# Wood Technological Properties of the Tree of Heaven (*Ailanthus altissima* (Mill.) Swingle) and Studies on Possible Applications

Christian Huber  Alfred Teischinger  Robert Stingl
Maximilian Pramreiter  Alexander Stadlmann  Reinhard Brandner
Ulrich Müller

## Abstract

The tree of heaven (*Ailanthus altissima* (Mill.) Swingle) is a neophyte that is classified as highly invasive. This study shows that in contrast to the challenges the forestry industry faces with this species, the wood of the tree of heaven has considerable promising technological and pulp and paper properties. The attractive wood is hardly distinguishable from European ash (*Fraxinus excelsior* L.) both visually and in its mechanical properties. Consequently, the wood of the tree of heaven also has a high potential for load-bearing and solid-wood applications. A final technological evaluation of the wood is challenging because the tree of heaven is currently being massively combated, which negatively affects the quality of the roundwood material. Therefore, noncontrolled free-standing trees were examined in this study.

The tree of heaven (*Ailanthus altissima* (Mill.) Swingle) belongs to the family Simaroubaceae and is native to China. Further information on its habit and growth (Hecker 2001, Panayotov et al. 2011, Kowarik and Säumel 2013) as well as on its origin, naming, and use in medicine and pharmacy can be found elsewhere (Swingle 1916, Hu 1979, Li et al. 2021). Individual specimens of this species were brought to Europe in the 1740s and planted as park and avenue trees (Schmidt and Heinrichs 2015). Thanks to its decorative appearance, rapid growth, and resistance to pests and pollutants, the tree species quickly became popular (Meyer 1982, Shah 1997, Udvardy 2004). As a pioneer species, it also spreads rapidly into surrounding forest areas (Kowarik and Säumel 2007).

The tree is relatively undemanding in terms of soil and precipitation, i.e., it has a wide physiological amplitude. However, low temperatures and frost are limiting factors (More and White 2005, Gurtner et al. 2015). In fact, the tree copes very well with the prevailing climatic conditions in Central Europe. Further information on site requirements is described in various studies (Kowarik and Böcker 1984, Hecker 2001, Kowarik and Säumel 2007, Wunder et al. 2018). Hu (1979), Lodge (1993), Knapp and Canham (2000), and Jörg (2017) provide information on further silvicultural properties and browsing. However, little is known about the forestry performance of the tree of heaven (Miller 1990). The central forestry significance of the neophyte tree of heaven is reduced to its high invasiveness (Kowarik and Säumel 2007, Nobis 2008, Kowarik and Rabitsch 2010, Frenes 2021). A species is classified as invasive if it poses

---

The authors are, respectively, PhD; Univ. of Natural Resources and Life Sci. (BOKU Univ.), Vienna, Austria; Dept. of Material Sci. and Process Engineering, Inst. of Wood Technol. and Renewable Materials, Tulln an der Donau, Austria and teacher; HTL Mödling, Abteilung Holztechnik, Mödling, Austria (christian.huber@htl.moedling.at); retired Professor and technician, Univ. of Natural Resources and Life Sci. (BOKU Univ.), Vienna, Austria; Dept. of Material Sci. and Process Engineering, Inst. of Wood Technol. and Renewable Materials, Tulln an der Donau, Austria (alfred.teischinger@boku.ac.at; robert.stingl@boku.ac.at); Senior Researcher, Univ. of Natural Resources and Life Sci. (BOKU Univ.), Vienna, Austria; Dept. of Material Sci. and Process Engineering, Inst. of Wood Technol. and Renewable Materials, Tulln an der Donau, Austria; Dept. of Environ. Sci., Policy, and Manag., College of Environ. Design, Univ. of California Berkeley, Berkeley, California (maximilian.pramreiter@boku.ac.at); Shareholder, HYCOBILITY Engineering and Technologies GmbH, Vienna, Austria (alexander.stadlmann@hycobility.com); Associate Professor, Graz Univ. of Technol., Inst. of Timber Engineering and Wood Technol., Graz, Austria (reinhard.brandner@tugraz.at); and Privatdozent and Senior Researcher, Univ. of Natural Resources and Life Sci. (BOKU University), Vienna; Dept. of Material Sci. and Process Engineering, Inst. of Wood Technol. and Renewable Materials, Tulln an der Donau, Austria (ulrich.mueller@boku.ac.at [corresponding author]). This paper was received for publication in October 2024. Article no. 24-00050.

Forest Prod. J. 75(2):109–119.
doi:10.13073/FPJ-D-24-00050

a real and demonstrable threat to other species and cannot be effectively controlled by silvicultural and other measures (Ammer et al. 2014, Vor et al. 2015). The tree of heaven is known to displace native vegetation (Blab 2002, Wunder et al. 2014, Siegrist and Holdenrieder 2016).

