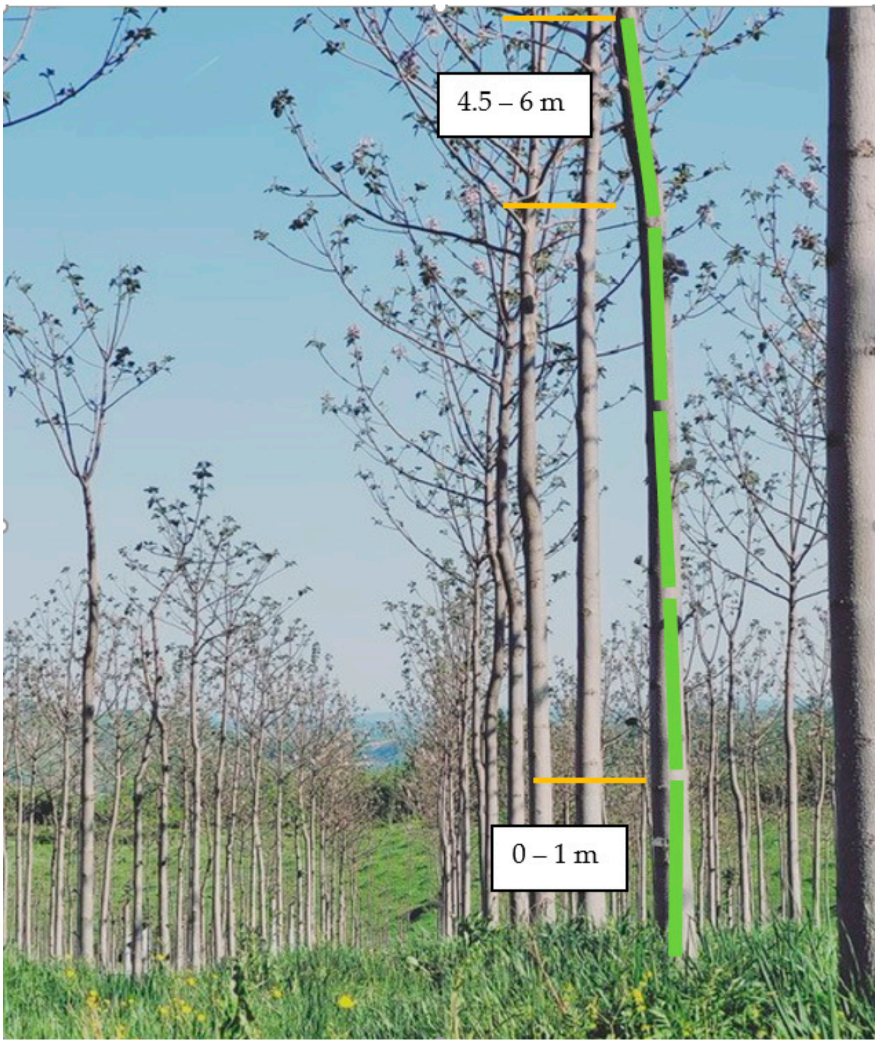

Figure 4. Two spots on the Paulownia stem (0–1 m and 4.5–6 m) selected after harvesting for the research investigation.

The diameters of the four logs and cutting direction (parallel and perpendicular to the grain) are presented in Table 1.

Table 1. Diameters of Paulownia logs depending on stem height.

Log (Extraction Position)	Diameter (cm)
1 (0–1 m) (cut parallel to the grain)	32
2 (4.5–6 m) (cut parallel to the grain)	27.5
3 (0–1 m) (perpendicular to the grain)	26
4 (4.5–6 m) (perpendicular to the grain)	21

The sawn wood extracted from stems was labelled using letters from A to F (Figure 3). The codification used to characterize the position in the cross-section was K—assigned for the core area, A—assigned for the outer area, and M—assigned for the middle area between the core and outer area (Figures 3–5). Determination of the properties within the cross-section was carried out at the low and high height levels and the mean value was calculated. The samples were extracted from the cross-section from sawn boards, eliminating the spots with pith, and were divided equally for the spots representing the core, middle, and edge. The results are shown in Figure 5. The samples were straight grained and generally knot free.

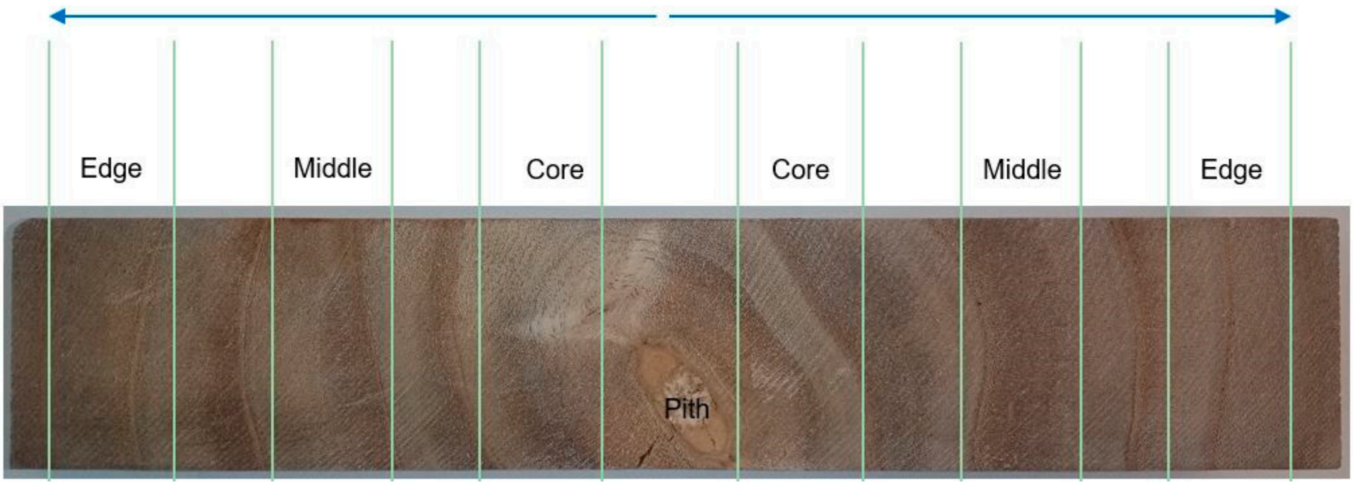

Figure 5. Radial areas from the pith to margins (core, middle, and edge) for the extraction of the samples.

