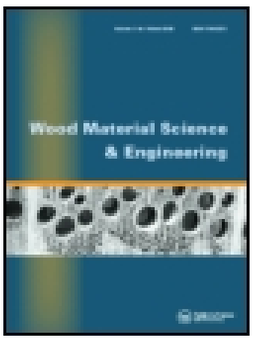

Wood Material Science & Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/swoo20

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To cite this article: Christian Huber, David Moog, Robert Stingl, Maximilian Pramreiter, Alexander Stadlmann, Georg Baumann, Gabriel Praxmarer, Roland Gutmann, Herfried Eisler & Ulrich Müller (2023): Paulownia (*Paulownia elongata* S.Y.Hu) – importance for forestry and a general screening of technological and material properties, Wood Material Science & Engineering, DOI: 10.1080/17480272.2023.2172690

To link to this article: https://doi.org/10.1080/17480272.2023.2172690

Published online: 04 Feb 2023.

WOOD MATERIAL SCIENCE & ENGINEERING
https://doi.org/10.1080/17480272.2023.2172690

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ORIGINAL ARTICLE

Paulownia (*Paulownia elongata* S.Y.Hu) – importance for forestry and a general screening of technological and material properties

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ABSTRACT

In Austria, paulownia (*Paulownia spp.*) has not been approved as a forest species. Because of the enormous annual growth and the promising mechanical and physical properties of this tree species, it is grown in short-rotation and value timber plantations in Central Europe. Previous studies have addressed the forestry and silvicultural aspects of different plant materials and issues in wood technology and wood physics based on small sample collections. Broad material screening for the technological evaluation of paulownia, samples obtained in large quantities from plantations, has not been conducted thus far. Therefore, this study aimed to provide a general overview of the technological, physical and mechanical properties of this wood species, in addition to basic forestry considerations. The wood samples for the experiments were obtained from an Austrian experimental plantation. In addition to wood drying, natural durability, workability and gluing, density and swelling/shrinking behaviour were investigated, and a comprehensive characterisation of all strength and stiffness properties was performed. The results will enable the modelling of paulownia wood to determine its static and dynamic loads, as well as the crash behaviour, using the finite element method (FEM) and well-founded assessments of the material's workability.

ARTICLE HISTORY
Received 17 November 2022
Revised 17 January 2023
Accepted 22 January 2023

KEYWORDS
Technological applications; material properties; paulownia; plantation; wood technology

1. Introduction

The paulownia tree (*Paulownia* spp.) has been cultivated and used in China for thousands of years. Among other applications, its wood has been used in furniture making, the production of traditional musical instruments and agroforestry systems to increase the yield of crops. The first paulownia trees were brought to Europe in the middle of the nineteenth century (Nimmervoll 2018). Because of its decorative appearance, large leaves and rapid growth, paulownia quickly became popular in Europe and was planted in gardens and parks. Today, this species has spread throughout the world. Currently, seven species and two cross-species of paulownia have been officially recognised (NCBI 2020). These differ in growth habit, ecological amplitude (i.e. temperature and water requirements) and appearance (Zhao-Hua *et al*. 1986).

Woods (2008) provided an overview of the paulownia tree as a new biomass. Even though this study dealt mainly with the technological, mechanical and physical properties of the Wooden material, the forest relevance of paulownia should have been considered. Despite its potential for the wood industry and its promising material properties, paulownia has not been approved as a forest plant in Austria. In this country, planting occurs exclusively in controlled plantations. Although there has been an increasing number of publications on aggressive neophytes, most work has focused on the invasive nature of paulownia and the options for controlling and containing the spread of this non-native wood species. All non-native plant species that were introduced by human activities before 1492 are called "archaeophytes". If they were introduced after 1492, they are called "invasive". When these non-native species have undesirable effects on native species, their communities or biotopes, they are called "invasive" (Neobiota 2020). In the case of neophytes, a clear distinction must be made between species that are permitted under forest law (Brawenz *et al*. 2015) and are cultivated in forest areas (e.g. *Quercus rubra* L., *Juglans nigra* L. and *Abies grandis* (Douglas ex D.Don) Lindl.) (Liesebach *et al*. 2008, Schuster 2015a, 2015b) and invasive species (e.g. *Ailanthus altissima* (Mill.) Swingle) (Kowarik and Säumel 2007, Nobis 2008, Kowarik and Rabitsch 2010, Frenes 2021) or species that are not permitted (e.g. *Paulownia* ssp.).

According to Ammer *et al*. (2014), a species is considered invasive if it poses a real and demonstrable threat and cannot be controlled by silvicultural or other measures or if control measures would be too costly. Relevant here is the effort required to control the spread of a species. According to Vor *et al*. (2015), the original biological characteristics of

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the species, such as dispersal, competition and reproductive behaviour, and their effects on other species at the respective site must be considered. According to Keil and Loos (2004), Remaley (2005) and Essl (2007), the dispersal potential of Paulownia can be described as high or expansive. It is assumed that climate change will further increase the invasion risk for native tree species (Essl 2007). Consequently, further research to assess "long-term invasion risks in semi-natural habitats" by neophytes is needed (Hubo *et al*. 2007, Nehring 2013).

In North America, where paulownia is considered highly invasive following large-scale disturbances, such as fires, the displacement of protected native plant species has already occurred in nutrient-poor and dry sites (Innes 2009). The increased pressure of invasiveness is likely due to large-scale paulownia cultivations in the 1970s and 1980s for the production of value timber (Zhao-Hua *et al*. 1986, Innes 2009). In Central Europe, under natural conditions, paulownia spreads preferentially on extreme sites that can be colonised by a few other native species. Therefore, according to Essl (2007), near-natural ecosystems have not yet been affected by its spread. However, in Switzerland Richter and Böcker (2001), observed that paulownia was spreading in coppice forests and forest clearings. It is possible that near-natural ecosystems in Central Europe will also come under greater pressure in the future, as areas under cultivation increase significantly, from individual paulownia trees originally planted in gardens and parks to large-scale cultivation in short-rotation plantations and agroforestry (Essel 2007, Thielen 2019, CATHAIA 2020).

The climate models projected by the Intergovernmental Panel on Climate Change (IPCC) result in higher temperatures (Stocker *et al*. 2014, Masson-Delmotte *et al*. 2021). An increase in temperature in the growing season would be beneficial for frost-sensitive paulownia species (P. *elongata* S.Y.Hu, P. *fortunei* (Seemann) Hemsley, and P. *tomentosa* (Thunb.) Steud.) (Zhao-Hua *et al*. 1986). In addition, other varieties could be adapted to Central European cultivation conditions (Stimm *et al*. 2013, CABI 2022). The most widespread paulownia species in Europe and the best studied is P. *tomentosa* (Thunb.) Steud. It is the most frost-resistant of the paulownia species, tolerating a wide temperature range from −20 °C to +40 °C. However, frost damage was observed in three trial plots in Bavaria (Bork *et al*. 2015). Under good light, nutrient conditions and sufficient water supply, it can reach extremely high growth rates. Its optimal growth has been shown during long warm periods at daily averages between 24 and 29 °C (Zhao-Hua *et al*. 1986).