The tree of heaven has been on the European Union list of invasive alien species since 2019 and therefore requires special treatment under the respective state nature conservation laws (EU 2019). Since the amendment of the Austrian Forest Act (November 16, 2023, Federal Law Gazette No. 144/2023), the tree of heaven is no longer considered forest vegetation. This means that active management of this species in forests is no longer permitted.

Control measures for the tree of heaven go back a long way. One possible method is targeted infection with *Verticillium* fungi (e.g., *Verticillium nonalfalfae*; Siegrist and Holdenrieder 2016). Despite vigorous control measures, further spread of this tree has not yet been prevented (Blab 2002, Kowarik and Säumel 2007, Ließ 2007, ÖWAV 2016). The tree of heaven exerts considerable competitive pressure, especially in poor locations with low precipitation where native trees are increasingly coming under pressure because of climate change. It is difficult to prevent its future spread. In this context, it can be assumed that ongoing climate change will further increase the risk of invasion for native tree species (Essl 2007, Bockel et al. 2019. Long-term consequences are difficult to assess (Hubo et al. 2007, Nehring et al. 2013).

In European forestry, the tree of heaven has so far been given only limited economic importance, although, as this study proves, it has certain wood-technological potential. In areas where control measures have been abandoned, it makes sense to discuss whether silvicultural measures to create higher roundwood qualities would be justified. A cautious assessment of this question, considering the necessary containment of invasive neophytes, should examine both the timber industry aspects regarding a reliable roundwood supply and the forestry aspects. This seems justified because the timber industry is of great economic importance, particularly for Central Europe, and secures numerous jobs.

The main part of this publication deals with the technological, mechanical, and physical properties of the wood material, but some forestry aspects of the tree of heaven are also discussed here because of the close connection between forestry and wood quality. Little is known about the wood properties of the tree of heaven and the correlation between properties such as density and mechanical properties or shrinkage and swelling behavior. The wood of this ring-porous species is visually almost indistinguishable from that of the native common ash (*Fraxinus excelsior*; Berki 2014). In the studies by Brandner and Schickhofer (2010, 2013), the mechanical properties were determined both in sawn timber dimensions and in small, defect-free samples. The measurements resulted in an average bending strength of 106 N/mm$^2$ for defect-free samples, whereas the strength values determined for sawn timber were around 50 percent lower. The bending strength is therefore in the range of the values given by Sell (1989) for ash wood (100 to 127 N/mm$^2$).

The average apparent bending modulus of elasticity (MOE; including shear deformation) for small defect-free samples was given by Hölbling (1989) as approximately 11,000 N/mm$^2$. The MOE determined by Brandner and Schickhofer (2010, 2013; approximately 14,600 N/mm$^2$) is not comparable with the values of Hölbling (1989), as this was determined from local deflections without shear strain in a four-point test. The average bending strength stated by Hölbling (1989; $\sim$100 N/mm$^2$) was in the range of the values published by Brandner and Schickhofer (2010, 2013). The bending strengths reported by Panayotov et al. (2011) were significantly lower than the two Austrian studies, at 71 N/mm$^2$, whereas the MOE measured in the bending test of about 12,000 N/mm$^2$ is closer to values reported by Hölbling (1989).

The compressive strengths found by Brandner and Schickhofer (2010, 2013), with an average of 48.5 N/mm$^2$, are in good agreement with Hölbling (1989), who determined an average compressive strength of 44.0 N/mm$^2$. The values published by Panayotov et al. (2011) were slightly higher, at approximately 56.0 N/mm$^2$.

Analogous to the bending strengths, Brandner and Schickhofer (2010, 2013) also found significantly higher tensile strengths (151 N/mm$^2$) for the small, defect-free samples compared with the investigated ungraded sawn timber (42.0 N/mm$^2$). At 41.6 N/mm$^2$, the average compressive strength of the sawn timber was almost in the same range as the tensile strength. The good mechanical properties presented by Hölbling (1989) and Brandner and Schickhofer (2010, 2013) were confirmed by values reported by Changjiu et al. (2000).

Hölbling (1989) stated a density of 0.56 to 0.64 g/cm$^3$ for the tree of heaven. This value was within the range of native, ring-porous hardwoods: oak (*Quercus* spp., 0.67 g/cm$^3$) and ash (*F. excelsior*, 0.69 g/cm$^3$; Sell, 1989). The density of black locust (*Robinia pseudoacacia*; 0.73 g/cm$^3$) is significantly higher. After storage in a normal climate (at 20°C and 65% relative humidity [RH]), Brandner and Schickhofer (2010, 2013) found an equilibrium moisture content (MC) of 13.5 percent, which almost corresponds to that of European ash. Panayotov et al. (2011) observed a high anisotropy in radial and tangential swelling in tree of heaven. In the study of Brandner and Schickhofer (2008), on the other hand, a ratio of about 1 to 2 between radial and tangential shrinkage was determined, which is usual for hardwood species.