Prior to testing, the raw material was conditioned at 20 °C and 65% relative air humidity for at least 30 days, until a constant mass was achieved. The moisture content after conditioning was 12%.

Several tests were carried out according to EN, ISO, and DIN norms to determine the physical and mechanical properties of Paulownia plantation wood from Serbia (Table 2), differentiated through the position in trunk and in the cross-section. The mechanical properties were tested with the Zwick Roell 250 universal testing machine (Ulm, Germany) and Emco Test Automatic (Hallein, Austria).

Table 2. Test preparation for Paulownia wood samples: norms, dimensions, and number of testing specimens.

Test	Norm	Number of Samples	Sample Dimension [mm]
Swelling and shrinkage	DIN 52184:1979-05	12	20 × 20 × 10
Bulk density (kg/m^3)	ISO 3131:1996	12	
Brinell hardness (N/mm^2)	EN 1534:2011-01	10	50 × 50 × 10
3-point modulus of elasticity (MOE) (N/mm^2)	DIN 52186:1978-06	12	20 × 20 × 360
3-point modulus of rupture (MOR) (N/mm^2)	DIN 52186:1978-06		
Compressive strength (N/mm^2)	DIN 52185:1976-09	12	20 × 20 × 50
Tensile shear strength (N/mm^2)	DIN 52188:1979-05	16	20 × 6 at predetermined breaking point
Screw withdrawal resistance (N/mm)	EN 320:2011-07	12	50 × 50

3. Results and Discussion

This section presents the results of the tests regarding density, sorption behavior, Brinell hardness, three-point modulus of rupture, three-point modulus of elasticity, compressive strength, tensile shear strength, and screw withdrawal resistance, measured at 0–1 m and at 4.5–6 m in the tree trunk height and also depending on the position in the cross-section (near to bark, in the core near the pith, and in between these two areas).

3.1. Density

Within the same tree, significant variations in density occurred from the bark to the pith, and up the trunk from level ground [38]. Variations in density in the cross-section of the stem are correlated with the amount of juvenile and mature wood [37]. Compared to mature wood, juvenile wood is characterized by a lower density, that increases significantly with new growth rings [4].

The density of Paulownia samples, measured according to ISO 3131:1996 [39], increases at 4.5–6 m (Figure 6). The average value of the bulk density at the basal portion of the stem (0–1 m) measured 245 kg/m^3, and at a height of 4.5–6 m, it was 274 kg/m^3 (30 kg/m^3 difference in density between these height spots). The wood extracted from the upper part of Paulownia stem (4.5–6 m) has a higher bulk density, which can be explained by the longer fiber length and lower microfibril angle. This tendency can be considered atypical, because for most of tree species, the samples extracted from the top part of the tree have lower density and strength properties [38,40].

In the cross-section, the bulk density increases from the core (near pith) to the edge (Figure 7). Near the bark (edge), the density was measured at 289 kg/m^3, in the middle it was 257 kg/m^3, and in the core it was 232 kg/m^3. There is a clear difference between juvenile (pith) and mature wood (near bark), with the former exhibiting a higher density due to longer fibers and considerably thicker cell walls [37]. This progressive increase in bulk density, from 202 kg/m^3 at the first ring (juvenile wood) towards 270 kg/m^3 for the sixth ring (mature wood), was determined by [4], who demonstrated that there is no significant difference in densities between the fifth and sixth rings. This suggests that the wood from the first to fourth rings can be considered juvenile wood, and from the fifth ring it can be considered mature wood. Besides a lower density, juvenile wood has a larger microfibril angle than mature wood [38].

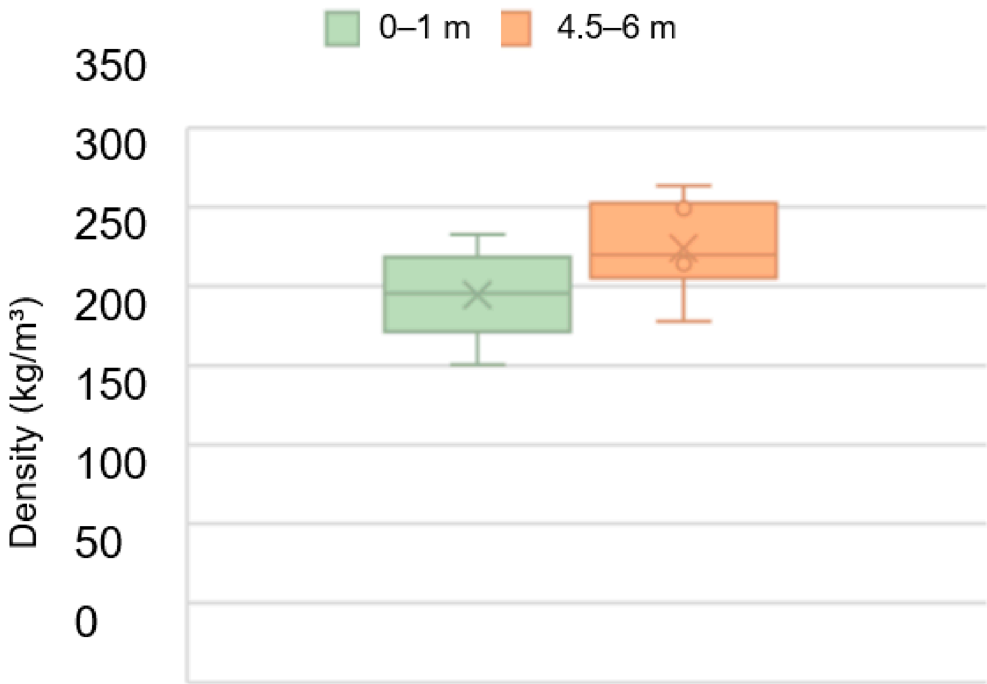

Figure 6. Density of Paulownia samples depending on the position in the tree trunk (0–1 m, 4.5–6 m).