At higher temperatures, more water is required for plants. However, in Central Europa, precipitation is limited during hot spells. Drought events in the growing season therefore also have a strong negative impact on the growth of paulownia (WBGU 2007). If unfavourable weather conditions occur, especially during the establishment phase, they have a negative effect on the survival rate of seedlings and lead to high failure rates (Wollenzien 2021). To avoid water stress, Zhao-Hua *et al*. (1986) recommended regular artificial irrigation at weekly intervals. However, under no circumstances, should waterlogging occur, as it can lead to the death of young plants after only three to four days.

Because of its pioneering character and high growth rate, the species is suitable for the recultivation of former open-cast mining areas, where it serves as erosion protection and contributes to soil improvement through the high nitrogen content of its leaf litter. Because of its deep root system, it can absorb many nutrients within a short time and therefore, has good potential for soil remediation. In China, the tree is even used as an intercrop in wheat cultivation. The use of its biomass extends beyond its wood to the tree's leaves and flowers. Young paulownia seedlings are resistant to widespread forest fungi. Even in their natural habitat, these trees are typically prone to grow in fresh deforestations, such as after fires. As a young plant, P. *tomentosa* (Thunb.) Steud. is comparatively weak in competition with other species if the rapid growth of its leaf canopy does not succeed in darkening the surrounding ground vegetation at an early stage. P. *tomentosa* (Thunb.) Steud. is an early successional species that is quickly displaced by later-emerging, more shade-tolerant species (Vor *et al*. 2015). In closed stands, it can no longer regenerate because it depends on an open soil substrate without litter for germination (Innes 2009). In doing so, its leaf litter not only reduces the germination rate of not only other species, but also its own species.

As already stated, the growth of the trees is rapid, and the wood obtained has an extremely low density. "European balsa" wood is therefore justified as a nickname for paulownia. The first plantations were established in 2009 by the WeGrow GmbH Company in Germany. In 2012, the Austrian company Plantownia GesbR started its first cultivation trials in plantations for value timber production in Austria. Currently, paulownia plantations in Austria are small (0.1–5 ha), and they are used by farmers to gain experience in growing the currently relatively unknown tree. Most of these plantations are deemed to generate high-quality (i.e. class A or B) wood. This method of cultivation is comparably labour-intensive. Growing paulownia wood as a biomass and energy source is currently uncommon, and it has been tested only in isolated small cultivations below 0.1 ha. In Austria, the first significant harvest (nlt. 35 cm diameter at breast height) of paulownia wood is expected to be available in 2026.

Cultivation conditions have been optimised in recent years, and plantation protocols have been successful regarding optimised growth rates and wood quality. Regarding climatology, optimised growth occurs at nlt. 700 mm of annual rain. During the early years of plantation, irrigation may be required in dry weather conditions to allow initial growth. After two to three years, the deep-rooting tree becomes more resilient against drought, and sporadic irrigation is required only in extreme dry conditions (e.g. no rain for several months in combination with sandy soil). The only pests that cause damage to young trees are mouse populations, which require annual countermeasures.

After its harvest, the tree can be grown again, sprouting from the existing root system, which is comparable to its crown. This guarantees the rapid growth of the second harvest, including higher resilience against drought. Despite the problems and challenges associated with the cultivation

of neophytes, climate change requires a critical examination of the concepts of forest management and the provision of roundwood resources that have been valid in Europe to date. Neophytes may have the potential to compensate for the loss of native trees due to drought and beetle calamity, especially Norway spruce (*Picea abies* (L.) H.Karst.). At the same time, because of the increasing number of environmental hazards, it is important to ensure that new silvicultural concepts do not cause additional problems. Previous studies in the literature on the technological potential of neophytes have not sufficiently addressed or comprehensively assessed the advantages, disadvantages, opportunities and risks involved in cultivating these trees. Essl (2007), Essl and Rabitsch (2013), Kleinbauer *et al*. (2010), Marana (2018) and Stringer (2007) conducted ecological assessments of paulownia in European and North American regions. In the case of P. *tomentosa* (Thunb.) Steud., a definitive statement on its invasiveness in native forest areas is not yet possible. Although there are indications of invasive behaviour, such as in the United States (Remaley 2005, Innes 2009), these findings cannot be readily transferred to Central European conditions (Nehring 2013). The danger of the uncontrolled spread of paulownia in Central Europe has been considered unlikely because of its growth characteristics. Therefore, compared with the tree of heaven (*Ailanthus altissima* (Mill.) Swingle), paulownia has been considered less invasive and aggressive.

In the search for a strategy for future adapted forest management, potential natural forest communities – that is, those that develop without silvicultural interventions – must be considered in selecting tree species (Kilian *et al*. 1993). The impairment of native tree species by invasive neophytes must be avoided. A prohibition on the cultivation of such species in forest areas is therefore justified, whereby risk assessments should be regionally related to the respective sites. In assessing the use of neophytes, the secure supply of roundwood to the timber industry must also be considered, as this industry is of great economic importance for Central Europe, particularly because it secures numerous jobs. Plantation could be a possible solution to this dilemma. The potential of alien forest plants could be investigated in demarcated areas. Particularly in the case of forest plants with short rotation times, sufficient information could be gathered quickly to determine whether a less labour-intensive plantation could also be used in forest areas. In the case of paulownia, the rotation time is only seven years.

In contrast to forestry considerations of paulownia, the wood technology assessment of this resource is clear. Paulownia's extremely low density of 261 kg/m^3 results in a high porosity of about 83% and a corresponding cell wall percentage of 17% (Kiaei 2013). According to Kiaei (2013), the fibre saturation point is high at 31.15%, and the cell wall is composed as follows: holocellulose (80.1%), cellulose (51%), lignin (23.5%) and extractives (11.8%). Fast-growing tree species have been planted in short-rotation plantations. In addition to various tree species, such as European poplar (*Populus* spp.) and willow (*Salix* L.), plants such as miscanthus (*Miscanthus* Andersson) have also been used (Kirov *et al*. 2014). Paulownia has excellent values in terms of volume growth per year and per hectare (Stimm *et al*. 2013, Sperr 2017). As a pioneer species, paulownia provides advantages in terms of stand stability and insensitivity to pest attacks in colonising difficult soils (Berdón *et al*. 2017, Wunder *et al*. 2018). However, at least some paulownia hybrids lag behind other species in terms of biomass production (Kirov *et al*. 2014). Another disadvantage of paulownia for energy wood production is the high cost of plant material and maintenance requirements and low frost hardiness (Sperr 2017). The pulp and paper properties of paulownia are considered disadvantageous of its low pulp content and fibre properties (Ates *et al*. 2008), although significant improvements could be achieved by adjusting the pulping process (García *et al*. 2011).

According to this study, the mean fibre length and width were 996 and 30.55 µm, respectively. The diameter of the lumen was 25.3 µm and the mean cell wall thickness was 5.25 µm. Spirchez *et al*. (2021) analysed briquettes and pellets obtained from paulownia. Kalaycioglu *et al*. (2005), Nelis *et al*. (2018) and Salari *et al*. (2013) studied the potential of this wood species for particleboard (PB) and oriented strand board (OSB) production, respectively. Because of its low weight, the wood species is particularly suitable for lightweight construction applications. For solid wood solutions and its use as part of a wood composite, the material properties and technological processability of paulownia must be determined. Some studies on the mechanical properties of paulownia are available in the literature (Zhao-Hua *et al*. 1986, Kaymakçı *et al*. 2013, Kiaei 2013, Reza Taghiyari *et al*. 2014, Koman *et al*. 2017, Müller and Stingl 2019, Koman and Feher 2020, Jakubowski 2022).

