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POTENTIAL OF PAULOWNIA WOOD FROM EUROPEAN PLANTATIONS

Marius Cătălin BARBU*
Transilvania University of Brasov, Romania
Salzburg University of Applied Sciences, Austria
E-mail: cmbarbu@unitbv.ro

Eugenia Mariana TUDOR
Transilvania University of Brasov, Romania
Salzburg University of Applied Sciences, Austria

Abstract:

Since more than 3 years at Campus Kuchl of Salzburg University of Applied Sciences is a constant interest regarding Paulownia, a wood species that originates from Asia and was naturalized in European plantations in the last decade. The research started with the assessment of physical and mechanical properties of Paulownia tomentosa x elongata wood influenced by the stem height (different distances above soil) and the radial position from the pith to bark (cross-section spot), but also with the potential analysis of the sawn wood from three plantation sites in Europe as well as its suitability for the manufacture of solid wood panels (1 and 3 layer), plywood and particleboards.

The results (based on Paulownia from Serbia) for the study of wood in the stem have shown that most properties are improved when the samples were taken from upper parts of the tree and from the near bark spot.

The results (based on Paulownia from Spain, Bulgaria and Serbia) for the study of the sawn wood show that the mechanical-physical properties were significantly influenced by the plantation site (climate, soil etc.). The samples from Spain have the higher density and mechanical properties. The plantation wood from Bulgaria has the largest of annual ring width and therefore lower density resulting also in lower mechanical properties.

The results for the study of edged glued solid wood panels (SWP), single-layered and three-layered made of Paulownia, both calibrated at a thickness of 19mm, were bonded with melamine-urea formaldehyde (MUF), polyurethane (PUR) and polyvinyl acetate (PVAc) resins. For the single-layered panels, the mechanical and physical properties did not differ significantly and are similar to those of massive Paulownia wood. For the three-layered panels, the adhesive application of PUR influenced positively all SWP properties. Considering the low density, these panels failed to achieve the performance of one- and single-layered panels made of spruce. The results of these findings recommend Paulownia SWP as lightweight and sustainable core materials for sandwich structures for furniture, packaging industry, etc.

Another aim of this research was to manufacture lightweight single-layered particleboard made of Paulownia plantation wood and to analyze the panel´s properties at two levels of density, 300 and 400 kg/m³ using urea-formaldehyde (UF) adhesive and high-frequency (HF) pressing technology. The physical and mechanical properties of the panels met at least the requirement for LP1 (light)particleboards for general purposes and use in dry conditions.

As a low-density fast-growing tree, Paulownia could have a positive forecast for the European wood markets and a wide range of possible uses, especially in lightweight applications and can replace successfully expensive tropical species as Balsa.

INTRODUCTION:

Paulownia is a fast-growing tree that originates in Asia, having at least nine species within the family, of which *Paulownia tomentosa*, *Paulownia elongata* and *Paulownia fortunei* (and their hybrids) are most prevalent (Koman and Feher 2020, Barbu et al. 2023a, Barbu et al. 2023b). Paulownia is also known as the princess tree, emperor tree, miracle tree or the European balsa (Barbu et al. 2022).

The variability of Paulownia species depends on plantation site, climatic conditions, irrigations, fertilization, insects and herbicide treatments and forestry management (Rodriguez-Seoane et al. 2020, Barbu et al. 2023a). Agro-forestry Paulownia plantations ensure sustainability for small rural communities. It is worth to mention that short-rotation plantations are not considered forests when the rotation time is less than 20 years (Yorgun et al. 2016, Barbu et al. 2023b). The trees represent a source of lumber, firewood, compost and coal and can easily adapt to new places. The Paulownia leaves are rich in nitrogen and can be introduced as feed for livestock (He et al. 2016, Barbu et al. 2022).

In the last decade, in Europe the interest for agroforestry plantations of Paulownia for industrial use increased. In this way the importation of Paulownia lumber form Asia could be diminished. For the soil

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*Corresponding author

protection Paulownia plantations contribute to decrease hazards by tree intercropping in farmlands (Jakubowsky 2022) and (winter) crop fields, considering that the trees in the dormant season will not compete for water and nutrients during the cold seasons (Wang and Shogren 1992). Paulownia help protect systems against erosion, flooding or wind damages (Feng et al. 2020) or to reduce soil degradation and air pollution, by improving the microclimate (Abbasi et al. 2020). Paulownia´s bark is commonly processed with the wood, because the bark is thin, difficult to remove and accounts for less than 1% of the overall volume (Lopez et al. 2012, Barbu et al. 2023a).

Since the end of last century several countries as Spain, Italy, France, Serbia, Romania and Bulgaria are experimenting Paulownia plantations (Jakubowski 2022, Moreno et al. 2017). Paulownia was gradually introduced in South America (Argentina, Brazil, Paraguay) and Australia and used for timber production (Pasiecznik 2022). Paulownia exhibits facile processability (Lee et al. 2022), acceptable fire resistance and high rate carbon absorption (Yorgun et al. 2016). Magar et al. (2018) calculated a rate of 33t CO_2/ha/year for Paulownia. The implementing it in agroforestry systems can help reducing the greenhouse emissions in cities or in the neighborhood of farmhouses, highlighting the carbon storage potential which is about 50-fold, 30-fold and 20-fold higher compared to oak, beech and lime tree (Icka et al. 2016, Barbu et al. 2023a).

Paulownia could be considered invasive species (Chongpinitchai et al. 2021, Snow 2015, Huber et al. 2023). Invasive tree species are probed able to survive, to reproduce and spread, unallied, sometimes at disturbing quotes, over the landscape (Van Wilgen et al. 2022), aggressively competing with native plants. As reported by (Remaley 2023), 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 European Union (European Commission, Barbu et al. 2023a).

Paulownia trees are coppiced (technical cut, maintaining 2cm of plant) rather during the second year of life. it means that the sapling is cut back to ground level, to determine the formation of a new shoot. The best of the buds will be selected to grow out (Rodriguez-Seoane et al. 2020). When the saplings are 2 or 3-year-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 these will constitute the sympodial-monochasium of the trunk. The condition is to keep the first 6-7 meters of the stem clear of branches (75%); for a stem height of 7-8m, after this height the canopy can be allowed to reach its natural shape (Crul 2023, Barbu et al. 2023a).

An adult tree has a trunk of 10 to 20m, with an increment of about 3m/year and 30 to 40cm diameter (Akyildiz and Kol 2017). Harvesting of 10 to 15-years old Paulownia trees from plantations with about 2000 trees/ha results in valuable timber (Ab Latib et al. 2020, Barbu et al. 2023a), but is can be harvested also in 6-7 years for low quality lumber. The timber volume per log is 0.3-0.5m³ (Akyildiz and Kol 2017). Paulownia wood is semi-ring porous to ring porous, soft, frequently knot free, with an average density of less than 300kg/m³ (Kalaycioglu et al. 2005). The wood is light coloured, soft, lightweight, easy to handle (Dogu et al. 2017, Barbu et al. 2022) and process, dimensionally stable and straight-grain (Dogu et al. 2017, Barbu et al. 2023a). The absence of knots and fibres that run parallel to the longitudinal axes are due to an appropriate Paulownia plantation management, considering site (southern facing exposure with protection from wind is preferred), well-drained soil (pH-value of 5-8) (Rodriguez-Seoane et al. 2020, Barbu et al. 2023a). The increased content of holo-cellulose (81%) determines a higher pulp yield for fine papers (Bergmann 1998) and acceptable strength properties (Tu et al. 2017). Paulownia wood is interesting also because do not crack or warp and is not susceptible to decay (Hussain et al. 2016). It has a low thermal conductivity and a high ignition point (Kalaycioglu et al. 2005, Bergmann 1998). It dries quick, is easy to shape, therefore these properties recommend it for industrial applications as furniture, building timber, packaging, solid wood products, plywood, insulation (Koman and Vityi 2017), for sculptures and handicrafts (Yadav et al. 2013) and as reinforcing filler for thermoplastic composites (Ayrilmis and Kaymakci 2013, Barbu et al. 2022).

Literature on the properties of Paulownia wood sourced from European plantations is still scarce (Koman and Feher 2020). This tree is renowned due to its fast growing, low density of 260 to 300kg/m³ (Lucas-Borja et al. 2011), gaining in the last period the nickname of “European balsa” (Cao et al. 2021, Barbu et al. 2022).