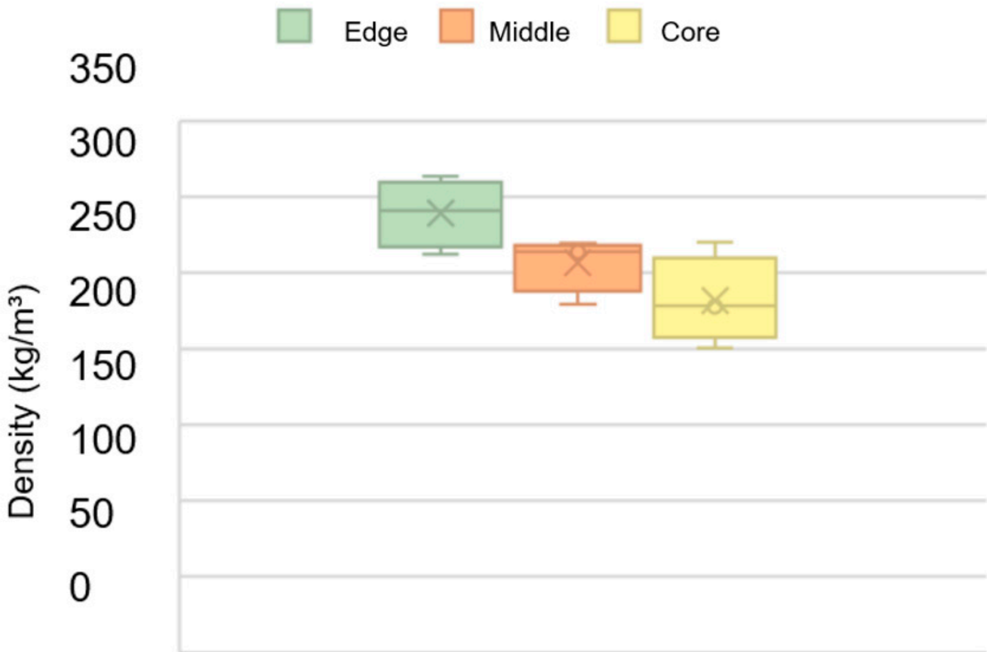

Figure 7. Density of Paulownia samples depending on the position in the cross-section (edge, middle, core).

Similar density ranges, but with no other details about the sample's spot and origin in tree, were reported in the study of Akyldiz and Kol [25], with a mean value of 272 kg/m^3 for the basic species *Paulownia tomentosa* from Turkey. Esteves et al. [6] measured a density of 460 kg/m^3 for Paulownia wood sourced from Portugal, which is way higher than the density of spruce with 430 kg/m^3 according to [41]. The lowest density of 216 kg/m^3 for a Paulownia plantation wood in Spain was reported by [19]. Jakubowski [7] showed that, at a 12% moisture content, Paulownia wood density varies from 220 to 350 kg/m^3, with an average value of 270 kg/m^3. This variability in density is justified by the growth conditions (soil, temperature, climate). Densities higher than 400 kg/m^3 were determined for *Paulownia tomentosa* in Turkey [25] and Portugal [6], and for *Paulownia* Siebold and Zucc. (from Bulgaria) [42].

3.2. Sorption Behavior

Figure 8 shows that the sorption behavior of wood, determined according to DIN 52184:1979 [43], was minimally influenced by the position in the tree stem. The mostly increased swelling was measured in the tangential section. In the axial and radial direction, wood swelling is less, as described by [38].

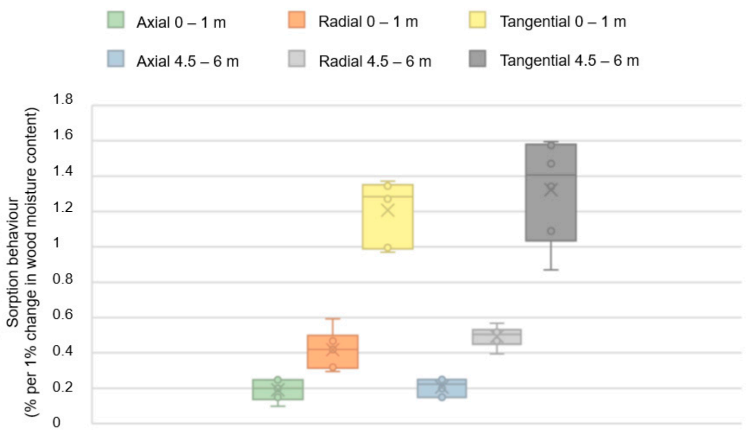

Figure 8. Sorption behavior in the axial, radial, and tangential direction of Paulownia samples extracted at 0–1 m and 4.5–6 m from the tree stem.

From Figure 9, the results show that in the axial direction, the wood swelling was the lowest (0.199%). In the radial direction, the shrinking was higher (0.456%). The differential swelling and shrinkage in the tangential direction was the highest (1.266%), which was also highlighted by [38].