Nevertheless, the literature lacks comprehensive technological and physical assessments of this tree species. In particular, the characteristic values of native plantation wood are not yet available. Therefore, the present study investigated an available sample of paulownia wood from an Austrian plantation was investigated. In addition to its physical properties, the technical drying of paulownia wood and its processability were assessed and described. This study examined the technological and material properties of samples of paulownia wood from this plantation. In addition to drying, the natural durability, workability, gluing, density, swelling and shrinking behaviour, thermal conductivity, Poisson's ratio, and all relevant strength and stiffness properties in all anatomical directions of the samples were investigated. This study provides a basis for considering the possible applications of paulownia wood.

2. Materials and methods

2.1. Wood material

This report summarises various trials and investigations conducted by the Institute of Wood Technology and Renewable Materials at University of Natural Resources and Life Sciences, Vienna (BOKU) in cooperation with the Plantownia GesbR Company (Bairisch Kölldorf, Austria) from 2018 to 2021. In addition to paulownia trees in plantations, those in parks and gardens with diameters at breast height of 25, 26, 35 and 60 cm and aged 9, 12, 14 or 53 years, respectively, were felled in 2018 and used to investigate the materials. A total of 14

Table 1. Standards and publications according to which the various tests were conducted and the number of specimens per test series. N describes the number of plantations (first number) and old growth trees (second number).

Title of the Standard	N/N	source
Testing of wood; determination of density	65/21	DIN 52182 (1976)
Testing of wood; determination of moisture content (MC)	17/21	DIN 52183 (1977)
Testing of wood; determination of swelling and shrinkage	17/21	DIN 52184 (1979)
Testing of wood; compression test parallel to grain	64/10	DIN 52185 (1976)
Testing of wood; determination of ultimate tensile stress parallel to grain	62/14	DIN 52188 (1979)
Testing of wood; compression test perpendicular to grain	95/7	DIN 52192 (1979)
Testing of wood; bending test	104/9	DIN 52186 (1978)
Testing of wood; Impact bending test; Determination of impact bending strength	63/9	DIN 52189-1 (1981)
Determination of the tensile strength perpendicular to the grain	101/7	Kumpenza *et al*. (2018)
Determination of Poisson's ratio	140	Kumpenza *et al*. (2018)
Determination of shear strength and shear modulus	144	Müller *et al*. (2015)
Determination of the shear strength according to ASTM	12/12	ASTM D143-22 (2022)
Adhesives for load-bearing timber structures – Test methods – Part 1: Determination of longitudinal tensile shear strength	37	ÖNORM EN 302-1 (2013)
Thermal resistance	5/4	Vay *et al*. (2021)

plantation trees were felled in 2019 (six trees) and 2020 (eight trees). At breast height (diameter of the tree at a height of 130 cm above ground), the diameter of the five- to seven-year-old trees ranged from 14–19 cm. In the first trial with old growth trees and six plantation trees were felled in 2018 and 2019, respectively, three to five specimens per tree were prepared for testing. In the second trial of eight plantation trees that were felled in 2020, at least three specimens per tree were prepared, resulting in different numbers of specimens that were tested, which are shown in Table 1.

2.2. Wood drying

After felling, the trees were cut into logs 3 m in length. For the investigations, the lowest log from the stem base was used in each case. The 3-m-long logs were sawn into 50 mm thick boards and then dried in a drying chamber (Mühlböck, Eberschwang, Austria). For the drying trials of the paulownia samples, a drying scheme developed for European poplar species was used. This drying scheme was adapted to investigate three drying rates: soft, moderate and fast.

Soft drying:
The sawn timber was dried carefully at a constant temperature of 60 °C. The heating time was 400 min, which corresponded to a heating rate of 1 degree per 10 min. Heating the core of the boards required 300 min. The drying gradient was 2.5 at the beginning, which slowly increased to 3 towards the end of the drying procedure. After a total drying time of 270 h, the sawn timber was conditioned for 10 h to guarantee a uniform moisture content (MC) of 12% across the cross sections of the boards. With an initial MC of approximately 72% and a final moisture content of approximately 12%, a drying time of approximately 290 h reduced the wood moisture content by approximately 83% of the initial moisture content. This corresponded to a decrease in wood moisture content of about 0.2% per hour.

Moderate drying

The drying rate was again increased continuously from 2.5–3. The time required to heat the chamber was 200 min and after another 300 min, the centre of the boards reached a drying temperature of 72 °C. After 190 h of drying and 10 h of conditioning, the process was completed with a target MC of about 12%.

Fast drying

As for moderate drying, the drying temperature was 72 °C. However, the drying rate increased from 2.7–3.7 during the process. The heating time was again 200 min, and the heating of the wood required 300 min. After a drying time of 155 and 10 h of conditioning, the target MC was reached. Drying stresses and deformation after the three drying experiments were measured according to DIN CEN/TS 14464 (2010).

2.3. Material characterisation

The sawn timber obtained was used to produce the samples according to various standards and publications. The type of test, the standard or publication, the description of specimen geometry, and the number of samples by test series are summarised in Table 1. All mechanical tests were performed using a universal testing machine (Zwick/Roell Z100 or Zwick/Roell Z20). A mechanical extensometer (makroXtens, Zwick/Roell, Ulm, Germany) was used to measure the specimen deformation in the compression test. In the bending tests, which were conducted according to DIN 52186 (1978), the modulus of elasticity and the bending strength were measured using the same mechanical extensometer, where the deflection in the middle of the bent part was determined at an accuracy of ± 1.5 µm. In the tensile tests and Poisson's ratio measurement, a laser extensometer (laserXtens, Zwick/Roell, Ulm, Germany) was used according to Kumpenza *et al*. (2018) and Moog (2021). The shear measurements were based on the Arcan method, and an electronic speckle pattern interferometry (ESPI, Q300, Dantec, Ulm, Germany) was used according to Kumpenza *et al*. (2019) and Müller *et al*. (2015). Impact bending was tested using a pendulum impact tester (Otto Wolpert-Werke, Germany), according to DIN 52189–1 (1981).

The tensile (t), compressive (c), bending (m) and shear (v) strengths (f) (test set-up described with the index at the first

position) were determined at an MC of approximately 10% (index at the second position) after conditioning to an equilibrium MC in the climate chamber at 20 °C and 65% relative humidity for at least 60 days in longitudinal (L), tangential (T) and radial (R) directions. The indices at the third and fourth positions described the load direction and the direction in the plane perpendicular to the load, respectively. Young's modulus (E) and Poisson's ratio (μ), which were determined on tensile specimens, were calculated by Equations (1) and (2) based on the deformations in the field of view (FoV) after loading.

$$E = \frac{\Delta\sigma}{\left(\frac{\Delta l}{l}\right)} \tag{1}$$

$$\mu = \frac{(\Delta d \times l)}{(d \times \Delta l)} \tag{2}$$

where Δσ [N/mm²] is the difference of the stresses in the specimen at 10 and 40% load levels in relation to the ultimate load and Δl and Δd [mm/mm] correspond to the deformation of the length (l) [mm] and width (d) [mm] of the FoV at the two load levels.