But similar to other fast-growing wood species, Paulownia has low performance of mechanical properties. One of the limitations of the industrial usage of Paulownia timber is due to the influence of the low density on the mechanical properties (Barbu et al. 2023a) such as modulus of rupture (on average 40N/mm²), modulus of elasticity (on average 4400N/mm²), and compressive strength (on average 25N/mm²) or tensile strength (on average 38N/mm²) for Paulownia Clone In Vitro 112 (Koman and Feher 2020), Paulownia COTE-2 (Lachowicz and Giedrowicz 2020) and *Paulownia tomentosa* x *elongata* from European plantations (Barbu et al. 2022, Barbu et al. 2023b)

The maximum moisture content of these wood species measures 350% (Tu et al. 2017), therefore kiln-drying schedules should be attentive selected and controlled. Paulownia air-dried wood is normally without drying defects (Esteves et al. 2022, Barbu et al. 2022).

The fibre saturation point is about 31% for *Paulownia fortunei*, 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 (Tu et al. 2017, Barbu et al. 2022).

Solid wood panels (SWP) made of Paulownia were studied hitherto in (Dogu et al. 2017) regarding their microscopic changes under thermal compression. The results of this study showed that Paulownia wood resembles balsa with respect to its reduced density and the occurrence of a hexagonal cell shape in its microstructure. The authors emphasise the idea that Paulownia can replace balsa wood as a core material in sandwich structures (Barbu et al. 2023b).

Less valuable stems can be chipped for heating, process to particles for PB or OSB and fibres for MDF or can serve as raw materials for biomass and biofuels (Barbu et al. 2022) having potential for second generation bioethanol production (Crul 2023, Barbu et al. 2023a).

Wood particles from fast-growing plantations are besides sustainable resource for PB production. Some examples include here radiata pine (*Pinus radiata*) (Garay et al. 2009), tree of heaven (*Ailanthus altissima* (Mill.) Swingle) (Lbadawi et al. 2015) and Paulownia (Nelis et al. 2018, Röllig et al. 2023). PB made of paulownia wood or combinations of paulownia with other wood species were studied by (Kalaycioglu et al. 2005, Nelis et al. 2018, Esteves et al. 2022), with urea-formaldehyde bonded wood particles and by (Van Pham et al. 2022), with phenol-formaldehyde resin. *Paulownia fortunei* particles, mixed with bio-waste cotton, were utilized for the manufacture of PB in the research study of (Khanjanzadeh 2012, Röllig et al. 2023).

The phenolic compounds in Paulownia have antioxidant properties therefore can be used in the pharma industry (Magar et al. 2018, Barbu et al. 2023a). Other uses of Paulownia stems were established by Chinese for medical purposes as a component of remedies for infections e.g. poliovirus due to its antioxidant properties (Kang et al. 1999, Barbu et al. 2022). In Asia, different elements as leaves, flowers, fruits and barks were used since centuries served as traditional medicines (Icka et al. 2016, Barbu et al. 2023a).

STUDY CASES

Physical and mechanical properties of *Paulownia tomentosa* x *elongata*-wood along and across the stem*

MATERIAL AND METHODS

The raw material was provided by Glendor Holding GmbH Company (Kilb, Austria) from a Paulownia plantation in Serbia. It consisted on two *Paulownia tomentosa* x *elongata* trees (7- years old) cut at different stem heights (0-1m and 4.5-6m), resulting in four logs. Two stems were extracted from the tree trunk close to the ground, 0-1m height and the other two. The logs processed to sawn wood were cut from tree trunk at a height of 4.5-6m.

The diameters of the four logs cut at different stem heights (0-1m and 4.5-6m) were 27-32cm (for 0 to 1m) and 21-26 cm (for 4.5-6m). Prior testing the wood was dried at a moisture content of 12%.

RESULTS AND DISCUSSIONS

The results of the tests regarding the physical and mechanical properties measured at two heights (0-1m and 4.5-6m) in the tree trunk and also depending on the position in the cross section (near to bark, in the core, near pith and between these two areas) are presented below.

Density:

Within the same tree, significant variations in density occur from the bark to the pith an up the trunk from the base (Niemz and Sonderegger 2021). Variations in density in the cross-section of the stem are correlated with the amount of juvenile and mature wood (Bao et al. 2001).

The density of Paulownia samples, measured according to ISO 3131:1996, increases at 4.5-6m. The average value of the bulk density at the basal portion of the trunk (0-1m) measured 245kg/m³ and at a height of 4.5-6m was 274kg/m³.

In the cross section, the bulk density increases from the core (near pith) to the edge. Near bark (edge) the density measured 289kg/m³, in the middle 257kg/m³ and in the core was 232kg/m³. There is a clear

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*The content of this study case originates from Barbu, M.C.; Tudor, E.M.; Buresova, K.; Petutschnigg, A. Assessment of Physical and Mechanical Properties Considering the Stem Height and Cross-Section of *Paulownia tomentosa* (Thunb.) Steud. x *elongata* (S.Y.Hu) Wood. Forests, 2023,14, 589.

difference between juvenile (pith) and mature wood (near bark), the former exhibiting higher density due to longer fibres and considerably thicker cell walls (Bao et al. 2001).

Similar density ranges, but with no hint about the sample´s spot and origin in tree, were reported in the study of Akyldiz & Kol (2010), with an average density of 272kg/m³ for the basic species *Paulownia tomentosa* from Türkiye. Esteves et al. (2022) measured a density of 460kg/m³ for Paulownia wood sourced from Portugal, which is way higher than the average density of spruce with 430kg/m³ according to Grosser (2007). The lowest density of Paulownia in Spain was reported by Lachowicz and Giedrowicz (2020), with a mean density of 216kg/m³. Jakubowski (2022) showed that, at 12% moisture content, Paulownia wood density varies from 220 to 350kg/m³, with an average value of 270kg/m³. This variability in density is justified by the growth conditions (soil, temperature, climate conditions). Densities higher than 400kg/m³ were determined for *Paulownia tomentosa* in Türkyie (Akyildiz and Kol (2010) and Portugal (Esteves et al. 2022) and for *Paulownia* Siebold and Zucc. (from Bulgaria) (Bardarov and Popovska 2017).

Sorption behavior:

The sorption behaviour of wood determined according to DIN 52184:1979 was minimally influenced by the position in the tree trunk. The mostly increased swelling was measured in tangential section. In axial and radial direction wood swelling is lesser, as described by (Niemz and Sonderegger 2021).

In axial direction, the wood swelling was the lowest (0.2%). In radial direction the shrinking was higher (0.5%). The differential swelling and shrinkage in tangential direction was the highest (1.3%).

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 0.19% whereas the shrinkage of the testing specimens extracted from the middle area was 0.20%. The shrinkage of the samples tested in the tangential direction differed minimally. In cross section, it was measured an average shrinkage of 1.40% on the edge area, 1.42% in the middle area and 0.98% in the core area.

Similar values of shrinkage, in all cutting directions, were determined by Fos et al. (2023). 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 (Fos et al. 2023). These values are consistent with the findings of Kiaei (2013), Koman and Vityi (2017), Sedlar et al. (2020). The high microfibril angle of juvenile wood is one of the main parameters that influences shrinkage and shrinkage anisotropy (Donaldson 2008).

It is important to emphasize the lower swelling ratios of Paulownia wood, that can be associated to narrower core rays (Jakubowski 2022). The medullar rays control the wood in radial direction and determine swelling up to 4% (Istok et al. 2020). Moreover, the narrow core rays did not influence higher swelling rates in tangential direction (Barbu et al. 2022). It was observed that juvenile wood had the lowest transverse shrinkage, which is consistent to the study of Bao et al. (2001).

Brinell Hardness (HB):

HB increases with height in all main sections (axial, radial and tangential) (EN 1534:2011-01). The HB values were in average with one third higher for the samples originating from a height of 4.5-6m of the tree trunk, especially in the axial direction. For a sample collected from a height of 0-1m from the stem, the HB was 4.2N/mm² in radial direction, 5.2N/mm² in tangential direction and 17.9N/mm² in axial direction. For the samples extracted from log at the height of 4.5-6m, these values of Brinell hardness increased in radial direction to 7.0N/mm², in tangential direction to 6.2N/mm² and in axial direction to 23.2N/mm². There is a direct correlation between Brinell hardness and density (Niemz and Sonderegger 2021).

By analyzing the tree stem cross-section, it cannot be drawn an uniform tendency. The HB in radial direction tends to increase from the edge to the core area. Near to bark, the HB in radial direction was 5.2N/mm² and increased at 7.7N/mm² near to pith.

At the seventh growth ring, near the bark, the tangential HB value was 5.9N/mm², and near the pith (first ring), it reached 5.3N/mm², which showed only a slight downward tendency.