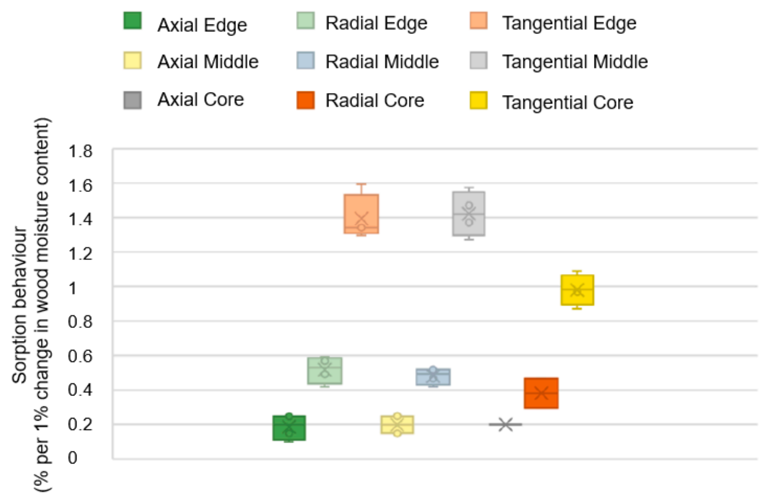

Figure 9. Sorption behavior in the axial, radial, and tangential direction of Paulownia samples extracted from the edge, middle, and from the core of the tree.

The samples seized from the edge of the stem showed very similar shrinkage compared to the samples extracted from the middle area of the cross-section. For example, the samples tested in the axial direction extracted from the edge area measured a shrinkage of 0.186%, whereas the shrinkage of the testing specimens extracted from the middle area was 0.199%. The shrinkage of the samples tested in the tangential direction showed only minimal change.

In the cross-section, an average shrinkage of 1.394% in the edge area, 1.422% in the middle area, and 0.981% in the core area were measured.

Similar values of shrinkage, in all cutting directions, were determined by [4]. For the first and second year rings, the longitudinal shrinkage was under 0.25%, decreasing towards areas with mature wood (fifth and sixth annual ring) to 0.1%. The radial shrinkage had similar mean values in the stem's cross-section. The tangential shrinkage exhibited higher values for the first ring (6%), with a 25% decrease towards mature wood in the sixth ring [4]. These values are consistent with the findings of [17,44,45]. The high microfibril angle of juvenile wood is one of the main parameters that influences shrinkage and shrinkage anisotropy [46].

It is important to emphasize the lower swelling ratios of Paulownia wood, which can be associated to narrower core rays [7]. The medullar rays control the wood in radial direction and determine swelling up to 4% [47]. Moreover, the narrow core rays did not influence higher swelling rates in the tangential direction [5]. It was observed that juvenile wood had the lowest transverse shrinkage, which is consistent to the study of [37]. The swelling and shrinkage behavior of wood is correlated with the bulk density, the proportion of latewood, the anatomical structure, and the lignin amount. The low longitudinal swelling or shrinkage is due to the orientation of the fibrils in the longitudinal direction and the relatively low proportion of cell walls lying transverse to the direction of the fibers [38].

3.3. Brinell Hardness

Brinell hardness (HB) [48] increases with height in all main sections (axial, radial, and tangential) (Figure 10). The HB values were, on average, one third higher for the samples originating from a height of 4.5–6 m of the tree stem, especially in the axial direction. For the samples collected from a height of 0 to 1 m from the stem, the Brinell hardness was 4.16 N/mm^2 in the radial direction, 5.21 N/mm^2 in the tangential direction, and 17.87 N/mm^2 in the axial direction. For the samples extracted from log at the height of 4.5 to 6 m, these values of Brinell hardness increased in the radial direction to 6.98 N/mm^2, in the tangential direction to 6.24 N/mm^2, and in the axial direction to 23.23 N/mm^2. There is a direct correlation between Brinell hardness and density [38].

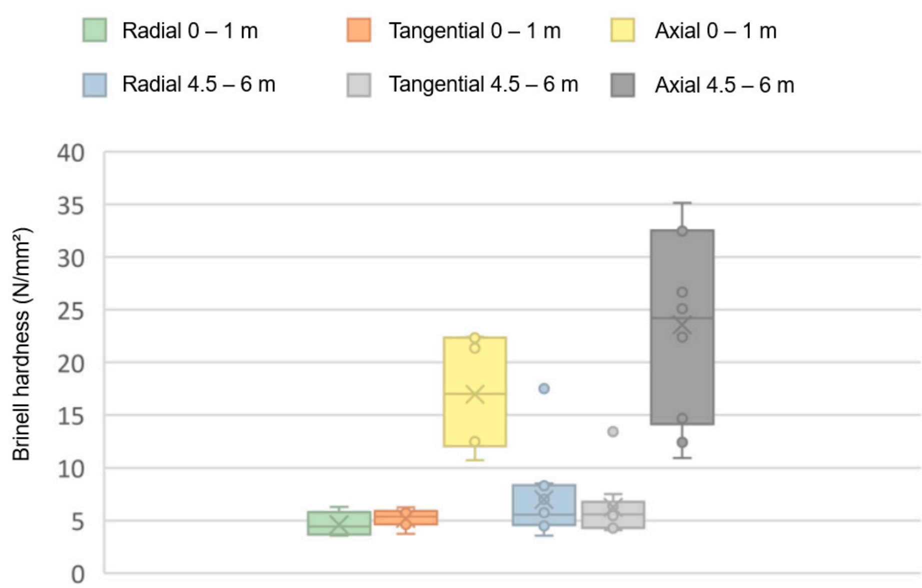

Figure 10. Brinell hardness in the axial, radial, and tangential sections of Paulownia samples extracted at 0–1 m and 4.5–6 m from the tree stem.

By analyzing the tree stem cross-section (Figure 11), Brinell hardness (HB) in the radial direction tended to increase from the seventh to the first growth ring. Near bark, HB in the radial direction was 5.19 N/mm^2 and increased to 7.65 N/mm^2 near the pith.