For example, $f_{t,10,LR}$ describes the tensile strength of the wood material at an MC of 10% loaded in the longitudinal direction, with the (FoV) laying parallel to the longitudinal and radial directions to determine the elastic constants Youngs-modulus ($E_{t,10,LR}$) and Poisson's ratio ($\mu_{t,10,LR}$) (see Figure 1). In measuring the Poisson's ratio, the deformation of the specimens was determined from four individual measurements to improve the signal-to-noise ratio of the strain measurement. For this purpose, the specimens were repeatedly loaded up to about 40% of the breaking load.

A detailed description of the use of Poisson's ratio (i.e. sample preparation, geometry of the samples and test set-up) was provided in Kumpenza *et al*. (2018). A detailed description of the methods, including the sample preparation, geometry of the samples as well as the equipment and test set-up used to determine Poisson's ratio and Young's modulus measurements in tension was provided in Kumpenza *et al*. (2018) and Moog (2021). To determine shear properties, Arcan shear tests were applied in tension mode, which provided a homogeneous strain field in the reduced midsection (Müller *et al*. 2015). The deformation in the shear field of the samples was measured by a speckle interferometer (ESPI, Q300 Ettemayer, Ulm, Germany). The preparation steps and sample dimensions, as well as the exact test procedure and test set-up, were provided elsewhere (Müller *et al*. 2015, Kumpenza *et al*. 2019).

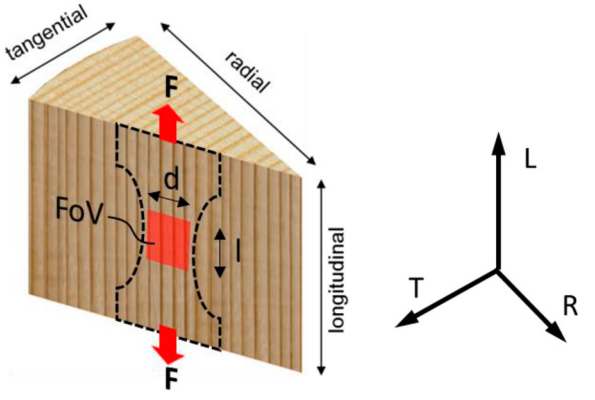

Figure 1. Schematic drawing of a tensile specimen with an MC of 10% loaded in the longitudinal direction with the FoV in the longitudinal-radial (LR) plane to determine the tensile strength ($f_{t,10,LR}$), Young's-modulus ($E_{t,10,LR}$) and Poisson's ratio ($\mu_{t,10,LR}$) in the LR direction.

Density samples were used to determine the equilibrium MC of the samples after storage in the climate chamber. Before the mechanical tests and before measuring kiln dry density and MC corresponding to DIN 52182 (1976) and DIN 52183 (1977), all samples were stored for at least 60 days in a climate chamber at 65% rel. humidity and 20 °C. To determine the shear strength (τ) of the material, a 1-component (1 K RP2760, Collano, Switzerland), a 2-component polyurethane (2 K RP 3007, Collano, Switzerland) and emulsion polymer isocyanate (EPI) adhesive (HR 390, Collano, Switzerland) were used. The adhesive spreading quantities were 180 g/m² (1 K PUR), 300 g/m² (2 K PUR) and 150 g/m² (EPI) according to the technical data sheets. The samples were cold pressed at about 0.8 MPa for 2 h. The thermal resistance (λ) of paulownia was determined using the λ-Meter EP500 (Lambda-Meßtechnik GmbH Dresden, Germany). λ [$Wm^{-1}K^{-1}$] was calculated corresponding to formula (3), where d [m] is the sample thickness, ΔT [K] is the temperature difference between the two sample surfaces, $\dot{Q}^*$ [W] is the heat flow equivalent to $P=(U^*I)$ [W] is the electrical power in watts, U [V] is the electrical voltage in volts, A [m²] corresponds to the cross-sectional area of the sample and I [A] is the current in amperes.

$$\lambda = \frac{\dot{Q}^* \times d}{(A \times \Delta T)} = \frac{(U \times I \times d)}{(A \times \Delta T)} \tag{3}$$

Natural durability:

To determine the natural durability of paulownia wood in ground contact, prismatic specimens (500 mm x 50 mm x 25 mm) were cut from the dried boards and tested following the field test method in to ÖNORM EN 252 (2014). The material was stored in a climatic chamber (20 °C and 65% rel. humidity) until equilibrium MC was reached. The boards were then buried in the soil on a suitable test site in Tulln/Donau, Austria (coordinates 48° 20′ N, 16° 3′ E, 180 m above sea level). Every six months, samples were taken from the soil and visually assessed for fungal and insect degradation.

Other samples were exposed to natural weathering according to ÖNORM EN 927-3 (2020) and ÖNORM EN ISO 2810 (2020). For this purpose, sample size 300 mm in length, 100 mm in width, and 18 mm in thickness were mounted outdoors at the same site in a southerly direction at an angle of 45°. During the three-year weathering period, the samples were regularly visually assessed, and the wood colour was determined by a Phyma Codec 400 Vis spectrometer according to ÖNORM EN ISO/CIE 11664-4 (2020). The following metrological data were recorded during the weathering period from September 12, 2019 to September 1, 2022 (about three years): average daily temperature, 11° (maximum value +36 to −14.5 °C); average daily precipitation,

1.5 mm (summed over the entire duration of weathering 1580 mm); average daily global radiation: 117 W/m² (summed up over the entire duration of weathering 128540 W/m²); average daily wind speed, 5.6 km/h (maximum wind speed 95 km/h). The meteorological data were taken from the Austrian central institute for meteorology and geodynamics office (ZAMAG 2023).

3. Results and discussion

3.1. Density and thermal conductivity

The kiln dry density (ρ_0) of all paulownia samples investigated showed a mean value of 236, SD ± 52.0 kg/m³ (minimum value 167, maximum value 389 kg/m³). The kiln dry density of the plantation trees was 215, SD ± 29.9 kg/m³ (minimum value 167, maximum value 282 kg/m³), which was significantly lower than the kiln dry density of the old growth trees, which had an average value of 299, SD ± 52.0 kg/m³ (minimum value 224, maximum value 389 kg/m³). Koman *et al*. (2017) studied a paulownia clone and reported a kiln dry density of 215 kg/m³. Koman *et al*. (2017) and Kaymakçı *et al*. (2013) reported slightly higher values of 275 and 250 kg/m³, respectively. Barbu *et al*. (2022) also reported higher values. The test material was sourced from three different plantations. The density scatter ranged as follows: Bulgaria (250 kg/m³), Serbia (259 kg/m³) and Spain (266 kg/m³). The highest density values of paulownia were reported by Frank and Voigt (2022) to be at 280 kg/m³. Hence, the kiln dry density of paulownia obtained in this study is in good agreement with the findings in the literature.

Balsa (*Ochroma pyramidale* (Cav. ex Lam.) Urb.), a known wood species with extremely low density, ranges from 80 to 340 kg/m³ (Galos *et al*. 2022). According to ÖNORM B 3012 (2003), the domestic light wood species European poplar and Norway spruce each have an average density of 441 kg/m³ and, thus, have a significantly higher kiln dry density than paulownia. Consequently, paulownia has high potential for use in lightweight construction. According to Kollmann (1982, pp. 507ff), wood and wood-based materials showed a more or less linear increase in thermal conductivity as density increased. These findings indicate that low-density wood species have significantly lower thermal conductivity compared with high-density wood species. Because paulownia has comparably low density, it provides comparable values with regard to thermal conductivity. In paulownia, a λ value of 0.06 and 0.09 W/m²K was determined in samples with densities of 200 and 300 kg/m³, respectively. A similar density dependence was observed in balsa, which had 0.05 and 0.07 W/m²K for density values of 150 and 200 kg/m³, respectively. A density dependence, however at a bit lower level was observed in balsa, which had 0.036 and 0.056 W/m²K for density values of 113 and 174 kg/m³, respectively (Kotlarewski *et al*. 2014).