Tree of heaven's good mechanical properties (Changjiu et al. 2000) suggest its use in construction, for tool handles, and sports equipment. In their research, Brandner and Schickhofer (2010) pointed out the high mechanical potential of tree of heaven. The wood could therefore be used as a possible replacement for ash in load-bearing applications.

The suitability of tree of heaven for pulp and paper production has been described in some technical articles (Adamik and Brauns 1957, Isenberg 1981). According to Adamik and Brauns (1957) and Narayanamurti and Singh (1962), the wood has properties that render it satisfactory for both pulp and fiberboard, in some cases better than aspen (*Populus tremula*). Moslemi and Bhagwat (1969) reported on the partial use of tree of heaven in pulp production in the United States. Adamik and Brauns (1957), in light of their detailed studies in Austria, recommended tree of heaven for the pulp industry because of its fast growth, fiber length (1.2 to 1.4 mm), easy pulping, and high yield (fiber content 60% to 70%). Härtel (1955), Hu (1979), and Alden (1995) also confirmed the suitability of the tree for pulp production.

Thanks to its high fiber content and long fibers, the tree's good paper properties have been postulated (Ferreira et al. 2013, Baptista et al. 2014). Narayanamurti and Singh (1962) experimented with chips and fibers of tree of heaven in connection with the production of particleboard and fiberboard and also attested to their high suitability and excellent properties in this area of application. Technical articles or scientific publications on the suitability of the tree of heaven for the production of wood-based materials are not available. As climate change may lead to an increase in the occurrence of tree of heaven in the future, it seems interesting to investigate the possible use of the material for the wood industry.

Hölbling (1989) reported good wood technology processing of tree of heaven. The wood of the tree is used to make furniture, wooden accessories, traditional musical instruments, and for cartwright work (Grabner 2017). Other applications include the medicinal use of extracts, in silk production, and as a fuel and energy wood (Hu 1979, Kowarik and Säumel 2007).

A search of the Chinese literature revealed no specialist articles or scientific publications on solid-wood applications or as construction timber for tree of heaven. The tree is not currently used on a large scale in China and neighboring markets for furniture construction, windows, doors, and parquet floors. Only a few small companies include the tree in their product range, offering it for use in limited quantities as flooring, veneer wood (Miao et al. 2014), for panel production, and for furniture manufacture. Regarding its use as veneer, the problem of dimensional stability has been pointed out (Miao et al. 2014). Compression drying or impregnation with synthetic resins is suggested as an improvement.

In this study, material from Österreichische Bundesforste AG was examined and compared with the available material parameters, with a view to considering the possible uses of tree of heaven wood. In addition to the mechanical and physical properties, the technical drying of the wood, its processability, and its use for paper, fiberboard, and particleboard production were evaluated and described. Its natural durability and gluing were also examined.

## Materials and Methods

### Wood material

A systematic recording of the wood properties from different locations is not possible because of the control measures of the tree of heaven in Austrian forests (Brandner and Schickhofer 2010, 2013). Therefore, individual, noncontrolled trees from forested areas were used as test material, which were assumed to be more representative than trees from combated stocks with tree of heaven. In cooperation with Österreichische Bundesforste, a total of eight trees (*A. altissima* (Mill.) Swingle), with an average breast height diameter of 30 cm (27 to 69 cm), was felled from a forest area in Donaudorf, Austria. The trees were cut into logs of a length of 3 m each. The first two logs of the eight trees were used for the study (i.e., $N = 16$ logs). The logs were processed into sawn timber (thickness of the boards in green condition 1.5 inches = 38 mm). The small sawmill (Preisberger, Gföhl, Austria) used a live (through and through) sawing pattern. A total of 1.45 $m^3$ of sawn timber was produced. The boards were largely knot free. The remaining tree material was processed into wood chips using an industrial standard chipper. The material was subsequently used for paper, fiber, and chipboard production.

### Wood chip drying

Technical drying of 40 kg of wood chips took place in a Weiss drying chamber (Weiss Klimatechnik GmbH, Germany). After 7 days of storage in the climate chamber, a wood MC of approximately 4 percent was achieved. The material for the refiner tests was stored at −19.7°C until 24 hours before milling.