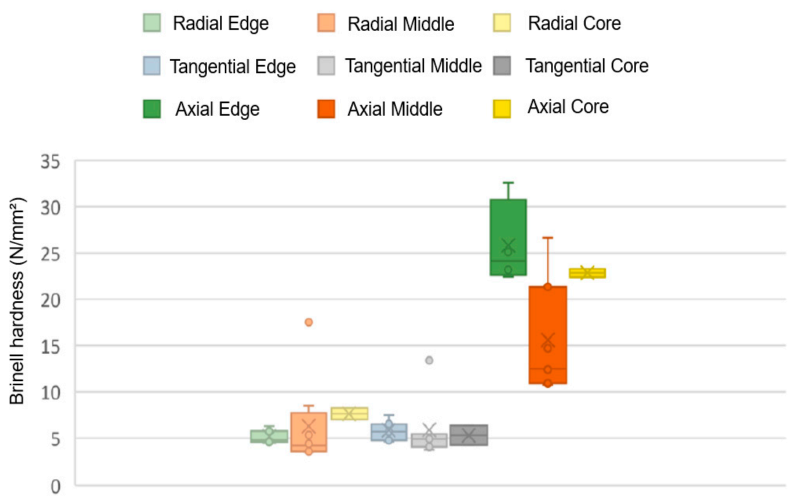

Figure 11. Brinell hardness in the axial, radial, and tangential section of Paulownia samples extracted from 10%, 50%, and 90% from the cross-section of Paulownia's tree stem.

At the seventh growth ring, near the bark, the tangential HB value was 5.87 N/mm^2, and near the pith (first ring), it reached 5.32 N/mm^2, which showed only a slight downward tendency.

The values of the HB in the transversal direction measured a maximum of 27.61 N/mm^2 on the seventh ring. In the middle area (between the third and fourth rings), HB was the lowest at 15.23 N/mm^2. Near the first growth ring, HB was 22.85 N/mm^2.

The low values of Brinell hardness were influenced by the low density of Paulownia wood, determining an increased indentation. Under a load parallel to the direction of the fibers, HB is at least 2.5 fold greater than the hardness in the radial or tangential direction [38]. Brinell hardness of *Paulownia tomentosa x elongata* plantation wood increases from the first to the sixth rings and measures the highest values in the longitudinal direction, as suggested by [4]. In the transversal direction, Paulownia hardness increases at the upper part of the tree stem.

In the axial direction, at a trunk height of 0–1 m, the HB value was similar with the findings of [1,5,25,42], but at a height of 4.5 to 6 m, the maximum of 35 N/mm^2 calculated in the present study had no equivalent in the studied literature. Akyldiz and Kol [25] determined a maximum of longitudinal HB of 19 N/mm^2, 9 N/mm^2 in the tangential, and 8 N/mm^2 in the radial direction. Lower values of HB were determined by [49] as follows: 10.61 N/mm^2 in the longitudinal direction, 5.63 N/mm^3 in the tangential direction, and 5.46 N/mm^2 in the radial direction. A comparison with other studies regarding HB of Paulownia samples extracted from different positions of the stem height is not yet possible considering state of the art of Paulownia short-rotation plantation wood.

3.4. Modulus of Rupture (MOR) and Modulus of Elasticity (MOE)

The three-point MOR, determined according to DIN 52186:1978 [50], exhibits the same tendency as bulk density (3.1): it increases with height (Figure 12) and it is at its highest near the bark (Figure 13). MOR was 33.9 N/mm^2 at a height of 0–1 m and 41.18 N/mm^2 at a height of 4.5–6 m. On the edge (Figure 10), MOR had an average value of 44.78 N/mm^2. In the central area, MOR was 33.44 N/mm^2, and in the core area, it was 31.27 N/mm^2.

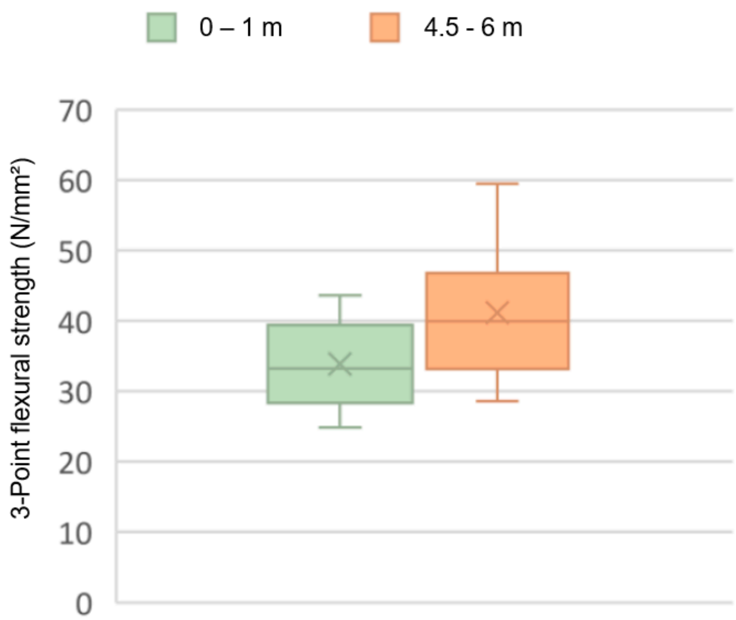

Figure 12. Modulus of rupture of Paulownia samples extracted at 0−1 m and 4.5−6 m from the tree stem.