The values of the HB in the transversal direction measured a maximum of 27.6N/mm² on the seventh ring. In the middle area (between the third and fourth rings), HB was the lowest at 15.2N/mm². Near the first growth ring, HB was 22.9N/mm².

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 (Niemz and Sonderegger 2021). 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 Fos et al. (2023). In the transversal direction, Paulownia hardness increases at the upper part of the tree stem.

In the axial direction, at a trunk height of 0-1m, the HB value was similar with the findings of Koman and Feher (2020), Barbu et al. (2022), Akyildiz and Kol (2010), Bardarov and Popovska (2017), but at a height of 4.5-6m, the maximum of 35N/mm² calculated in the present study had no equivalent in the studied literature. Akyldiz and Kol (2010) determined a maximum of longitudinal HB of 19N/mm², 9N/mm² in the tangential, and 8N/mm² in the radial direction. Lower values of HB were determined by Mania et al. (2022) as follows: 10.6N/mm² in the longitudinal direction, 5.6N/mm² in the tangential direction, and 5.5N/mm² in the radial direction.

Modulus of rupture (MOR) and Modulus of elasticity (MOE):

The 3-point MOR, determined according to DIN 52186:1978 exhibits the same tendency as bulk density: it increases with height and is highest near bark. MOR was 33.9N/mm² at a height of 0-1m and 41.2N/mm² at a height of 4.5-6m. On the edge, MOR measured an average value of 44.8N/mm². In the central area MOR was 33.4N/mm² and in the core area 31.3N/mm².

These MOR values are consistent with the interval of 24-44N/mm² presented in the review study of (Jakubowski 2022). Lachowicz and Giedrowicz (2020) reported from similar up to double values of 23.9-53.2N/mm², with an average of 38.6N/mm². Esteves et al. (2022) measured a higher 3-point flexural strength of 53.5N/mm² for Paulownia plantation wood from Portugal.

In the trunk area of 0-1m, the MOE was 4124 N/mm², and at a height of 4.5-6m, it was 4941N/mm².

For the trunk cross-section, a decreasing tendency of MOE can be observed from the edge towards the core. On the edge was measured an average MOE of 5249N/mm². In the core area, MOE was significantly lower, namely 3843N/mm².

Relatively similar values were reported by Barbu et al. (2022) from 4500 to 4900N/mm². Almost a half of these values, namely 1900N/mm² was MOE analyzed by Lachowicz and Giedrowicz (2020). The bending properties of Paulownia were significantly influenced by density and porosity of wood. Kiaei (2013) measured a high porosity rate of 83% for Paulownia species sourced from Iran. In this study, MOR was in average 41N/mm² and MOE 3740N/mm², which are consistent with the finding of this study considering a trunk height of 0-1m and the area positioned between pith and near bark of the samples of Paulownia sourced from Serbia.

Compressive strength:

The compressive strength, measured according to DIN 52185:1976 of Paulownia wood is highest at a height of 4.5-6m with a value of 23.4N/mm² and also at the edge of the log cross-section with 25.1N/mm². At the height of 0-1m, the compressive strength reached 19.4N/mm². By scrutinizing the compressive strength of the samples extracted in trunk´s cross-section, the compressive strength in the middle area was 18.7N/mm² and in the core area 19.3N/mm².

The compressive strength of Paulownia wood analyzed in the present study is similar to the findings of Barbu et al. (2022), where compressive strength ranged from 19 to 23N/mm². Higher values were reported by Akyildiz and Kol (2010) of 26N/mm², and significantly higher values (36N/mm²) were measured by Sell (1997); however, much lower values, 14N/mm², have been reported in the study of Lachowicz and Giedrowicz (2020).

Tensile strength (TS):

Tensile strength, measured according to DIN 52188:1979 decreases slightly when the samples were extracted in the upper stem´s part (4.5-6m). The average value of the tensile strength was 40.4N/mm² from 0-1m height and 39.9N/mm² from 4.5-6m height.

In the core area of the tree trunk the TS decreased significantly (31.1N/mm²), because the density in the core is very low and therefore the wood can undergo little tensile stress. Between bark and pith, the TS reached the maximum average value of 49N/mm². The TS near bark was 40.9N/mm².

The results of TS are consistent with the findings presented by Barbu et al. (2022), from 36 to 44N/mm² and 33N/mm², and as reported by Koman and Vityi (2017)

Screw withdrawal resistance (SWR):

The higher the position of extracted samples in tree trunk, the higher the SWR. SWR was determined in concordance to EN 320:2011. In the area close to the ground (0-1m), the mean value of SWR was 54.8N/mm and at height of 4.5-6m reached 57.8N/mm.

In the stem cross-section, SWR measured 55.4N/mm between the fifth and seventh annual ring, 47.9N/mm in the middle area (third to fourth growth ring), and near the second and first annual ring, it was 41N/mm. Typical values of SWR range from 31 to 57N/mm, per the results from the studies of Barbu et al. (2022), Akyildiz and Kol (2010). Akyldiz (2014) determined significantly lower SWR in the tangential, radial, and transversal direction for *Paulownia tomentosa* Steud., namely 19N/mm, 18N/mm, and 16N/mm for the samples with a moisture content of 12%.

Physical and mechanical properties of *Paulownia tomentosa* x *elongata* sawn wood from Spanish, Bulgarian and Serbian plantations[**]

MATERIAL AND METHODS

The *Paulownia tomentosa* x *elongata* wood was provided from the company Glendor Holding GmbH (Kilb, Austria) and originates from plantations from Spain, Bulgaria and Serbia. Mostly juvenile wood samples from 5-7 years old trees were used for the tests.

The plantation wood was delivered as rough-sawn lumber of approximately 1.5m length, 20-30cm width and thickness of 20-25mm. Prior to testing, the raw material was conditioned to constant weight at 20°C and 65% relative air humidity for at least 14 days, until constant weight was achieved.

RESULTS AND DISCUSSIONS

The results for the physical and mechanical properties for Paulownia wood sourced from three locations (Bulgaria, Serbia and Spain) will be compared with the values of Paulownia wood from other European plantations and with Balsa, poplar and spruce from literature sources.

Density:

The average density of wood from all three sites for *Paulownia tomentosa* x *elongata* is 258kg/m³. The Paulownia wood from Spain had the highest average density of 266kg/m³, followed by the Serbian wood with 259kg/m³, and the lowest average value had the Bulgarian wood with 250kg/m³.

In their study, Akyildiz and Kol (2010) determined an average density of 272kg/m³ for the basic species *Paulownia tomentosa* from Türkiye. This value is lower for Paulownia wood from Hungary at 246kg/m³ (Koman and Feher 2020) or from Spain at 215kg/m³ (Lachowicz and Giedrowicz 2020). Esteves et al. (2022) found a high value of 460kg/m³ for Portuguese Paulownia wood, which is even higher than the average density of spruce with 430kg/m³ according to Grosser (2007).

Lachowicz and Giedrowicz (2020) found the lowest value of all the mentioned Paulownia (Spain) value with a mean density of 216kg/m³. Considering the values reported from Byrne and Nagle (1997) and Borrega and Gibson (2015). Balsa wood has a lower density with 160kg/m³ and the poplar has a density of about 440kg/m³ (Grosser 2007; Ciftci and Kaya 2019).

At 12% moisture content, Paulownia wood density varies from 220 to 350kg/m³, with an average of 270kg/m³ (Jakubowski 2022). This variability in density is determined by growth conditions. The higher Paulownia densities, about 400kg/m³ were reported for *Paulownia tomentosa* (Akyildiz and Kol 2010; Esteves et al. 2022) and for Siebold and Zucc. (Bulgaria) (Bardarov and Popovska 2017).

Sorption behaviour:

The measured values of the sorption behaviour tests for Spanish, Bulgarian and Serbian Paulownia wood were carried out according to DIN 52184:1979.

Spanish Paulownia wood had shrinkage in the axial direction of 0.38%, in the radial direction of 0.50%, in the tangential direction of 1.58%. Bulgarian Paulownia wood has an axial shrinkage of 0.16%, 0.50% in radial section, and 0.98% in tangential section. The shrinkage of Serbian Paulownia wood is 0.20% in axial section, 0.46% in radial section, and 1.30% in tangential section.

It can be observed that the Bulgarian Paulownia wood swells and shrinks the least in all cutting directions. Compared to the Paulownia, balsa wood has a much lower sorption behavior. In the tangential direction, it shrinks and swells between 3.4-7%. Radial shrinkage is 1.4-2.1% and volume shrinkage is 5.1-9.3% (Wiepking and Doyle 1960).