3.2. Dimensional stability

Because of the high porosity of paulownia, a maximum water absorption capacity of 350% can be reached (Kiaei 2013). The evaluation of MC after storage in the climate chamber in the present study showed that paulownia, with an average of 9.5%, had a significantly lower equilibrium MC than native wood species, which ranged closely around the value of 12% (Kollmann 1982). A striking feature of paulownia is its extremely low swelling and shrinkage. Table 2 shows a comparison of the maximum swelling values of paulownia and different native wood species. In the various anatomical directions of wood, paulownia had just 40% of the swelling capacity of beech (*Fagus sylvatica* L.). Sell (1987) reported swelling rates of 0.085 and 0.185% per % MC for balsa in radial and tangential directions, respectively. The swelling rates of paulownia in the radial and tangential directions were 0.065–0.085 and 0.125–0.197% per % MC change, respectively, which was comparable to balsa. This low swelling-shrinking behaviour partly explains why paulownia wood is relatively easy to dry. Therefore, it has the potential to be used for technical purposes (e.g. sports equipment, furniture, interior cladding, panelling, etc.). Moreover, it is easy to apply because only small deformations, compared with common wood species, are expected to occur during the moisture uptake of components.

3.3. Drying properties

3.3.1. Soft drying

During the drying time of 290 h, the MC was reduced by 60%, which corresponded to a drying rate of 0.2% per hour. The MC of the individual boards also showed a high variation of 80–100% before the drying test. After the conditioning period, the boards had a MC from 8–13%. The MC across the boards showed that soft drying resulted in homogeneous MC (i.e. less than 1%), which corresponded to very low drying stresses, according to DIN CEN/TS 14464 (2010), at 0.41 mm directly and 0.38 mm 24 h after drying. No cell collapses, cracks or significant warping and twisting were observed either before or after drying. Slight deformations were observed only in some cases. The drying process resulted in a relatively strong discolouration from a brownish colour to red and purple colours.

Table 2. Kiln dry density (ρ_0) and swelling properties (β) of paulownia compared with some native wood species growing in Austria. Indices a, r, t and v stand for axial, radial, tangential and volume respectively.

Wood species	ρ_0 (g/cm³)	β_a (%)	β_r (%)	β_t (%)	β_v[4] (%)
Paulownia (*Paulownia* spp.)[1]	0.24	0.2	1.7	4.7	6.7
Paulownia (*Paulownia tomentosa* (Thunb.) Steud.)[2]	0.28	0.7	2.2	3.7	6.3
Paulownia (*Paulownia tomentosa* (Thunb.) Steud.)[3]	0.29	-	2.5	5.9	8.4
Weymouth pine (*Pinus strobus* L.)[5]	0.37	0.2	2.3	5.8–6.0	8.3–9.7
European poplar (*Populus* spp.)[5]	0.41	0.3	5.2	8.3	10.7–14.3
Norway spruce (*Picea abies* (L.) H.Karst.)[5]	0.41	0.3	3.6	7.8	11.6–12.0
Ash (*Fraxinus excelsior* L.)[5]	0.67	0.2	5.0	8.0	12.8–13.6
Oak (*Quercus* spp.)[5]	0.67	0.4	4.0–4.6	7.8–10.0	12.6–15.6
Beech (*Fagus sylvatica* L.)[5]	0.67	0.3	5.8	11.8	14.0–21.0

[1]These values were sourced from Müller and Stingl (2019).
[2]These values were sourced from Koman *et al*. (2017).
[3]These values were sourced from Akyildiz and Kol (2010).
[4]These values were sourced from Wagenführ and Wagenführ (2022).
[5]Native wood species growing in Austria (ρ_0, β_a, β_r, β_t) were sourced from ÖNORM B 3012 (2003).

However, discolouration affected only the uppermost wood surface (less than 1 mm).

3.3.2. Moderate drying

The drying rate was 0.25% per hour, and the variations in MC values after drying (8–14%) were slightly higher than in the case of soft drying. The MC profiles across the boards (about 1%) and drying stresses (0.12 mm) were in the same range. With the exception of a few cracks near the pith of two boards, moderate drying was satisfactory. The discolouration on the board surfaces corresponded to that induced buy soft drying.

3.3.3. Fast drying

The drying rate was 0.35% per hour, resulting in significantly higher MC variability (7–13%) after the conditioning phase. Pronounced MC profiles were visible along and across the boards (up to 3%), corresponding to clearly visible drying stresses, which were 2.58 mm immediately after the drying experiment and 2.89 mm 24 h later. Most boards showed significant warping. However, except for some cracks near the pith, no drying cracks or cell collapse were observed. The discolouration of the board surfaces was similar to that found in the other two drying tests. Before drying the wood, the drying stresses were also measured on the boards according to DIN CEN/TS 14464 (2010). The values obtained (0.09–0.11 mm) were very low, which was striking because of the low density and the very high growth rate of the trees, with an average annual ring width in the centimetre range. It was assumed that good drying properties could be explained by the low swelling/shrinkage rate, as shown in Table 2. A poplar drying schedule was adapted from company Mühlböck (Eberschwang, Austria). A drying rate of 2.5–3.7 was found to be suitable for paulownia. Compared with natural hardwood species, such as oak (*Quercus* spp.) and beech, the drying rate and drying speed can be classified as simple and very high. The drying behaviour of the 50 mm thick paulownia boards was similar to those of softwood species, such as pine (*Pinus sylvestris* L.) and Norway spruce, which is only about 30% faster. For industrial purposes, drying between medium and fast is recommended. However, the drying tests were conducted based on a drying programme that was actually developed for poplar wood. For industrial paulownia sawn timber production, a separate paulownia drying programme is required.

3.4. Technological properties

3.4.1. Processability

The production of a high number of samples for the different tests and experiments required processing a large amount of paulownia wood. Because of the several working hours required to process the log material and timber, a qualitative assessment by the workers was possible. Overall, the processing of the material was uncomplicated because of its very low density. Low growth and drying stresses allow for easy processing with a circular saw. Only during planing and sanding were smaller fibrous tear-outs observed, suggesting the presence of tension in the wood.

3.4.2. Glueability

The tensile shear tests showed a wood fracture percentage of 100% for all three glues. There was no significant difference between the shear strength (τ) of EPI joints (4.2 ± 0.60 N/mm^2) and 2 K PUR joints (4.11 ± 0.6 N/mm^2), whereas slightly higher strength values were found for 1 K PUR joints (4.69 ± 0.48 N/mm^2). The higher strength values of 1 K PUR might be explained by the higher ductility of this kind of adhesive (Müller *et al*. 2005, Gindl and Müller 2006). Because neither shallow wood failure nor cohesive failure of the adhesives was observed, it can be assumed that the three adhesives used in this study had a higher shear strength than the wood substrate and that a stable wood–adhesive interphase was formed. Because of the effective gluing properties and the high dimensional stability, it can be assumed that paulownia is not prone to delamination.