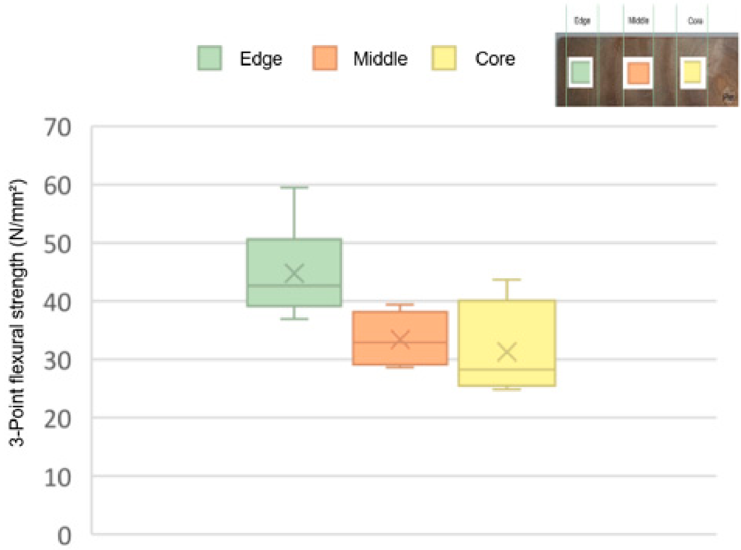

Figure 13. Modulus of rupture in the cross-section of the Paulownia's tree stem.

These MOR values are consistent with the interval of 23.98–43.56 N/mm^2 presented in the review study of [7]. Lachowicz and Giedrowicz [19] reported values from similar up to double at 23.89–53.17 N/mm^2, with an average of 38.63 N/mm^2. Esteves et al. [6] measured a higher three-point flexural strength of 53.5 N/mm^2 for Paulownia plantation wood from Portugal.

In the trunk area of 0–1 m, the MOE was 4123.75 N/mm^2, and at a height of 4.5–6 m, it was 4941.22 N/mm^2 (Figure 14).

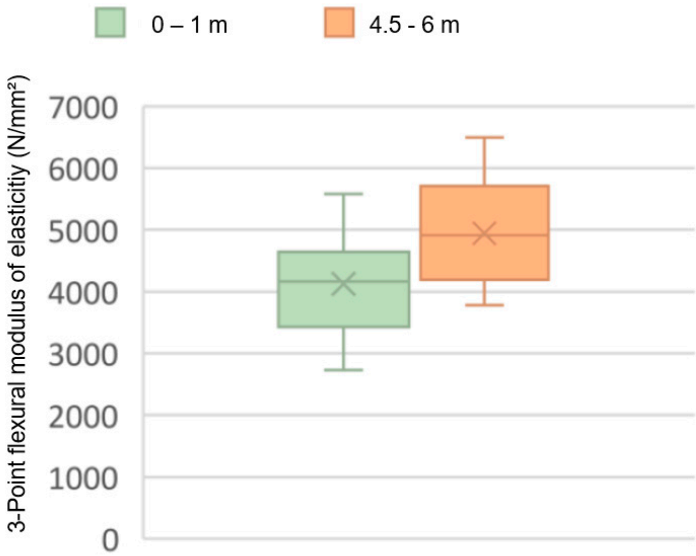

Figure 14. Modulus of elasticity of Paulownia samples extracted at 0−1 m and 4.5−6 m from the tree stem.

For the trunk cross-section, a decreasing tendency of MOE can be observed from the edge towards the core (Figure 15). On the edge, an average bending modulus of elasticity was measured as 5249.37 N/mm^2. In the core area, MOE was significantly lower, namely 3842.75 N/mm^2.

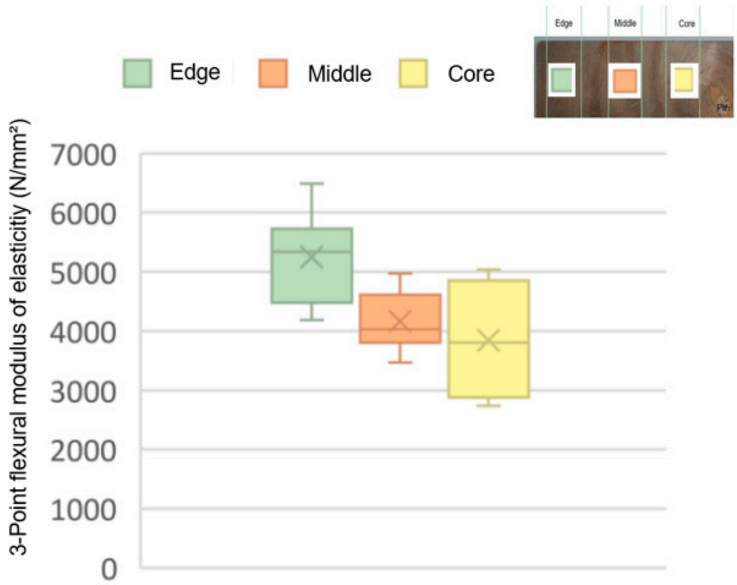

Figure 15. Modulus of elasticity in the cross-section of the Paulownia's tree stem.

Relatively similar values were reported by [5], from 4500 to 4900 N/m^2. Almost half of these values, namely 1900 N/mm^2, was MOE analyzed by [19]. The bending properties of Paulownia were significantly influenced by the density and porosity of the wood. Kiaei [17] measured a high porosity rate of 83% for Paulownia species sourced from Iran. In this study, MOR was, on average, 41 N/mm^2 and MOE was 3740 N/mm^2, which are consistent with the finding of this study considering a trunk height of 0–1 m and the area positioned between the pith and near the bark of the samples of Paulownia sourced from Serbia. The high microfibril angle (mostly of juvenile wood) significantly influenced the elastic behavior of Paulownia plantation wood. A comparison with other studies regarding elastic properties of Paulownia samples extracted from different height positions from the stem or cross-sections cannot be made considering insufficient data on Paulownia plantation wood.