It is important to emphasize the lower ratios of swelling. This behavior of Paulownia wood can be attributed to narrower core rays. The rays are narrow, occupying a single row up to 0.5mm, but also multi-seriate rays can occur (Jakubowski 2022). Firstly, they control the wood in a radial direction and ensure values up to 4% (Sedlar et al. 2020), such as for most species (at this density). Secondly, the small width of core rays did not influence higher rates of swelling in tangential direction.

[**] The content of this study case originates from Barbu, M.C.; Buresova, K.; Tudor, E.M.; Petutschnigg, A. Physical and mechanical properties of *Paulownia tomentosa* x *elongata* sawn wood from Spanish, Bulgarian and Serbian plantations. Forests, 2022, 13(10),1543

Width of annual rings:

The average annual ring width of all Serbian Paulownia wood was 1.7cm. Paulownia trees from Spain had larger annual ring width of 2.8cm, but the largest annual ring width was measured for Bulgarian Paulownia, namely 4.6cm.

Serbian Paulownia wood had the smallest annual ring width, which is due to soil and climatic conditions. The tree ring width decreases as the height of the tree increases. The diameter of the tree tapers with increasing height.

As already noted by Koman and Vityi (2017), there are very large fluctuations in tree ring width within the first five years (up to 30%) (from 1 to 3.5cm). From the beginning of the fifth year, the annual ring width becomes constant and is hardly subject to fluctuations anymore.

Brinell hardness (HB):

In the case of Paulownia wood source from Bulgaria, HB in axial direction was 18.7N/mm², 5.6N/mm² in radial direction and 5.3N/mm² in tangential direction. For Paulownia wood from Spain was measured the HB in axial direction of 21.2N/mm², 6.1N/mm² in radial direction and 5.8 N/mm² in tangential direction. For Paulownia wood from Serbia were measured the highest values of HB: 21.2N/mm² in axial direction, 6.1N/mm² in radial direction and 5.8N/mm² in tangential direction. The latter values are consistent with the results of Bardarov and Popovska (2017) and Koman and Vityi (2017). Compared to balsa wood, with a HB of 7N/mm² (Finger 2016), Paulownia has significantly increased hardness. Other lightweight hardwood species is poplar, with a hardness of 25-33N/mm², in concordance with the results of Koman and Vityi (2017) of 27.5N/mm².

Modulus of rupture (MOR) and Modulus of elasticity (MOE):

Paulownia wood from Spain achieved the highest MOR of 39.8N/mm² and of MOE 4867N/mm². The Paulownia wood from Bulgaria had the lowest values of MOR of 35.5N/mm² and of MOE 3714N/mm². Paulownia wood from Serbia is in the middle range with a MOR of 37.5N/mm² and MOE 4533N/mm².

Jakubowski (2022) analyzed in a review article the mechanical properties of Paulownia wood and reported a range for MOR from 24.0 to 43.5N/mm². Lachowicz and Giedrowicz (2020) measured a similar MOR ranging from 23.9 to 53.2N/mm² with a mean value of 38.6N/mm² and Esteves et al. (2022) found a higher mean value of 53.5N/mm² for Paulownia from Portugal. The higher value for MOR achieved by the Paulownia from Türkiye (Akyildiz and Kol 2010) was at least 20% lower than that the one for black poplar (Sell 1997).

All these values are at least two-fold higher compared to MOR for balsa wood, which is about 17N/mm² and MOE which is between 1900 to 2900N/mm² (Kotlarewski et al. 2016; Lachowicz and Giedrowicz 2020).

Compressive strength (CS):

Paulownia wood from Spain has a CS of 22.5N/mm². The Bulgarian Paulownia wood has a CS of 18.8N/mm² and the Serbian Paulownia wood has a CS of 21.4N/mm². Other values for Paulownia from other plantations are ranging from 25.6N/mm² (Akyildiz and Kol 2010) and 35.6N/mm² (Kaymakci et al. 2013) for Paulownia from Türkyie and significant lower, of 14.2N/mm², as results from the research of Lachowicz and Giedrowicz (2020).

The value is comparatively similar for black poplar, which has a minimum value of 30N/mm² (Grosser, 1998). The balsa wood has a mean value of 10N/mm², which is half of the Paulownia woods (Borrega and Gibson 2015).

Tensile strength (TS):

The Spanish Paulownia wood has a TS of 44.1N/mm². The TS of Paulownia wood from Bulgaria was 36.2N/mm² and the TS for the Paulownia wood from Serbia reached a value of 40.1N/mm². For Paulownia sourced from Hungary, Koman and Vityi (2017) reported a TS of 33.3N/mm³, which is consistent the values presented in this study. The TS of Balsa wood is considerably lower with 14N/mm² (Kaymakci et al. 2013). The TS of European lightweight species as black poplar is about 40% higher than that of Paulownia (Grosser 1998).

Screw withdrawal resistance (SWR):

Paulownia wood from Spain measured a SWR a value of 56.6N/mm. The results for SWR for the Paulownia from Bulgaria are consistent with the findings of Akyildiz (2014), where plantation wood was extracted from Türkiye, therefore it can be supposed that Paulownia from Black Sea region exhibits similar properties. Compared with SWR of hardwood species, the overall values for Paulownia are at least two to three-fold lower (Aytekin 2008).

Lightweight solid wood panels made of Paulownia plantation wood***

MATERIAL AND METHODS

The Paulownia European plantation timber (*Paulownia tomentosa* x *elongata*) was provided by Glendor Holding GmbH (Kilb, Austria) and sourced from 5 - to 7 - year-old trees. The plantation wood from Petrinja, Croatia, was delivered by Moserholz GmbH (Pettenbach, Austria) dried at 12% moisture content as rough-sawn lumber of approximately 100cm length and 20-30cm width and with a thickness of 20-25mm.

For the manufacture of single - and three - layered SWPs with a thickness of 19mm, two types of lamellae with the following dimensions were cut with a circular saw and planed: 112x3.2x2.2cm for the single-layer SWPs and 98x6.6x1cm for the 3-layer SWPs.

A lamella width of 32mm (single-layered board) was opted for according to the dimension of the core layer of a standard industrial blockboard from Moralt AG (Hausham, Germany). A lamella width of 66mm (3-layered board) was chosen after optimizing the available raw material in order to obtain the maximum yield.

Both the single - and three - layered SWPs were glued using polyvinylacetate (PVAc) type Pattex® PV/H, category D3 (Pattex, Düsseldorf, Germany); melamine urea formaldehyde (MUF), type Dynea Prefere 4564 with hardener Prefere 5013, at a ratio of 100:8 (Dynea Austria GmbH, Krems, Austria) and polyurethane Kleiberit® PUR 501.0 (Kleiberit SE & Co.KG, Weingarten, Germany). The adhesive amount was as follows: for the PVAc, 330g/m², for the MUF, 340g/m² and 210g/m² for the PUR.

For the single-layered SWPs made of Paulownia, the lamellae were previous glued with PVAc, MUF and PUR and consequently cold-pressed at 0.68N/mm² with screw clamps for two hours. The single-layer panels were calibrated using a wide belt sander, grit 60, to a thickness of 19mm, a width of 446mm and length of 950mm.

The individual layers of the 3-layer SWP were formatted to 92x92cm and calibrated. The top layers (faces) had a thickness of 5.75mm and the middle layer (core) 7.5mm, considering the model of a standard spruce 3-layer panel from Binderholz GmbH (St.Georgen, Austria) of 19mm thickness (2x5.75+7.5mm). The adhesive was applied to the individual layers of the 3-layer SWP with a notched trowel with tooth size B1 for all adhesive types. The 3-layer SWP were pressed at 60°C for 15 minutes in a veneer press OTT (Lambach, Austria) with a pressure of 0.6N/mm² for all panel types (bonded with MUF, PUR and PVAc).

The testing specimens were prepared from the 1-layer and 3-layer SWPs according to EN 326-1:2005 and then stored in a standard climate (20°C and 65% relative air humidity). For the density determination of the 1- and 3-layer SWPs, test specimens were prepared for each type of board according to EN 323:2005. The mechanical properties of 3-point flexural strength (MOR) and modulus of elasticity (MOE) in bending were determined according to EN 310:2005. In the case of the 3-layer SWPs, test specimens for each board were tested parallel and perpendicular to the grain. To test the quality of the bond for SWP 1 (24h water storage), test specimens per board were used to determine the compressive shear strength according to EN 13354:2009.

RESULTS AND DISCUSSIONS

The results for the physical and mechanical properties of Paulownia single- and three layered SWPs (tested parallel and perpendicular to the grain) are compared with industrial manufactured SWP1 panels made of spruce.