3.4.3. Natural durability

Colour was measured by spectrophotometer (Phyma CODE 400) at wavelengths ranging from 400–700 nm. The light source was defined by the standard illuminant D65 with an observer of 2° (Teischinger *et al*. 2012, Meints *et al*. 2017). The diameter of the FoV was 20 mm, and the analysis of the colour data was expressed according to the CIE L*a*b* colour space (ÖNORM EN ISO 11664: 2008). Before the weathering period, the initial colour of the wood was determined, and the following values were found: lightness of the colour L* = 72.9; red-green axis value a* = 4.6; yellow–blue axis value b* = 14.4; chroma C* = 15.2; hue angle h° = 68.8°. The colour was identified in 10 measurement spots per sample, and a mean value was calculated. The same spots were used for all 10 measurements within the three-year weathering period. The colour measurements of the individual samples were determined approximately every four months; that is, 10 colour measurements (including determination of the initial colour) were conducted during the three-year weathering period. The colour measurements were conducted in spring (March), summer (July) and late autumn (November).

After three years of exposure outdoors, the samples showed typical grey discolouration, and it was noted that samples with wide annual rings were subject to more rapid weathering. Accordingly, the plantation-grown paulownia with very wide annual rings showed significantly faster weathering compared with the naturally grown trees. After only two years, all samples had turned grey and showed only slight seasonal fluctuations in colour. The colour measurement showed the following values at the end of the experiment: L* = 49.0; a* = 1.5; b* = 3.5; chroma C* = 3.8; hue angle h° = 66.6°. The wood colour showed a colour distance (ΔE*) of 26.45, became darker (ΔL* - 23.9) and lost much of its colour intensity (ΔC* - 11.4). The sample material showed no significant changes except for the colour change. No wood-destroying organisms (e.g. fungi or wood-destroying insects) or cracks were detected, and the surface hardness was slightly reduced.

3.4.4. Natural durability with ground contact

The natural durability of paulownia wood in contact with the ground was tested according to ÖNORM EN 252 (2014). At the first inspection at six months, the first signs of fungal infestation appeared. After one year of exposure, the samples buried in the soil showed considerable to complete destruction and a high loss of mass due to wood-destroying microorganisms. About 90% of all samples failed after two years of soil contact. This means that these samples were partially or completely destroyed during the standard impact test (slight blow/hit on the buried sample) or upon digging out or visual inspection. In some cases, the degradation of the material was so advanced that the wood could no longer be distinguished from the soil. Compared with reference wood species, such as pine splint wood or other wood species, such as poplar or alder, the paulownia samples in this study must be placed in the lowest durability class five, "not durable".

3.5. Mechanical properties

In addition to its low density and swelling and shrinkage values, one of the most prominent characteristics of paulownia is its low strength, which is significantly weaker than that of native wood species. Because of the large number of results and the objective of providing exact characteristic values, including the observed scatter by numerical methods, the values derived from the mechanical tests are summarised in Table 3. To compare wood species with each other and with other materials, the concepts of specific stiffness (E_{spec}) and strength (f_{spec}) according to Ashby (2010) should be introduced here. If kiln density (ρ_0) was used to determine the specific characteristics, the specific modulus of elasticity and the specific strength were calculated according to Equations 4 and 5:

$$E_{spec}\left(\frac{Nm}{g}\right) = \frac{E\left(\frac{N}{mm^2}\right)}{\rho_0\left(\frac{g}{cm^3}\right)} \quad (4)$$

$$f_{spec}\left(\frac{Nm}{g}\right) = \frac{f\left(\frac{N}{mm^2}\right)}{\rho_0\left(\frac{g}{cm^3}\right)} \quad (5)$$

For example, the specific tensile strength ($f_{spec,t,12}$) of paulownia was 148 Nm/g in the plantation trees, which is within the range of the European poplar at 146 Nm/g. In contrast, the mechanically highly efficient Norway spruce has a specific tensile strength of 186 Nm/g, which is about 25% higher than the value of the two broadleaf tree species.

To simulate the material of paulownia wood by means of (FEM), an appropriate material model dependent on the requirements must be found. If only the linear elastic material behaviour is of interest, it would be sufficient to have characteristic strength and stiffness values such as E, ft, fc, fv, fm and G in the different anatomical directions of the wood. For the crash simulation, however, information on material behaviour over wide deformation ranges until complete failure is necessary. Therefore, stress–strain curves ranging from the linear elastic region to complete material softening must be provided. The basic procedure for the numerical simulation of wood was described by Baumann *et al.* (2019) and Müller and Stingl (2019). Different modelling approaches and programmes are beyond the scope of this article. However, it is essential for all numerical calculation methods that appropriately representative measurement data and so-called middle curves are used as inputs for the simulation of wood species. In the tensile tests, the simple averaging of all stress–strain curves led to discontinuities caused by failures at different stress and strain levels, which did not correspond to the curves of the individual specimens. To avoid these "jumps", the mathematical approach of Klug *et al.* (2019) was used. A mean curve that describes transverse compression behaviour is shown in Figure 2.

Table 3 shows the mean values and standard deviations of the tension and compression properties of the plantation paulownia and old growth trees.

Table 3. Mechanical properties of the Paulownia species under investigation. Divided into old-growth and plantation trees. Mean values (mean), standard deviation (SD), coefficient of variation (CoV) and number of specimens per test run (N) of the tensile, compression and bending experiments determining tensile strength (f_t), tensile Youngs modulus (E_t), compression strength (t_c), compression Youngs modulus (E_c), bending strength (f_m) and bending Youngs modulus (E_m) of the paulownia material in the different wood anatomical directions L_R, L_T, R_L, R_T, T_L, T_R. The values of the old growth trees are highlighted in light grey. All strength and stiffness values are given in N/mm². The material was tested at 9.5% MC.