3.5. Compressive Strength

The compressive strength, according to DIN 52185:1976 [51], of Paulownia wood is highest at a height of 4.5–6 m, with a value of 23.41 N/mm^2, and also at the edge of the log cross-section, with 25.11 N/mm^2 (Figures 16 and 17). At the height of 0–1 m, the compressive strength reached 19.41 N/mm^2. By scrutinizing the compressive strength of the samples extracted from the trunk's cross-section, the compressive strength in the middle area was 18.65 N/mm^2 and in the core area 19.25 N/mm^2.

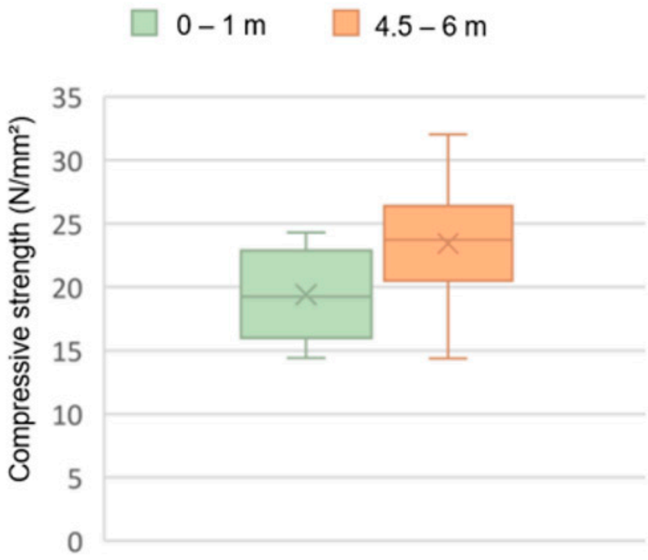

Figure 16. Compressive strength of Paulownia samples extracted at 0−1 m and 4.5−6 m from the tree stem.

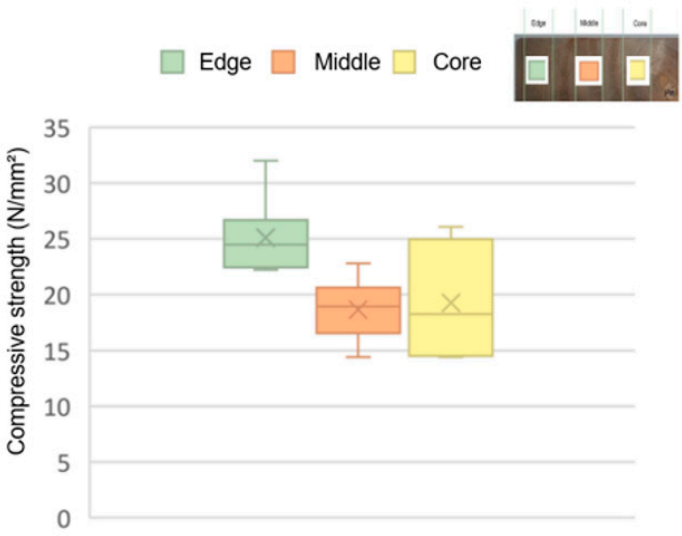

Figure 17. Compressive strength of Paulownia samples extracted from the cross-section.

The compressive strength of Paulownia wood analyzed in the present study is similar to the findings of [5], where compressive strength ranged from 19 to 23 N/mm^2. Higher values were reported by [25], of 26 N/mm^2, and significantly higher values (36 N/mm^2) were measured by [52]; however, much lower values, 14 N/mm^2, have been reported in the study of [19]. A comparison with other studies regarding the compressive strength of

Paulownia samples extracted from different positions from stem height or cross-section cannot be made yet considering state of the art of Paulownia short-rotation plantation wood.

3.6. Tensile Strength

Tensile strength, according to DIN 52188:1979 [53], decreases slightly when the samples were extracted from the top part of the tree (4.5 to 6 m) (Figure 18). The average value of the tensile strength was 40.44 N/mm^2 from 0–1 m height and 39.85 N/mm^2 from 4.5–6 m height.

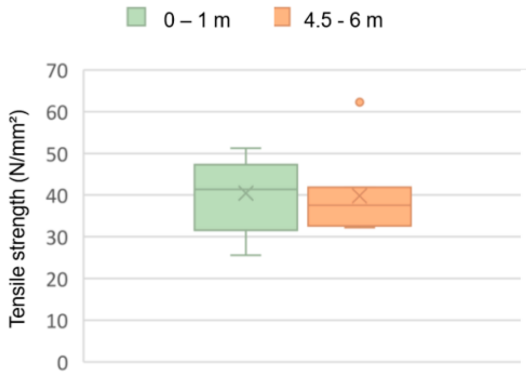

Figure 18. Tensile strength of Paulownia samples extracted at 0−1 m and 4.5−6 m from the tree stem.

It can be observed that in the core area of the tree trunk, the tensile strength decreased significantly (31.07 N/mm^2), because the density in the core is very low and, therefore, the wood can undergo little tensile stress. Between the bark and pith, the tensile strength reached a maximum average value of 49 N/mm^2. The tensile strength near the bark was 40.94 N/mm^2 (Figure 19).

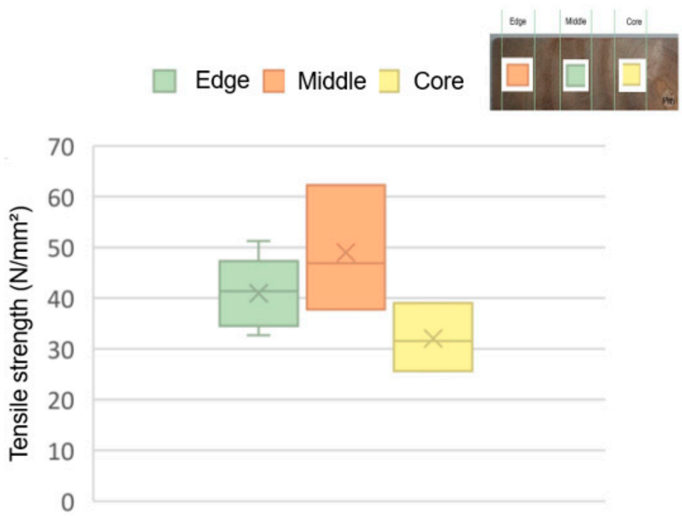

Figure 19. Tensile strength of Paulownia samples extracted from the cross-section.