### Sawn timber drying

The board material was divided into three stacks of the same size and fed to three different drying processes, air drying and kiln drying without and with steaming. The material before drying had an average MC of approximately 65 percent (range 40% to 85%). Investigation of drying stresses after both drying experiments was carried out according to ÖNORM ONR EN/TS 14464 (2010).

*Air drying.*—The undried boards were stored outdoors (shaded or covered and adequately ventilated) for 4 summer months. The material was then conditioned in a climatic room (at 20°C and 65% RH) for about 8 weeks.

*Kiln drying.*—Kiln drying was carried out in a 2-$m^3$ lab-sized kiln-drying chamber (Mühlböck Holztrocknungsanlagen GmbH, Austria). An industry-standard program for ash was used for drying, and 10 wood moisture sensors were used for process control and documentation. The drying temperature was kept at approximately 40°C until the fiber saturation point. From this point on, it was continuously raised to approximately 58°C. The drying gradient was in the range of 2.3 to 2.8 (average 2.5). Within 14 days, a final MC of the sawn timber of 12 ± 1.5 percent could be achieved.

*Sawn timber steaming followed by kiln drying.*—At the beginning of this process, the boards were steamed (steaming process analogous to European beech [*Fagus sylvatica*]) to reduce growth stresses in the material. A chamber atmosphere of almost 100 percent RH and 95°C was achieved. After 50 hours, a gentler drying procedure was started, using a drying temperature of approximately 40°C up to the fiber saturation range. Then the chamber temperature was increased to approximately 45°C and kept constant for the remaining drying time. The drying gradient was between 1.8 and 2.3 (average 2.0).

### Material characterization

The sawn timber obtained from both controlled drying experiments was used for the production of samples according to the various standards and publications. The type of test, standard, or publication describing the specimen geometry and number of samples by test series are summarized in Tables 1 and 2. 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 DIN 52188 (1979) tensile and DIN 52185 (1976) compression tests. In the bending tests according to DIN 52186 (1978), the MOE was measured in addition to the bending strength using the same mechanical extensometer, whereby the deflection in the middle of the specimen was determined with an accuracy of ±1.5 μm. The speed of the crosshead for all mechanical experiments was selected in accordance with the cited standards. Impact bending was tested with a pendulum impact tester (Otto Wolpert-Werke, Germany) corresponding to DIN 52189-1 (1981).

The tensile (t), compressive (c), bending (m), and shear (v) strengths ($_f$) were determined at an equilibrium MC of approximately 12 percent after conditioning in a climate chamber at 20°C and 65 percent RH for at least 60 days. The indices ($_L$) and ($_T$) describe the load direction in and perpendicular to the grain, respectively. The MOEs determined on compression

*Table 1.—Overview of the tests, sample sizes, and references (standards) according to which the various tests were performed, as well as the number (N) of samples per test series for tree of heaven (Ailanthus altissima).*

| | *N* | Reference |
|---|---|---|
| Testing of wood; determination of density | 338 | DIN 52182 (1976) |
| Testing of wood; determination of moisture content | 200 | DIN 52183 (1977) |
| Testing of wood; compression test parallel to grain | 76 | DIN 52185 (1976) |
| Testing of wood; compression test perpendicular to grain | 93 | DIN 52192 (1979) |
| Testing of wood; tensile test parallel to grain | 20 | DIN 52188 (1979) |
| Testing of wood; bending test | 65 | DIN 52186 (1978) |
| Testing of wood; impact bending test; determination of impact bending strength | 78 | DIN 52189-1 (1981) |
| Determination of shear strength according to ASTM | 81 | ASTM D143-22 (1922) |
| Wood flooring—determination of resistance to indentation—test method | 107 | ÖNORM EN 1534 (2010) |
| Adhesives for load-bearing timber structures—test methods—Part 1: Determination of longitudinal tensile shear strength | 55 | DIN EN 302-1 (2013) |

($E_c$) and tensile ($E_t$) specimens were calculated for the center of the specimen after loading in accordance with the standards DIN 52188 (1979) and DIN 52185 (1976) by Equation 1:

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

where $\Delta\sigma$ is the difference between the stresses of the sample at 10 and 40 percent of the maximum stress at failure. $\Delta l$ corresponds to the elongation of the sample within the measuring base of length $l$ at the two load levels.

For the bending specimens, the MOE ($E_m$) was determined according to DIN 52186 (1978) using Equation 2:

$$E = \frac{\Delta F \;\; l3}{48 \;\; \Delta\delta \;\; I} \tag{2}$$

$\Delta$F corresponds to the difference between the load levels of the specimen at 10 and 40 percent of the maximum load level at break, $l$ is the span length of the specimen, $\Delta\delta$ is the difference in deflection at the corresponding load levels 10 and 40 percent, and $I$ is the moment of inertia of the specimen.