Mechanical properties	mean (N/mm²)	SD (N/mm²)	CoV (%)	N
$f_{t,12,LR}$ of the old growth trees*	45.8	± 7.9	17.3	14
$E_{t,12,LR}$ of the old growth tress*	4703	± 567.5	12.1	14
$f_{t,12,LR}$ of the plantation trees	35.7	± 11.1	30.9	38
$E_{t,12,LR}$ of the plantation trees	4679	± 1132.1	24.2	38
$f_{t,12,LT}$ of the plantation trees	36.2	± 8.6	23.7	24
$E_{t,12,LT}$ of the plantation trees	4752	± 985.5	20.7	24
$f_{t,12,RL}$ of the old growth trees*	4.1	± 0.4	8.2	7
$E_{t,12,RL}$ of the old growth trees*	525	± 56.3	10.7	7
$f_{t,12,RL}$ of the plantation trees	2.7	± 0.5	19	30
$E_{t,12,RL}$ of the plantation trees	330	± 83.6	25.4	30
$f_{t,12,RT}$ of the plantation trees	2.5	± 0.8	33.6	23
$E_{t,12,RT}$ of the plantation trees	336	± 50.6	15.1	23
$f_{t,12,TL}$ of the plantation trees	2.5	± 0.9	37.1	24
$E_{t,12,TL}$ of the plantation trees	149	± 37.3	25.1	24
$f_{t,12,TR}$ of the plantation trees	2.7	± 0.4	15.4	24
$E_{t,12,TR}$ of the plantation trees	145	± 23.1	15.9	24
$f_{c,12,LR}$ of the old growth trees*	30.0	± 3.0	10.1	10
$E_{c,12,LR}$ of the old growth tress*	-	-	-	-
$f_{c,12,LR}$ of the plantation trees	22.8	± 4.5	19.5	40
$E_{c,12,LR}$ of the plantation trees	4934	± 740.7	15	40
$f_{c,12,LT}$ of the plantation trees	23.9	± 4.1	17.2	24
$E_{c,12,LT}$ of the plantation trees	4539	± 851.7	18.8	24
$f_{c,12,RL}$ of the old growth trees*	3.9	± 0.5	13.1	7
$E_{c,12,RL}$ of the old growth trees*	488	± 83.7	17.1	7
$f_{c,12,RL}$ of the plantation trees	1.8	± 0.4	19.6	26
$E_{c,12,RL}$ of the plantation trees	265	± 60.9	22.9	26
$f_{c,12,RT}$ of the plantation trees	1.7	± 0.1	7.1	21
$E_{c,12,RT}$ of the plantation trees	268	± 41.0	15.3	21
$f_{c,12,TL}$ of the plantation trees	1.8	± 0.2	11.2	24
$E_{c,12,TL}$ of the plantation trees	131	± 19.3	14.8	24
$f_{c,12,TR}$ of the plantation trees	1.8	± 0.2	11.9	24
$E_{c,12,TR}$ of the plantation trees	132	± 20,0	14.3	24
$f_{m,12,LT}$ of the old growth trees*	53.4	± 8.7	16.3	9
$E_{m,12,LT}$ of the old growth trees*	5381	± 732.8	13.6	9
$f_{m,12,LT}$ of the plantation trees	38.6	± 7.0	18.1	59
$E_{m,12,LT}$ of the plantation trees	4959	± 801.7	16.2	59
$f_{m,12,LR}$ of the plantation trees	36.4	± 5.8	15.8	45
$E_{m,12,LR}$ of the plantation trees	4703	± 591.0	12.6	45

* Values of the old growth trees

Tensile and compression tests were conducted to determine Poisson's ratios in the LT and LR directions. The difference between the two test runs indicates only the rotation of the lateral surface of the sample by 90°. Accordingly, a t-test did not yield a significant difference between the LR ($f_{Z,10,LR} = 35.74 \pm 11.05$ N/mm^2) and the LT directions ($f_{Z,10,LT} = 36.22 \pm 8.58$ N/mm^2). The mean value of the series in the LT and RL direction was $f_{Z,10,L} = 35.92 \pm 10.09$ N/mm^2. Moreover, no significant difference was observed for the Young's modulus in the LR ($E_{Z,10,LR} = 4679.41 \pm 1132.10$ N/mm^2) and the LT ($E_{Z,10,LT} = 4752.20 \pm 985.54$ N/mm^2) direction.

Significant differences in all strength values were found in the comparisons between the old growth trees and the plantation trees. The ring widths of the old growth trees were generally narrower than those of the plantation trees, which had ring widths ranging from one to two centimetres. Accordingly, as previously mentioned, the density of the plantation trees was lower than that of the old growth trees. Nevertheless, similar values were observed in the longitudinal Young's modulus. Moreover, no significant differences in the strength and modulus of elasticity were observed between RL and RT or between TL and TR, including tension and compression.

The compression strength in the longitudinal direction (mean value of the LT and LR was 23.22 N/mm^2) was in good agreement with Koman and Feher (2020) and Koman *et al*. (2017), who reported compression strengths of 19.9 and 22.14 N/mm^2, respectively. The tensile strength in the longitudinal direction in Koman *et al*. (2017) (33.23 N/mm^2) was slightly lower than values measured in this study. However, the Young's modulus determined in the longitudinal direction was about 30% higher than the values found in previous studies (Kaymakçı *et al*. 2013, Kiaei 2013, Koman *et al*. 2017), which ranged between 3492 and 3883 N/mm^2.

Slightly higher bending values in the LT compared with the LR direction were found in the plantation trees in the three-point bending experiments. The mean values of both directions were found to be 37.61 ± 6.54 N/mm^2, which aligns with Kaymakçı *et al*. (2013) and Koman *et al*. (2017), who reported bending strength values of 35.79 and 32.3 N/mm^2, respectively. As in the compression and tension experiments, higher Young's modulus values were found in the bending experiments compared with those found in previous studies (Kaymakçı *et al*. 2013, Kiaei 2013, Koman *et al*. 2017). On one hand, there were certain inconsistencies in Kaymakçı *et al*. (2013) regarding the reported compressive (35.56 N/mm^2) and bending strengths (35.79 N/mm^2), which were in the same strength range. The compressive strengths of different wood species are usually significantly lower than the bending strengths.

In contrast, the values of bending (41.07 N/mm^2) and compressive strength (14.61 N/mm^2) reported by Kiaei (2013) showed significant differences, which indicates that these values need to be critically questioned. It should be emphasised that in the current study, the strength values and Young's modulus were in very good agreement in both the longitudinal and transverse directions (see Table 2). Furthermore, significantly larger sample sizes were examined in the current study than in previous studies. Therefore, it is assumed that the values shown in Table 2 are much more representative of plantation paulownia trees with an oven dry density in the range of 215 kg/m^3.

Regarding impact bending strength, significantly higher values were determined for the old growth trees in the current study (36.04 ± 22.98 kJ/m^2) than for the plantation trees (13.16 ± 5.42). The higher values could be partly explained by the higher density. However, the sample size (N = 9) was small, and the value scatter (CoV = 63.77%) was high in this group, indicating that they may not be representative. In contrast, the sample size of the plantation trees (N = 63) was large, and the data scatter (CoV = 41.19%) was much lower. It can therefore be assumed that paulownia has a very low impact strength because of its low density. Furthermore, the impact bending strength of this tree species was characterised by a relatively large scatter.

The Poisson's ratios determined in all six wood anatomical directions are summarised in Table 4. The same equipment used by Kumpenza *et al*. (2018, 2019) and Matz (2017) was used in the current study to determine these values. In previous studies, oak and Norway spruce were investigated. Previous measurements of Poisson's ratios of wood have rarely been conducted because they are labour-intensive and time consuming (Hörig 1935, Wommeldorff 1966, Neuhaus 1981, Niemz and Caduff 2008, Keunecke *et al*. 2008). The problems with different measurement methods and the value scatter were discussed in detail in Kumpenza *et al*. (2018, 2019) and Matz (2017). The wood species measured by Kumpenza *et al*. (2018, 2019) and Matz (2017) were not anatomically comparable with paulownia. If necessary, a comparison with balsa can be made because of the latter's low density. For example, Hearmon (1948) reported the following values:

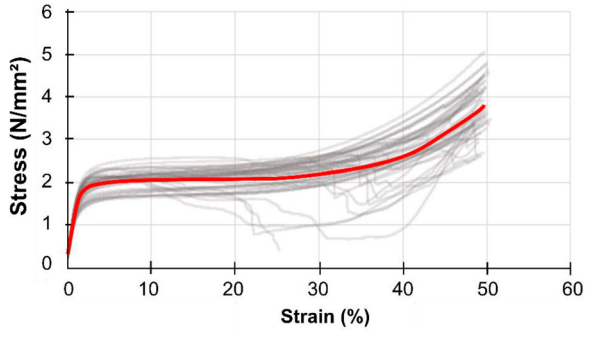

Figure 2. Stress–strain curves of all specimens investigated in transverse compression. The red line indicates the so-called middle curve, calculated corresponding to Klug *et al*. (2019).