Density:

The raw density of the Paulownia boards, single and three-layered SWP are similar. Average values of 258kg/m³ were measured for the single layered boards bonded with MUF and PVAc. The single-layered panel bonded with PUR had a density of 249kg/m³.

In the case of the three-layered boards, the density exhibited average values of 280kg/m³.

It can be observed that the density values for the single-layered panels are consistent with the raw density of Paulownia wood in results from studies concerning plantation wood from Spain, Serbia and Bulgaria (Barbu et al. 2022; Barbu et al. 2023 a) and Hungary (Koman and Feher 2020; Fos et al. 2023).

The three-layered SWPs had a light increased density due to the adhesive application and there was no difference regarding the extraction of samples parallel or perpendicular to the direction of production/or the grain.

***The content of this study case originates from Barbu, M.C.; Radauer, H.; Petutschnigg, A. Tudor, E.M.; Kathriner, M. Lightweight Solid Wood Panels Made of Paulownia Plantation Wood. Applied Sciences, 2023, 13, 11234.

Modulus of rupture (MOR) and Modulus of elasticity (MOE):

For the single-layered SWPs, there is no significant difference between the average values of MOR (32-33N/mm²) for panels with the three types of adhesive application (minimum of 29N/mm² and maximum of 40N/mm²).

The MOR was tested for the three-layered SWPs parallel and perpendicular to the grain. The MOR average values for the samples tested perpendicular to the grain were at least three times lower (8-10N/mm²) compared to the other testing direction, parallel to the grain (28-36N/mm²). The highest MOR was achieved by the boards with PUR (36N/mm²).

The values for MOE are similar for the single-layer SWPs. Again, MUF, PUR and PVAc have no significant influence on these. The knot-free structure of the Paulownia lamellae (Fos et al. 2023), straight-grained (Dogu et al. 2017), determines the relative related average values for MOE (3539-3733N/mm²) for the single layered SWPs (minimum of 3134N/mm² and maximum of 4528N/mm²).

For the three-layered SWPs, the MOE was higher when the samples were tested parallel to the grain (3998-4604N/mm²) and about eight times lower (461-541N/mm²) when the testing was performed perpendicular to the grain.

A comparison of the MOR and MOE of Paulownia SWPs with other lightweight wood products made of balsa, for example, is relatively difficult, as balsa is used in sandwich structures with glass-fibre reinforcements (Galos et al. 2022) and is mostly composed as end-grain in a setup that consists of two face sheets (skins) and a core structure (Osei-Antwi et al. 2013).

Compressive shear strength (CSS):

The CSS after 24h of water storage was 2.7-3.2N/mm² for all single-layered SWPs (minimum of 1.8N/mm² and maximum of 3.8N/mm²), compared to 2N/mm² for the three-layered SWPs bonded with PUR and PVAc (minimum of 1.5N/mm² and maximum of 2.6N/mm²). The CSS of the 3-layer panels glued with MUF was 1.6N/mm² (minimum of 1N/mm² and maximum of 2.1N/mm²).

These results are consistent with the findings of Osei-Antwi et al. (2013), which studied the shear strength of balsa end-grain solid wood panels for densities ranging from 200 to 300kg/m³. Although the orientation of the balsa blocks was different compared to the direction of the production of the Paulownia SWPs, the values of the shear strength for balsa panels (0.5-2N/mm²) for both parallel and perpendicular grain orientations of the testing specimens, are in line with the results obtained for the single and three-layered Paulownia SWPs. A major difference, however, is in the panel thickness, which was 5-fold higher for the balsa SWPs. Other solid wood composite panels with a thickness of 20mm, with a mixture of balsa blocks (flat-grain and end-grain) with a side reinforcement of Brazilian fern wood (*Schizolobium parahyba* (Vell.) Blake), are an industrial product with a shear strength of 4.1N/mm² (Bcomp 2023).

The wood breakage rate after testing the compressive shear strength was relatively high for all panel types (more than 95%), with a smaller rate of 80% for the panels bonded with PVAc. This is the case when the stress is perpendicular to the longitudinal axis and wood breakage may develop as intercellular failure due to cells being split up and peeling. Cracks are multiplied via the compound middle lamella (which is also called intercellular fracturing) (Karinkanta et al. 2018).

Effect of the particle geometry on lightweight particleboards from Paulownia using high frequency pressing technology****

MATERIAL AND METHODS

The Paulownia wood used was supplied provided by Glendor GmbH (Kilb, Austria) from the same Croatian plantations in Petrinja. Based on the annual rings the age of the logs was five to six years. The Paulownia roundwood had a moisture content of 160%. It was debarked by hand and cut into 30cm long pieces. The particles were generated with a Mihoma disk flaker (Leipzig, Germany) with tangential infeed. For the further processing of particles was used a Condux Netzsch impact mill (Hanau, Germany). Subsequently, the particles were fractionated into four classes with an Allgaier tumbler screen (Uhingen, Germany). Only the fractions B (0.5 to 2.0mm) and C (2.0 to 4.0mm) were used for the particleboard (PB) production. The target thicknesses of the particles were 0.35mm, 0.70mm and 0.90mm. The target length of the particles was 30mm. The oven dried density was 210 - 230kg/m³.

For the gluing of the PB were used urea-formaldehyde resin (UF) BASF SE (Basf, Ludwigshafen, Germany), Hydrowax 138 paraffin emulsion (Hywax, Hamburg, Germany) and a 30% solution of ammonium

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****The content of this study case originates from Röllig, P.; Tudor, E.M.; Barbu, M.C.; Direske, M.: Effect of the particle geometry on lightweight particleboards from Paulownia using high frequency pressing technology. Wood Material Science & Engineering, 2023 (in print), doi: 10.1080/17480272.2023.2286625 nitrate as hardener. The particles were glued at 10% resin content using a rotary drum blender (Häntzschel, Dresden, Germany).

The resinated particles were manually distributed into a 42x46cm mould and cold pre-pressed for 60 seconds in a high-frequency (HF) laboratory press (Höfer, Taiskirchen, Austria) at a pressure of 200kN. With an applied anode current of 2.7A, the particle mats were pressed to a target temperature in the core of 140°C. The target board thickness was 16.5mm, adjusted by the pressing program. Besides the HF-pressing a laboratory a hot press (Höfer, Taiskirchen, Austria) was used as reference for lightweight panel production. The cooled and conditioned boards were sanded, edge trimmed, cut into test specimens and stored in a climate chamber at 20°C and 65% relative air humidity.

Based on the particle size distribution four different particle variants were used for board production. For each particle variant, boards were produced in two different levels of target density (300 and 400kg/m³). Two boards were produced for each variant.

Modulus of elasticity (MOE) and modulus of rupture (MOR) were determined according to the EN 310:2005, the density according to the EN 323:2005, the moisture content (MC) according to the EN 322:1993, the thickness swelling (TS) and water absorption (WA) after 24h according to the EN 317:1993 and the internal bond strength (IB) according to the EN 319:1993. In addition, the board density profile was measured with a DAX 6000 (Fagus-GreCon, Alfeld, Germany).

RESULTS AND DISCUSSIONS

Bulk density:

On the one hand the bulk density decreases with decreasing particles thickness and on the other hand decreases with increasing particle length. Subsequently the bulk density increases with a decreasing slenderness ratio. For the fraction B with 0.38mm particle thickness the bulk density was 60.9kg/m³ and for the 0.53mm particle thickness 64.3kg/m³. For the fraction C with 0.38mm particle thickness the bulk density was 34.4kg/m³ and for the 0.53mm particle thickness 42.1kg/m³.

Modulus of rupture (MOR) and Modulus of elasticity (MOE):

Particle thickness shows a significant influence on MOR of the tested specimens at both panel densities. PB made of 0.53mm particle thickness achieve higher values (5.5N/mm² at 300kg/m³ and 12.5N/mm² at 400kg/m³). The particle thickness has no influence on MOE (800N/mm² at 300kg/m³ and 1500N/mm² at 400kg/m³). MOE and MOR can be influenced by the density of the PB. An increase of the board density from 300 to 400kg/m³ double these values.

The length and width of the particles significantly influence MOE and MOR. PB made of fraction C (longer particles than B) have significantly higher MOR (6.3N/mm² at 300kg/m³ and 12.1N/mm² at 400kg/m³) than PB made of fraction B (5.1N/mm² at 300kg/m³ and 10.4N/mm² at 400kg/m³). The MOE of PB made of fraction C (920N/mm² at 300kg/m³ and 1510N/mm² at 400kg/m³) are higher compared to PB made of fraction B (730N/mm² at 300kg/m³ and 1380N/mm² at 400kg/m³).