To investigate the suitability of tree of heaven for flooring applications, not only the strength properties but also the hardness (ÖNORM EN 1534 2010) were examined and compared with 23 samples each of ash and oak.

To determine the equilibrium MC of the samples after storage in the standard climate chamber, density samples were used. Before the mechanical tests and before measuring the kiln-dry density and MC corresponding to DIN 52182 (1975) and DIN 52183 (1977), all samples were stored for at least 60 days in a climate chamber (65% RH and 20°C).

For determining tensile shear strength ($\tau$) corresponding to DIN EN 302 (2013) in dry (A1) and wet conditions (A5) of the material, a one-component polyurethane (PUR; Purbond HBS309, Henkel, Switzerland), urea–formaldehyde (UF; Aerolite UP4535, Synthesa, Austria), melamine–urea–formaldehyde (MUF; Metadynea, Krems, Austria), phenol–resorcinol–formaldehyde (PRF; Aerodux 185, Friebe Luftfahrt-Bedarf, Germany), and emulsion polymer isocyanate (EPI; Jowat, Switzerland) were used. All the resins examined are approved for load-bearing structures and are also used in other studies (e.g., Bockel et al. 2019), making it easy to compare the results with those of other hardwood species. The adhesive spreading quantity was chosen according to the technical data sheets and was between 150 and 220 g/m$^2$. The samples were pressed at room temperature at about 0.8 MPa for 2 hours. The same number of samples with the abovementioned adhesives was also produced for European beech wood (*F. sylvatica*), tested and compared with the results for tree of heaven.

*Table 2.—Parameters for the production of laboratory particle- and fiberboard. Degree of gluing refers to the dry mass of the wood, the proportion of hardener to the mass of the solid resin.*

| Investigation | Particleboard | Fiberboard |
|---|---|---|
| Target density (kg/m$^3$) | 650 | 650 |
| Glue content (%) | 12 | 8 |
| Pressing factor (s/mm) | 10 | 10 |
| Press temperature of the heating plates (°C) | 200 | 200 |
| Solid resin content (%) | 66 | 65 |
| Hardener content (%) | 3 | 3.3 |
| Thickness of the boards (mm) | 16 | 16 |
| Number (*N*) of laboratory boards produced | 20 | 20 |

All experiments performed to determine the mechanical properties and wood MC and density are summarized in Table 1, with a list of the corresponding standards.

## Pulping

The pulp tests were conducted in the Mondi laboratory (Mondi Frantschach, St. Gertraud, Austria). All pulp and paper properties were gained by using following standards: (1) sheet formation (ISO 2004), (2) pulping pulp freeness index (PFI) and buffer used (ISO 2002), (3) degree of grinding (ISO 1999), (4) sheet weight (ISO 2012), (5) air resistance (ISO 2003), (6) strength properties (ISO 2005), (6) bursting strength (ISO 2001), and (7) whiteness (ISO 2004). To obtain a basis for comparison with the tests carried out on tree of heaven, measurements were also taken on Norway spruce (*Picea abies*). Comparative investigations of raw material resources with regard to their pulp properties are only meaningful if they are carried out at similar kappa numbers (i.e., residual lignin contents). A total of 15 tries had to be performed to reach a comparable kappa range for tree of heaven and Norway spruce.

A so-called PFI laboratory refiner was used for the pulping. The cooking conditions were as follows: (1) tree of heaven: dry content 93.2 percent, alkali content 14.5 to 16.5 percent, temperature 165 to 170°C, pressure 6 to 6.3 bar, residual alkali 0 to 1.3; (2) Norway spruce: dry content 90 percent, alkali content 22 to 25 percent, temperature 165 to 170°C, pressure 6 to 6.3 bar, residual alkali 10.6 to 18.5 percent.

Material was obtained from the pulp produced at different rotation speeds (2,000 to 9,000 revolutions per minute [rpm]) and laboratory sheets were made from it. On the basis of these laboratory sheets, the basis weight (g/m$^2$), air resistance according to Gurley (s per liter [m$^2$ s]$^{-1}$), tensile strength index (Nm/g), elongation at break (%), elongation stiffness (kN/m), specific tear propagation resistance (kPam$^2$/g), specific tensile fracture work (J/g), and the degree of whiteness according to ISO (%) were determined. The fiber morphology was also determined.