Table 4. Poisson's constants (μ) of paulownia plantation trees in all anatomical directions of wood. SD and CoV describe the standard deviation and the coefficient of variation. N describes the sample of specimens per test run. LR = longitudinal-radial direction, LT = longitudinal-tangentially; RL = radial-longitudinal; RT = radial-tangentially, TL = transverse-longitudinal; TR = transverse-radial.

Direction	LR	LT	RL	RT	TL	TR
μ value	0.37	0.50	0.10	1.02	0.04	0.44
SD	± 0.12	± 0.18	± 0.07	± 0.19	± 0.03	± 0.07
CoV	32.41	35.83	66.24	18.60	83.03	15.30
N	24	24	24	20	24	24

$\mu_{LR} = 0.23$, $\mu_{LT} = 0.49$, $\mu_{RL} = 0.018$, $\mu_{RT} = 0.66$, $\mu_{TL} = 0.009$, $\mu_{TR} = 0.24$.

Arcan shear tests (Arcan *et al*. 1978) on paulownia were conducted following the experimental procedures in Kumpenza *et al*. (2019) and Müller *et al*. (2015) to determine the shear strength and shear modulus in all wood anatomical directions. In particular, in the Arcan method, the determination of the shear strength transverse to the grain (RL and LT directions) is problematic because of the low transverse compressive and tensile strengths of wood compared with the strengths longitudinal to the grain. A detailed discussion of the problems, advantages and disadvantages of the experimental set-up and equipment used in this study can be found elsewhere (Müller *et al*. 2015, Kumpenza *et al*. 2019). Overall, paulownia has been found to be characterised by low shear moduli, primarily because of its low density. In the current study, the rolling shear (RT and TR directions) ranged between 21.50 and 25.53 N/mm^2 (Table 5). The longitudinal and transverse values were about 10 times as high. It was observed that the values along the grain (LR and LT directions) were below the values across the grain (RL and TL directions), which were not observed in Norway spruce (Müller *et al*. 2015) or beech (Krüger and Wagenführ 2020). However, these wood species differ significantly from the microstructure of paulownia.

Table 4 shows the shear modulus (G) and shear strength values (fv) found in all Arcan shear tests in the different anatomical directions of wood. A comparison of the values found by the block shear test according to ASTM D143-22 (2022) with those obtained from the Arcan shear test showed that significantly higher shear strength values were determined in the LR or LT directions. The higher values found in the block shear test were previously known (Sretenovic *et al*. 2004). This problem may be more pronounced in paulownia, as the transverse compressive strengths were very low, and the compaction of the material may have led to a stronger increase in the shear values found in the block shear test. In any case, FEM analyses of wood showed that the block shear tests yielded higher strength values, as high normal stresses acted in this test set-up (Sretenovic *et al*. 2004).

Light wood species are considered for use in many lightweight and sandwich structures, constructions and materials. Galos *et al*. (2022) discussed in detail the different properties and applications of balsa. Like balsa, paulownia is fast-growing and shows a wide range of density variations. However, paulownia can be cultivated in domestic plantations and is thus available in increasing quantities in Europe. In their study, Borrega and Gibson (2015) tested balsa specimens with different densities for their mechanical behaviour. These values were in good agreement with the values reported by Galos *et al*. (2022). Both studies included mechanical and physical values in different density ranges. The values of balsa were compared with the values in the current study of paulownia Austrian plantation wood in the same density range of about 220 kg/m^3. The values presented by Borrega and Gibson (2015) indicated a wood MC of 5.8%. Slight changes in stiffness and strength due to the different wood moisture contents were not considered.

Table 5. G and fv values of the Arcan shear experiments. G describes the shear modulus and fv the shear strength values. N describes the sample of specimens per test run. LR = longitudinal-radial direction, LT = longitudinal-tangentially; RL = radial-longitudinal; RT = radial-tangentially, TL = transverse-longitudinal; TR = transverse-radial.

Direction	LR	LT	RL	RT	TL	TR
G (N/mm^2)	169.13	96.88	243.12	21.50	214.77	25.53
SD (N/mm^2)	94.25	36.50	111.59	5.27	78.66	6.80
CoV (%)	55.73	37.67	45.90	24.50	36.63	26.63
fv (N/mm^2)	2.30	2.73	3.89	0.80	4.50	0.85
SD (N/mm^2)	0.61	1.20	0.45	0.24	0.75	0.30
CoV (%)	26.51	44.11	11.63	30.54	16.69	35.82
N	24	24	24	20	24	24

In the current study, the longitudinal and transverse compressive strengths of paulownia were 24.6 and 1.6 N/mm^2, respectively, which compared very well with balsa (23 and 1.6 N/mm^2, respectively). In terms of flexural strength, paulownia at 38 N/mm^2 was slightly above the values of balsa (31.9 N/mm^2), whereas slightly higher shear strengths were found for balsa (4.9 MPa) than for paulownia (4.2 MPa). The moduli of elasticity derived from the bending test were similar in both balsa (4900 N/mm^2) and paulownia (4936 N/mm^2). Perpendicular to the grain, both wood species showed a similar Young's modulus value of about 270 N/mm^2. At 310 N/mm^2, slightly higher shear moduli in the TL and RL directions were found for balsa than for paulownia (see Table 4). This rough comparison indicates that paulownia could be an effective substitute for balsa. In technical applications, paulownia could even be advantageous because of its excellent low swelling properties.

4. Conclusion

1. This study conducted a comprehensive material screening of paulownia, which showed that the specific strengths and stiffness of this non-native wood species were significantly lower than those of native tree species. In addition to its low density and good thermal insulation, the particularly high dimensional stability of paulownia wood should be emphasised.
2. The gluing and drying of this tree species were found to be unproblematic in dry conditions. With regard to the natural durability of paulownia wood, the results of the first test showed very low durability in contact with soil and rapid greying when exposed to weather. The technical properties of the paulownia samples were comparable to those of balsa having the same density.
3. For a final forestry assessment of the currently available plant material, further findings should be gained through the current trial plots on plantations. Therefore, potential risks in the wider cultivation of this wood species could be assessed. In the case of a positive assessment, paulownia represents an interesting roundwood resource according to current knowledge.

Acknowledgments

The authors are grateful for research funding from the Federal Ministries BMK and BMDW as well as the Province of Styria within the Competence

Centres for Excellent Technologies (COMET) programme, as well as from the companies ACstyria Mobilitätscluster GmbH, Collano AG, IB STEINER, DYNAmore Gesellschaft für FEM Ingenieurdienstleistungen mbH, EJOT Austria GmbH & Co KG, Forst-Holz-Papier, Fill Gesellschaft m.b.H, Glanzstoff Management Consulting GmbH, Holzcluster Steiermark GmbH, Klumpp Coatings GmbH, LEAN Management Consulting GmbH, Volkswagen AG and Weitzer Wood Solutions GmbH. The COMET programme is administered by the Austrian Research Promotion Agency (FFG 882.509) and the Styrian Business Promotion Agency (SFG 1.000.065.896).

The authors would also like to thank Veronika Knoblich and Birgit Brandstätter for preparation the sample. Furthermore, the authors would like to thank Christian Plomberger from Fischer Sports GmbH and DI Christian Tippelreither, MBA and DI(FH) Erhard Pretterhofer from Holzcluster Steiermark GmbH for their kind support.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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