All manufactured PB variants meet the requirements for bending strengths according to DIN 16368:2014 for type LP1 of 16mm thickness (MOR: 3N/mm² and MOE: 700N/mm²). For all PB with densities of 400kg/m³, the requirements for type LP2 of 16mm thickness used for furniture (MOR: 7N/mm² and MOE: 900N/mm²) are met.

Internal bond (IB):

At a board density level of 300kg/m³, PB made of 0.53mm particle thickness show a significant higher IB (0.42N/mm²) than boards made of 0.38mm particles thickness (0.31N/mm²). At a higher density (400kg/m³), the IB increased for both particle thicknesses (0.58 - 0.60N/mm²). PB made of B fraction have an IB significantly higher for both density (300 and 400kg/m³) then PB made of fraction C. It can be assumed that shorter, narrower particles (fraction B) have a positive influence on IB.

These results are consistent with the findings of Esteves et al. (2023), where IB for Paulownia PB ranged from 0.4 to 0.7N/mm² at densities under 500kg/m³, but at a board thickness of 8mm (vs. 16mm in this study). For a Paulownia PB with 10mm thickness, Nelis et al. (2018) obtained an IB of 0.8N/mm², for a density of 350kg/m³ and 1.25N/mm² for 500kg/m³. In the case of 3-layered paulownia PB of 18mm studied by Kalaycioglu et al. (2005) the IB was 0.67N/mm² for a density of 550kg/m³.

All manufactured board variants in this study meet the requirements for IB according to DIN 16368:2014 for type LP1 of 16mm thickness (0.24N/mm²). For all PB with densities of 400kg/m³ and partially of 300kg/m³ (particle type B and of 0.53 particle thickness), the requirements for type LP2 of 16mm thickness used for furniture (0.35N/mm²) are met.

Water absorption (WA) and thickness swelling (TS) after 24h:

At a density of 300kg/m³, the WA after 24h (193%) of PB made of 0.38mm particle thickness is significantly lower (203%) than when using thicker particles (0.53mm). A reduced WA after 24h for the panels density of 400kg/m³ (142%) is consistent with the study of Roffael and Rauch (1972). Panels made of fraction C have lower WA after 24h (300kg/m³: 193% and 400kg/m³: 142%) than panels made of fraction B (300kg/m³: 199% and 400kg/m³: 148%).

PB with 300kg/m³ made of 0.53mm particles thickness have lower TS after 24h (14.5%) than panels made of 0.38mm particles thickness (19.5%). With increasing raw density, TS after 24h increases for both particle thicknesses (21 - 22%). An influence of the particle thickness on the TS can no longer be detected at panel with a density of 400 kg/m³. The PB made of fraction C have an increased TS after 24h at both levels of the density (300kg/m³: 19.5% and 400kg/m³: 22%). Differences between the used particle fractions are observed at 300kg/m³ density (B: 17% and C: 19.5%).

Previous studies showed that for panel density of 500kg/m³, TS increases at 12.5%, but water absorption decreases at 75% (Nelis et al. 2018). For a PB of 8mm, the swelling in thickness for densities between 400 and 500kg/m³ was 15.5 to 25% and the WA 110 to 145% (Esteves et al. 2023).

CONCLUSIONS

Study case 1 (Barbu et al. 2023a):

This 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 270kg/m³. 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 sawn wood could increase substantially.

Paulownia wood from the upper part of tree trunk (4.5-6m) 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

Study case 2 (Barbu et al. 2022):

The physical and mechanical properties of Paulownia wood have shown that the location of these plantations (Iberian Peninsula and Balkans), the type of soil and the environmental conditions strongly influence the wood properties. The density is directly corelated with the mechanical properties. The low density of all these tested samples ensures that the wood is filled with a lot of air and thus has heat-insulating and lightweight properties.

As expected, Paulownia wood achieved significantly lower values in physical and mechanical properties compared to conventional species such as poplar but better than Balsa.

Paulownia wood can be classified very low and low for MOR, MOE and compression strength and for these reasons is not recommended for structural uses, which require high mechanical strength and stiffness.

In view of all the results, the conclusion is that Paulownia has enormous potential for special lightweight application in construction, model making and thermal insulating and offers many possibilities in non-load-bearing structures and can successfully replace other tropical wood species, which are more expensive and rarer. The comparisons of mechanical properties of these two light wood species demonstrates that it might be suitable to focus on the possibility of using Paulownia wood as a substitute for Balsa wood as core material for composites.

For further investigations, it is important to pay close attention from which log section was extracted the sample. There are large variations in strength within a log and therefore different mechanical properties, depending on the spot of the log where the test specimen was cut. There are significant differences in the width of annual rings which greatly affects the woods properties.

Study case 3 (Barbu et al. 2023b):

Paulownia SWPs can be processed well with conventional woodworking machines. The basic prerequisites are well-sharpened tools for the production of the lamellae and SWPs, as well as the appropriate settings of the processing machines. Due to the wide annual rings in Paulownia wood, the variance of testing results for mechanical properties such as modulus of elasticity, bending strength and compression shear test, both positive and negative, is increased. Single-layered SWPs have similar properties even if they are bonded with MUF, PUR or PVAc. In the case of three-layered SWPs, the use of PUR adhesive influences positively the mechanical properties of the panel. The presence of PUR based adhesive joints may influence the elasticity and the shear response of the panels.

The use of Paulownia wood to produce one-layer and three-layer SWPs is certainly possible. The results obtained suggest, among other things, their use in lightweight construction, and these could find a variety of applications in the furniture and door industry, in interior construction or in means of transport. In Europe, however, the availability of Paulownia sawn timber or lamellae for the production of SWPs is still an open question. Furthermore, the issue of the market preparation and market introduction of SWPs made of Paulownia wood still needs to be considered. Paulownia wood from European plantations resembles Balsa wood and can successfully replace this lightweight wood species in sandwich structures as the core layer or in engineered products such as three-layered solid wood panels.

In order to meet the demand for ecologically compatible binders and the reduction of emissions from adhesives, it is recommended to carry out further series of tests with protein based binders, such as casein-based adhesives. As further research, it is recommended to carry out further tests on Paulownia SWP with regard to surface treatment, in terms of surface treatment, moisture behaviour and creep behaviour too. Another aspect to consider for the bonding of Paulownia wood can be the examination of the wood surfaces to be bonded. Different production methods are possible for industrially produced lamellae. These can be cut or split and then further processed in this form, or still be planed or sanded. These surface properties influence the quality of the bonding and offer further possibilities for various test arrangements.

Study case 4 (Röllig et al. 2023):

Low density particleboard made of Paulownia with 400 kg/m³ fulfilled the performances of LP1 type (general purpose lightweight panels for use in dry conditions) and LP2 type (non-load-bearing lightweight panels for interior use in dry conditions with high dimensional stability and stiffness) in terms of bending properties, internal bond and dimensional stability. For water absorption and thickness swelling were achieved the requirements for a LP3 type (non-load-bearing panel for use in dry and humid conditions with high dimensional stability and stiffness). The high-frequency pressing technology reduced the pressing times, improved the heat distribution in the matt and the adhesive curing.

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REFERENCES

Abbasi M, Pishvaee MS, Bairamzadeh S (2020) Land suitability assessment for Paulownia cultivation using combined GIS and Z-number DEA: A case study. Computers and Electronics in Agriculture 2020, 176, 105666, doi:10.1016/j.compag.2020.105666

Ab Latib H, Choon Liat L, Ratnasingam J, Law EL, Abdul Azim AA, Mariapan M, Natkuncaran J (2020) Suitability of Paulownia wood from Malaysia for furniture application. BioResources, pp. 4727-4737.

Akyildiz MH, Kol HS (2010) Some technological properties and uses of Paulownia (*Paulownia tomentosa* Steud.) wood. J Environ Biol, pp. 351-355.

Akyildiz MH (2014) Screw-nail withdrawal and bonding strength of Paulownia (*Paulownia tomentosa* Steud.) wood. J. Wood Sci., 60:201-206.

Ayrilmis N, Kaymakci A (2013) Fast growing biomass as reinforcing filler in thermoplastic composites: *Paulownia elongata* wood. Industrial Crops and Products, 43:457-464, doi:10.1016/j.indcrop.2012.07.050

Aytekin A (2008) Determination of screw and nail withdrawal resistance of some important wood species. Int. J. Mol. Sci., 9:626-637, doi:10.3390/ijms9040626

Bao FC, Jiang ZH, Jiang XM, Lu XX, Luo XQ, Zhang SY (2001) Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. Wood Science and Technology, 35:363-375, doi:10.1007/s002260100099

Barbu MC, Buresova K, Tudor EM, Petutschnigg A (2022) Physical and Mechanical Properties of *Paulownia tomentosa* x *elongata* Sawn Wood from Spanish, Bulgarian and Serbian Plantations. Forests 2022, 13:1543, doi:10.3390/f13101543.