## Fiber- and particleboard

Norway spruce is the standard material used by the Central European timber industry and is well researched. A comparison with this wood species with respect to particle- and fiberboard provides important practical information for the possible future use of the tree of heaven in Europe. For the production of particleboard, 20 kg of tree of heaven chips and Norway spruce chips from a sawmill (Binderholz GmbH, Fügen, Austria) were processed into particles (Gebr. Jehmlich GmbH, Nossen, Germany) using a cutting mill with a 2-mm sieve insert. Before further processing, the particles were dried to a wood MC of 3 percent using a self-made tunnel dryer.

The fibers for the fiberboards were produced using laboratory refiners. The 12-inch refiner (connected load = 45 kW, motor speed 3,200 rpm) was equipped with a rotating disc and a fixed disc. Unidirectional grinding discs with three rows of bars spaced at 7, 4, and 1 mm (Andritz AG, Graz, Austria) were used for refining experiments. The grinding disc spacing was 0.25 mm and the screw conveyor was operated at minimum speed (∼5 rpm). Before milling, the wood chips of tree of heaven and Norway spruce were cooked in an integrated pressure boiler at 165°C (heating rate 10°C/min). When the set temperature was reached, the screw conveyor was activated and the blow valve opened. During milling, the boiler temperature dropped to 130°C. The power consumption was measured during milling. The fibers were dried to a wood MC of 3 percent, analogous to the particle material.

For the production of all boards, a commercial E 0.5 MUF resin (Metadynea Austria GmbH) was used. This product is widely used in the wood industry and in applied research. Gluing was done in a standard laboratory gluing drum by spraying in the glue. During the production of the laboratory panels, the hydrophobic treatment customary in the industry was dispensed with to enable a better differentiation between the two types of wood regarding the thickness swelling. The key data for production of the particle- and fiberboard are summarized in Table 2. The same amounts of adhesive and production processes were used for a comparison of the particleboard and fiberboard produced.

Thickness swelling ($N = 20$), internal bond strength ($N = 20$), and bending strength ($N = 9$) of the boards were tested according to European standards (DIN EN 317 1993, ÖNORM EN 319, 310 2005).

## Natural durability

Tree of heaven can be used as a substitute for European ash in solid-wood applications. Ash is also frequently used in outdoor applications (e.g., decking). Consequently, it is recommended to examine the natural durability to assess the technical potential of the tree of heaven. To determine the natural durability of this wood species in ground contact, prismatic specimens (500 by 50 by 25 mm) were cut from dried and conditioned boards and tested following the field test method in ÖNORM (2014). The material was stored in a climatic chamber (20°C and 65% RH) until equilibrium MC was reached. The boards were then buried in the soil on a suitable test site in the Vienna area (48°20′N, 16°3′E, 180 m above sea level). With an annual average precipitation of >700 mm at the site, there is sufficient moisture in the soil to promote the activity of fungi and other wood-destroying microorganisms. This method is therefore well suited to determining the natural durability in practice. Every 6 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, samples 300 mm in length, 100 mm in width, and 24 mm in thickness were mounted outdoors at the same site in a southerly direction at an angle of 45°. During the 3-year weathering period, the samples were regularly visually assessed and the wood color was determined by a spectrophotometer (Phyma CODEC 400) at wavelengths ranging from 400 to 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 field of view was 20 mm, and the analysis of the color data was expressed according to the CIE L*a*b* color space (ÖNORM EN ISO/CIE 11664-4 2020).

The following meteorological data were recorded during the weathering period from 23 June 2015 to 28 August 2019 (1,532 days ≈ 4 yr): average daily temperature 10.5° (+36 to –17.2°C); average daily precipitation 1.5 mm (summed over the entire duration of weathering, 2,300 mm); average daily global radiation 115 W/m$^2$ (summed over the entire duration of weathering, 175,375 W/m$^2$); average daily wind speed 5.7 km/h (maximum 95 km/h). The meteorological data were taken from the weather station, which is positioned directly at the location of the samples.

# Results and Discussion

## Solid-wood properties

Starting at first with some more general data, the assumption, indicated by some literature sources (e.g., Hu 1979), that tree of heaven is subject to widespread use in its homeland China could not be confirmed. As part of this study, a native Chinese speaker, using Chinese keywords, also conducted an intensive internet search for wood technology information on tree of heaven but found no significant new results. This is because the roundwood supply in China comes mainly from plantation cultivation, poplar species in the north, and Southern blue gum (*Eucalyptus globulus*) mainly in the south. In total, only four companies were found to use tree of heaven for wood panel production. Fourteen companies used it in flooring production. However, the most widespread application in China seems to be in furniture production. Apart from this, the decorative, visually appealing wood of tree of heaven differs only slightly from native European ash (Berki 2014). A large amount of tree of heaven wood was processed during the study. The joinery work and the assessment of the workability of tree of heaven were carried out by a master joiner who has sufficient experience in working and processing hardwood species. The good machinability was in line with much-cited studies (Hölbling 1989, Panayotov et al. 2011, Brandner and Schickhofer 2010, 2013) and considered uncomplicated and comparable with European ash. Only boards with higher internal stresses (see drying properties) showed certain limitations during sawing and planning owing to stronger warping. However, it possible that these higher internal stresses originate from the lack of forest management.