The results of tensile strength are consistent with the findings presented by [5], from 36 to 44 N/mm^2 and 33 N/mm^2, and as reported by [44]. A comparison with other studies regarding the tensile strength of samples extracted from different positions of the stem height or cross-section are not yet available.

3.7. Screw Withdrawal Resistance (SWR)

The higher the position of the extracted samples in the tree trunk, the higher the screw withdrawal resistance (SWR). SWR was determined in concordance to EN 320:2011 [54]. In the area close to the ground (0–1 m), the mean value of SWR was 54.77 N/mm, and at a height of 4.5–6 m, it reached 57.82 N/mm (Figure 20).

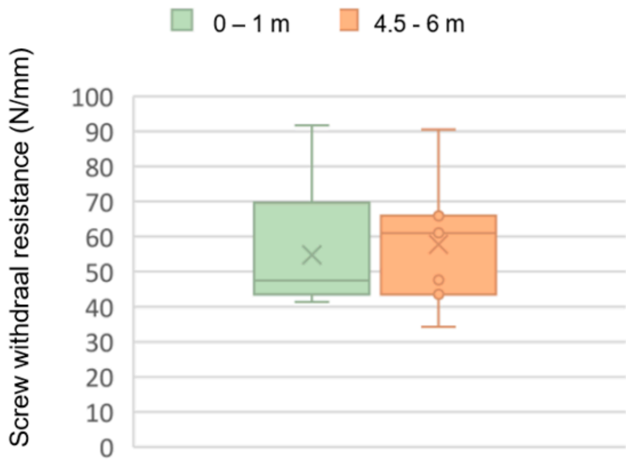

Figure 20. Screw withdrawal resistance of Paulownia samples extracted at 0–1 m and 4.5–6 m from the tree stem.

In the stem cross-section (Figure 21), SWR measured 55.39 N/mm between the fifth and seventh annual ring, 47.93 N/mm in the middle area (third to fourth growth ring), and near the second and first annual ring, it was 41 N/mm. Typical values of SWR range from 31 to 57 N/mm, per the results from the studies of [5,25]. Akyldiz [55] determined significantly lower SWR in the tangential, radial, and transversal direction for *Paulownia tomentosa* Steud., namely 19 N/mm, 18 N/mm, and 16 N/mm for the samples with a moisture content of 12%.

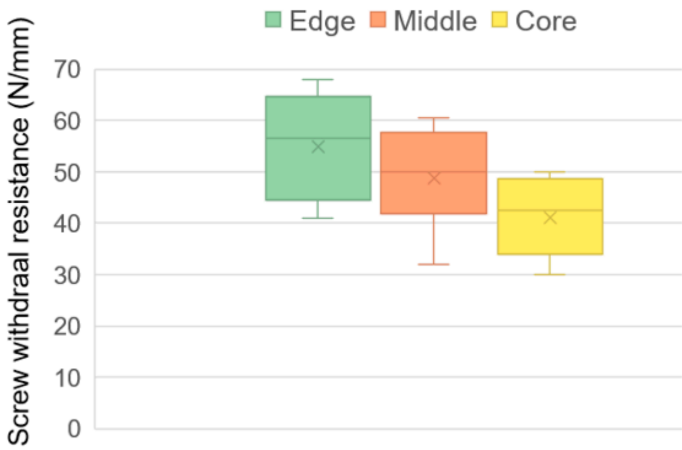

Figure 21. Screw withdrawal resistance of Paulownia samples extracted from the cross-section.

4. Conclusions

The present study assessed the physical and mechanical properties of Paulownia plantation wood, which were determined considering the tree stem height and position in the cross-section (near the bark, in the core, and in between these areas). The sampling height and cross-section site are of importance to any studies and in the processing of Paulownia plantation wood.

Fast-growing sawn wood from short-rotation plantations consists mostly of juvenile wood, with a lower density and larger microfibril angle than adult wood. There are clear differences between mature and juvenile wood, with higher strength properties for the former. Juvenile wood has a considerably lower modulus of rupture and elasticity, and maximum crushing strength in compression to that of mature wood. The relatively lower values of overall mechanical properties are dictated by density, with an average of 270 kg/m^3. Moreover, the results of this study indicate that *Paulownia tomentosa x elongata* plantation wood stabilizes from the fifth year of growth in terms of material density and shrinkage. For practical purposes, it should be considered the transition from juvenile to mature wood and the fact that high quality Paulownia timber can be harvested when the trees are older than 7 years. In this way, the yield of quality Paulownia sawn wood increases substantially.

Paulownia sawn wood extracted from the upper part of tree trunk (4.5–6 m) has a longer fiber length and lower microfibril angle, hence a higher bulk density that significantly influences the mechanical properties. This tendency can be considered atypical for Paulownia, because for most tree species, the samples extracted from the top part of the tree have lower density and strength properties.

There are large fluctuations in strength within a log and, therefore, large variations in mechanical properties. This could be important in raw material assessing, processing, targeting the added value and sustainable new products.

Due to its physical and mechanical properties Paulownia wood cannot be used in for the manufacture of structural components, where strong criteria are imposed for CE certification.

For further investigations, it is important to pay closer attention to the properties of Paulownia lumber depending on the position in the stem. A precise determination of wood characteristics should involve collecting samples from the whole tree height, at different tree ages, with a maximum of 15 years, that deliver the best yield for Paulownia short-rotation plantation timber.

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