Barbu MC, Tudor EM, Buresova K, Petutschnigg A (2023a) Assessment of Physical and Mechanical Properties Considering the Stem Height and Cross-Section of *Paulownia tomentosa* (Thunb.) Steud. x *elongata* (S.Y.Hu) Wood. Forests 2023a, 14:589, doi:10.3390/f14030589

Barbu MC, Radauer H, Petutschnigg A, Tudor EM, Kathriner M (2023b) Lightweight Solid Wood Panels Made of Paulownia Plantation Wood. Applied Sciences 2023b, 13:11234, doi: org/10.3390/app132011234

Bardarov N, Popovska T (2017) Examination of the properties of local origin Paulownia wood (*Paulownia* sp. Siebold & Zucc.). Manag. Sustain. Dev, pp. 75-78

Bcomp. bCores Qx + Sb; Bcomp: Fribourg, Switzerland (2023) Available online: https://pdf.nauticexpo.com/pdf/bcomp-ltd/bcores-qx-sb/51016-104454.html#open546181

Bergmann BA (1998) Propagation method influences first year field survival and growth of Paulownia. New Forests 1998, 16:251-264, doi:10.1023/A:1006529622871

Borrega M, Gibson LJ (2015) Mechanics of balsa (*Ochroma pyramidale*) wood. Mechanics of Materials, 84:75-90, doi:10.1016/j.mechmat.2015.01.014

Byrne CE, Nagle DC (1997) Carbonization of wood for advanced materials applications. Carbon 1997, 35:259-266, doi:10.1016/S0008-6223(96)00136-4.

Cao Y, Sun G, Zhai X, Xu P, Ma L, Deng M, Zhao Z, Yang H, Dong Y, Shang Z (2012) Genomic insights into the fast growth of Paulownias and the formation of Paulownia witches' broom. Mol. Plant 2021, 14:1668-1682, doi:10.1016/j.molp.2021.06.021

Chongpinitchai AR, Williams RA (2021) The response of the invasive princess tree (*Paulownia tomentosa*) to wildland fire and other disturbances in an Appalachian hardwood forest. Global Ecology and Conservation, 29, e01734, doi:10.1016/j.gecco.2021.e01734

Ciftci A, Kaya Z (2019) Genetic diversity and structure of *Populus nigra* populations in two highly fragmented river ecosystems from Turkey. Tree Genetics & Genomes 2019, 15, doi:10.1007/s11295-019-1370-5

Crul A (2023) Paulownia Plantages Management in Central Europe. Coppicing and Pruning. Expert interview, (accessed on 7 February 2023)

Deutsches Institut für Normung. Leichte Spanplatten - Anforderungen, Berlin, Germany, 2014 (DIN 16368:2014)

Deutsches Institut für Normung (2022) Solid biofuels - Determination of moisture content - Part 1: Reference method (ISO 18134-1:2022) Berlin, Germany, 2022 (DIN 18134-1:2015)

Deutsches Institut für Normung. Testing of Wood (1979) Determination of Swelling and Shrinkage; Berlin, Germany, (DIN 52184:1979-05)

Deutsches Institut für Normung. Testing of Wood(1976) Compression Test Parallel to Grain; Berlin, Germany, (DIN 52185:1976-09)

Deutsches Institut für Normung. Testing of Wood (1978) Bending Test; Berlin, Germany, (DIN 52186:1978-06)

Deutsches Institut für Normung. Testing of Wood (1979) Determination of Ultimate Tensile Stress Parallel to Grain, Berlin, Germany, (DIN 52188:1979-05)

Dogu D, Tuncer FD, Bakir D, Candan Z (2017) Characterizing Microscopic Changes of Paulownia Wood under Thermal Compression. BioResources, pp. 5279-5295

Donaldson L (2008) Microfibril angle: Measurement, variation and relationships-A review. IAWA J. 29:345-386.

Esteves B, Cruz-Lopes L, Viana H, Ferreira J, Domingos I, Nunes LJR (2022) The Influence of Age on the Wood Properties of *Paulownia tomentosa* (Thunb.) Steud. Forests 2022, 13, 700, doi:10.3390/f13050700

European Comission. List of Invasive Alien Species of Union concern. Available online: https://ec.europa.eu/environment/nature/invasivealien/list/index_en.htm.

EN 13354:2009. Solid Wood Panels (SWP) - Bonding Quality - Test Method. European Committee for Standardization: Brussels, Belgium, 2009

EN 1534:2011-01. Wood Flooring - Determination of Resistance to Indentation-Test Method. European Committee for Standardization: Brussels, Belgium, 2011

EN 310:2005. Wood-Based Panels; Determination of Modulus of Elasticity in Bending and of Bending Strength. European Committee for Standardization: Brussels, Belgium, 2005

EN 317:1993. Particleboards and fibreboards - Determination of swelling in thickness after immersion in water. European Committee for Standardisation, Brussels, Belgium, 1993

EN 319:1993. Particleboards and fibreboards - Determination of tensile strength perpendicular to the plane of the board. European Committee for Standardisation, Brussels, Belgium, 1993

EN 320:2011. Particleboards and Fibreboards - Determination of Resistance to Axial Withdrawal of Screws; European Committee for Standardization: Brussels, Belgium, 2011

EN 322:1993. Wood-based panels - Determination of moisture content. European Committee for Standardization: Brussels, Belgium, 1993

EN 323:2005. Wood-Based Panels - Determination of Density. European Committee for Standardization: Brussels, Belgium, 2005

EN 326-1:2005. Wood-Based Panels - Sampling, Cutting and Inspection - Part 1: Sampling and Cutting of Test Pieces and Expression of Test Results. European Committee for Standardization: Brussels, Belgium, 2005

Feng Y, Cui L, Zhao Y, Qiao J, Wang B, Yang C, Zhou H, Chang D (2020) Comprehensive selection of the wood properties of Paulownia clones grown in the hilly region of southern China. BioResources, pp. 1098-1111

Finger M (2016) Balsaholz (*Ochroma pyramidale*), Available online: http://www.holzwurm-page.de/holzarten/holzart/balsaholz.htm

Fos M, Oliver-Villanueva JV, Vazquez M (2023) Radial variation in anatomical wood characteristics and physical properties of *Paulownia elongata* x *Paulownia fortunei* hybrid Cotevisa 2 from fast-growing plantations. Eur. J. Wood Prod., pp. 81

Galos J, Das R, Sutcliffe MP, Mouritz AP (2022) Review of balsa core sandwich composite structures. Materials & Design 2022, 221, 111013, doi:10.1016/j.matdes.2022.111013

Garay R, MacDonald F, Acevedo M, Calderón B, Araya J (2009) Particleboard made with crop residues mixed with wood from *Pinus radiata*. BioResources, 4(4):1396-1408

Grosser D (2007) Die Hölzer Mitteleuropas: Ein mikrophotographischer Lehratlas, Reprint der 1. Auflage von 1977, Kessel: Remagen, ISBN 3935638221

He T, Vaidya B, Perry Z, Parajuli P, Joshee N (2016) Paulownia as a Medicinal Tree: Traditional Uses and Current Advances. EJMP 2016, 14:1–15, doi:10.9734/EJMP/2016/25170.

Huber C, Moog D, Stingl R, Pramreiter M, Stadlmann A, Baumann G, Praxmarer G, Gutmann R, Eisler H, Müller U (2023) Paulownia (*Paulownia elongata* S.Y.Hu) – importance for forestry and a general screening of technological and material properties. Wood Material Science & Engineering, pp. 1–13, doi:10.1080/17480272.2023.2172690

Hussain K, Nasir GM, Hussain T (2016) Comparison of wood anatomy of different Paulownia species grown in Pakistan. The Pakistan Journal of Forestry, pp. 1–7

International Organization for Standardization (1996) Wood-Determination of Density for Physical and Mechanical Tests; Brussels, Belgium.

Lbadawi M, Osman Z, Tahir PD, Nasroun T, Kantiner W (2015) Mechanical and physical properties of particleboards made from ailanthus wood and UF resin fortified by acacias tannins blend. Journal of Materials and Environmental Science, 6:1016-1021

Icka P, Damo R, Icka E (2016) *Paulownia Tomentosa*, a Fast Growing Timber. Ann. of ”Valahia” University of Agriculture, pp. 14-19.