Table 3 summarizes the values of the tests carried out on solid wood. Regarding the bending, compression, and tensile tests, the results were in good agreement with the values

Table 3.—Summary of the test results corresponding to Table 1 (tests performed), showing mean values (mean), standard deviation (SD), minimum (min.), and maximum (max.) values.

| Investigation | Units | *N* | Mean | SD | Min. | Max. |
|---|---|---|---|---|---|---|
| Density (ρ) | $kg/m^3$ | 338 | 611 | 50 | 453 | 726 |
| Moisture content | % | 200 | 12.7 | 0.9 | 10.3 | 14.6 |
| Compression strength parallel ($c_{fL}$) | $N/mm^2$ | 76 | 43.2 | 3.72 | 33.9 | 53.4 |
| Modulus of elasticity compression parallel ($E_{CL}$) | $N/mm^2$ | 75 | 12,414 | 4,033 | 7,950 | 29,100 |
| Compression strength perpendicular ($c_{fT}$) | $N/mm^2$ | 93 | 10.9 | 1.06 | 8.48 | 14.8 |
| Modulus of elasticity compression perpendicular ($E_{CT}$) | $N/mm^2$ | 76 | 1,382 | 295 | 1,040 | 3,850 |
| Tensile strength parallel ($t_{fL}$) | $N/mm^2$ | 20 | 142 | 25.6 | 89.3 | 195 |
| Modulus of elasticity tension parallel ($E_{tL}$) | $N/mm^2$ | 20 | 13,301 | 2928 | 8,040 | 20,500 |
| Bending strength ($m_f$) | $N/mm^2$ | 65 | 100 | 9.02 | 77.0 | 117 |
| Modulus of elasticity bending ($E_m$) | $N/mm^2$ | 65 | 11,590 | 1,124 | 8,630 | 14,200 |
| Work of fracture impact bending ($I_m$) | $J/mm^2$ | 78 | 49.9 | 20.3 | 26.8 | 67.0 |
| Shear strength (ν) | $N/mm^2$ | 81 | 12.8 | 1.09 | 10.9 | 16.3 |
| Brinell hardness | $N/mm^2$ | 107 | 28.1 | 3.37 | 18.7 | 35.9 |

published by Brandner and Schickhofer (2010, 2013). The bending strength ($m_f$) of 100 ± 9 $N/mm^2$ was very similar to that of the samples examined by Hölbling (1989). The tensile strength along the grain ($t_{fL}$) showed a high range of variation, whereas the bending ($m_f$) and compressive strengths along the grain ($c_{fL}$) showed a much smaller variation. Except for the values published by Panayotov et al. (2011), the compressive strengths obtained showed good agreement with Hölbling (1989) and Brandner and Schickhofer (2010, 2013).

Regarding the investigated samples of tree of heaven, a MC of 12.7 ± 0.9 percent was observed after standard climate storage. At this MC, a density of 611 ± 50 $kg/m^3$ (SD) was determined. The density values were thus slightly below the values of earlier studies reported by Hölbling (1989), Panayotov et al. (2011), and Brandner and Schickhofer (2010, 2013).

The determination of the MOEs from bending ($E_m$), compression, and tensile tests provided slightly higher values for the tensile tests. The observed MOEs were relatively uniform at 12,000 to 13,300 $N/mm^2$ and showed high agreement with the values published by Hölbling (1989) and Panayotov et al. (2011). Compared with the investigations by Brandner and Schickhofer (2010, 2013), there was a high level of agreement with the tensile MOEs, but not for the MOEs from the compression tests, which were significantly lower than in this study. The reason could possibly lie in a higher measurement scatter of samples that were not optimally axially oriented. For perfectly compressed specimens, no significant difference between the MOE in compression and bending should be observed (Kollmann 1951). The deviations between the compression MOEs between the two studies should therefore be put into perspective. However, the significantly higher MOEs reported by Brandner and Schickhofer (2010, 2013) in the bending test of 14,590 $N/mm^2$ compared with their own measurements of 11,590 $N/mm^2$ cannot be explained by the different test methods (three-point vs. four-point bending test) alone. The differences may be due to different laboratory standards, lower density, or other natural scatter of the sample material. Overall, the investigations conducted in the present study confirmed the previous studies.