Istok I, Kucinic M, Jambrekovic B, Drvodelic D, Sefc B, Sedlar T (2020) Physical properties of juvenile wood of two Paulownia hybrids. Drv. ind. 2020, 71:179-184, doi:10.5552/drvind.2020.1964

Jakubowski M (2022) Cultivation Potential and Uses of Paulownia Wood: A Review. Forests 2022, 13:668, doi:10.3390/f13050668

Kalaycioglu H, Deniz I, Hiziroglu S (2005) Some of the properties of particleboard made from Paulownia. J Wood Sci 2005, 51:410-414, doi:10.1007/s10086-004-0665-8

Kamperidou V, Lykidis C, Barmpoutis P (2018) Utilization of wood and bark of fast-growing hardwood species in energy production, Journal of Forest Science, 64(4):164-170.

Kang KH, Huh H, Kim BK, Lee CK (1999) An antiviral furanoquinone from *Paulownia tomentosa* Steud. Phytother. Res., 13:624-626, doi:10.1002/(SICI)1099-1573(199911)13:7<624:AID-PTR551>3.0.CO;2-A

Karinkanta P, Ämmälä A, Illikainen M, Niinimäki J (2018) Fine grinding of wood - Overview from wood breakage to applications. Biomass Bioenergy, 113:31-44.

Kaymakci A, Bektas I, Bal BC (2013) Some mechanical properties of Paulownia (*Paulownia elongata*) wood. In Proceedings of the International Caucasian Symposyum, Artvin, Turkey, 26–27 September 2013; pp. 917-920.

Khanjanzadeh H (2012) Utilization of bio-waste cotton (*Gossypium hirsutum* L.) stalks and underutilized Paulownia (*Paulownia fortunei*) in wood-based composite particleboard. Afr. J. Biotechnol., 11(31), doi: 10.5897/AJB12.288

Kiaei M (2013) Technological properties of Iranian cultivated Paulownia wood (*Paulownia fortunei*). Cellul. Chem. Technol. 47:735-743.

Komán S, Vityi A (2017) Physical and mechanical properties of *Paulownia tomentosa* wood planted in Hungaria. Wood Research, pp. 335-340.

Koman S, Feher S (2020) Physical and mechanical properties of Paulownia clone in vitro 112. Eur. J. Wood Prod., 78:421-423, doi:10.1007/s00107-020-01497-x.

Kotlarewski NJ, Belleville B, Gusamo BK, Ozarska B (2016) Mechanical properties of Papua New Guinea balsa wood. Eur. J. Wood Prod. 74:83-89.

Lachowicz H, Giedrowicz A (2020) Charakterystyka jakości technicznej drewna Paulowni Cote-2. Sylwan, 164(5):414-423, doi:10.26202/sylwan.2020024

Lee SH, Lum WC, Boon JG, Kristak L, Antov P, Pędzik M, Rogoziński T, Taghiyari HR, Lubis MAR, Fatriasari W, et al. (2022) Particleboard from agricultural biomass and recycled wood waste: a review. Journal of Materials Research and Technology, 20:4630-4658, doi:10.1016/j.jmrt.2022.08.166

Lucas-Borja ME, Wic-Baena C, Moreno JL, Dadi T, García C, Andrés-Abellán M (2011) Microbial activity in soils under fast-growing Paulownia (*Paulownia elongata* x *fortunei*) plantations in Mediterranean areas. Applied Soil Ecology, 51:42-51, doi:10.1016/J.APSOIL.2011.08.011

López F, Pérez A, Zamudio MA, Alva HE de, García JC (2012) Paulownia as raw material for solid biofuel and cellulose pulp. Biomass and Bioenergy, 45:77-86, doi:10.1016/j.biombioe.2012.05.010

Magar LB, Khadka S, Joshi JRR, Pokharel U, Rana N, Thapa P, Sharma KRSR, Khadka U, Marasini BP, Parajuli N (20180 Total Biomass Carbon Sequestration Ability Under the Changing Climatic Condition by *Paulownia tomentosa* Steud. Int J Appl Sci Biotechnol, 6:220-226, doi:10.3126/ijasbt.v6i3.20772

Mania P, Hartlieb K, Mruk G, Roszyk E (2022) Selected Properties of Densified Hornbeam and Paulownia Wood Plasticised in Ammonia Solution. Materials 2022, 15:4984

Moreno JL, Bastida F, Ondoño S, García C, Andrés-Abellán M, López-Serrano FR (2017) Agro-forestry management of Paulownia plantations and their impact on soil biological quality: The effects of fertilization and irrigation treatments. Applied Soil Ecology, pp. 117-118, 46–56, doi:10.1016/j.apsoil.2017.05.001

Nelis PA, Michaelis F, Krause KC, Mai C (2018) Kiri wood (*Paulownia tomentosa*): can it improve the performance of particleboards? Eur. J. Wood Prod., 76(2):445-453. doi: 10.1007/s00107-017-1222-7

Niemz P, Sonderegger WU (2021) Holzphysik: Eigenschaften, Prüfung und Kennwerte, 2. aktualisierte Auflage, Hanser 2021, München, ISBN 978-3-446-46749-1

Osei-Antwi M, Castro J de, Vassilopoulos AP, Keller T (2013) Shear mechanical characterization of balsa wood as core material of composite sandwich panels. Construction and Building Materials, 41:231-238, doi:10.1016/j.conbuildmat.2012.11.009

Pasiecznik N (2022) *Paulownia tomentosa* (Paulownia). CABI Compendium 2022, CABI Compendium, doi:10.1079/cabicompendium.39100

Remaley T (2023) Non-native Plants - Rock Creek Park. Available online: https://www.nps.gov/rocr/learn/natu re/non-native-plants.htm (accessed on 7 February 2023)

Rodriguez-Seoane P, Díaz-Reinoso B, Moure A, Domínguez H (2020) Potential of Paulownia sp. for biorefinery. Industrial Crops and Products, 155:112739, doi:10.1016/j.indcrop.2020.112739

Roffael, E.; Rauch, W. Einfluss der Rohdichte auf phenolharzgebundene Spanplatten. Holz als Roh- und Werkstoff, 1972(30),178–181

Röllig P, Tudor EM, Barbu MC, Direske M (20230 Effect of the particle geometry on lightweight particleboards from Paulownia using high frequency pressing technology. Wood Material Science & Engineering 2023 – *in print - doi: 10.1080/17480272.2023.2286625*

Sedlar T, Sefc B, Drvodelic D, Jambrekovic V, Kucinic M, Istok I (2020) Physical properties of juvenile wood of two Paulownia hybrids. Drv. Ind. 2020, 71:179-184.

Sell J (1997) für das Holz Lignum, S.A. Eigenschaften und Kenngrössen von Holzarten; 4., überarb. und erw. Auflage; Baufachverl: Dietikon, Switzerland, ISBN 3855652236

Snow WA (2015) Ornamental, crop, or invasive? The history of the Empress tree (Paulownia) in the USA. Forests, Trees and Livelihoods, 24:85-96, doi:10.1080/14728028.2014.952353

Tu J, Wang B, McGrouther K, Wang H, Ma T, Qiao J, Wu L (2017) Soil quality assessment under different *Paulownia fortunei* plantations in mid-subtropical China. J Soils Sediments, 17:2371-2382, doi:10.1007/s11368-016-1478-2

van Pham T, Biziks V, Mai C (2022) Effects of low and high molecular weight of phenol-formaldehyde (PF) on the properties of strand boards from kiri wood (*Paulownia tomentosa*). Wood Material Science & Engineering 2022, 17(5):337-344, doi: 10.1080/17480272.2020.1867239

van Wilgen BW, Zengeya TA, Richardson DM (2022) A review of the impacts of biological invasions in South Africa. Biol Invasions 2022, 24:27-50, doi:10.1007/s10530-021-02623-3

Wang Q, Shogren JF (19920) Characteristics of the crop-Paulownia system in China. Agriculture, Ecosystems & Environment 1992, 39:145–152, doi:10.1016/0167-8809(92)90050-L

Wiepking CA, Doyle DV (1960) Strength and related properties of balsa and quipo woods, Madison, USA, 1960. Available online: https://ir.library.oregonstate.edu/concern/defaults/sx61dq95c?locale=en

Yadav NK, Vaidya BN, Henderson K, Lee JF, Stewart WM, Dhekney SA (2013) Joshee, N. A Review of Paulownia Biotechnology: A Short Rotation, Fast Growing Multipurpose Bioenergy Tree. AJPS 2013, 04:2070-2082, doi:10.4236/ajps.2013.411259

Yorgun S, Yıldız D, Şimşek YE (2016) Activated carbon from Paulownia wood: Yields of chemical activation stages. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 38:2035-2042, doi:10.1080/15567036.2015.1030477