Especially for load-bearing structures such as glued laminated timber, the shear strengths and the strengths transverse to the grain represent a limiting parameter (Liu et al. 2016). For this reason, these two material properties were analyzed as well. Table 3 shows the block shear strength according to ASTM 143 D (ASTM 1992) and the transverse compressive strength according to DIN 52192 (1979). Regarding the shear strength (ν; 12.8 $N/mm^2$), slightly higher values were observed than in the study by Brandner and Schickhofer (2010, 2013; 11.5 $N/mm^2$), who determined the shear strength using DIN 52 187 (1979). The small differences can be explained on the one hand by the natural variability of the investigated sample material and on the other hand by the different measurement methods (DIN 52187 1979 vs. ASTM 143D 1992; Stretenovic et al. 2004).

With a mean Brinell hardness of 28.1 ± 3.4 $N/mm^2$, the values of tree of heaven were significantly lower than those of European ash (37.7 ± 6.7 $N/mm^2$) and oak (35.0 ± 8.4 $N/mm^2$). Tree of heaven is therefore of limited suitability for highly stressed floors in the commercial sector. However, from a technological point of view, the similar optical, technological, and mechanical–physical properties would allow tree of heaven to be used as a substitute for European ash.

For the bending specimens and the specimens for Brinell hardness, the density was determined in addition to the mechanical properties. The coefficient of determination for the bending strength vs. density was $R^2 = 0.39$ and for the hardness vs. density $R^2 = 0.48$. The correlation between the mechanical properties and the density was thus within the range of comparable studies (Verkasalo and Liban 2002).

## Wood drying and effects on wood processing

After completion of the two kiln-drying processes, the final wood MC, new cracking and tension in the wood, change of shape and color, and machinability were determined. To assess the workability of dried or steamed tree of heaven wood, several boards were cut on a circular saw and planed with a jointer. An experienced carpenter carried out the assessment using practical evaluation criteria.

*Kiln drying*.—The evaluation of the wood moisture profiles showed a highly regular wood MC in all boards. The final MC of 12 percent varied by only ±1.5 percent. Cracking during drying was very low: only cracks could be perceived on the face of the wood. However, most of the dried sawn timber showed strong cupping and twisting. The measurement of case hardening according to ÖNORM EN 14464 (2010) gave a gap for the samples prepared in accordance with the standard dimensions of 3 to 5 mm, which indicated clear drying stresses. The drying problem was also addressed by Liu (1990). The maximum drying temperature was just below 60°C;

therefore, the dried wood showed only slight discoloration, the color becoming slightly more yellow–reddish.

*Steaming followed by kiln drying.*—During steaming, the wood MC hardly changed. The subsequent drying showed a similarly good result in terms of wood moisture, the moisture gradient being <1.5 percent. As a result of the steaming process, cracks were clearly visible on the face of the board and on the surface of the wood. However, there was clearly little change in the shape of the individual boards—only in rare cases did a slight cupping occur. Furthermore, the case hardening was significantly reduced, the gap width being <1 mm. Steaming (duration approximately 50 h and temperature ~95°C) in an almost saturated steam atmosphere as described above resulted in a significant color change. The wood became much darker and more color intensive, and the hue turned reddish. The early- and latewood structure was particularly evident on the wood surface.

The assessment of the machinability of both drying experiments yielded the following results:

- Cutting through a board with a circular saw (across the board axis): Here, the steamed boards could be moved past the saw blade more quickly and with less resistance. The lower stresses in the wood could be clearly noticed in comparison with the boards that were dried only.
- Jointing/milling the boards: In the first step, the boards were passed over the planing knives at a low chip removal rate. No significant difference could be observed here. However, at higher chip removal, the steamed boards showed a better and smoother surface structure.

Parallel to the kiln drying, the remaining sample material was dried to a wood MC of 12 percent by air drying and a subsequent conditioning phase.

The results from the three drying experiments indicated that significantly better results can be achieved at lower drying temperatures. This means that, for more general use of tree of heaven for solid-wood applications, a separate drying program should be developed. For further drying optimization, the drying temperatures should be kept as low as possible.

As expected, the steaming process led to a clear color change. The color tone corresponded to slight modification levels of a thermal treatment (Stingl et al. 2013). To reduce further stresses in the material or, if necessary, to improve the optical properties of tree of heaven, the material could be subjected to a thermal treatment or steaming afterward. Which technological and process parameters achieve the desired effects would have to be clarified in future studies.

## Gluing

Solid-wood applications, regardless of whether they are used for load-bearing or nonload-bearing purposes, require not only optically appealing properties and advantageous mechanical/physical properties but also good bondability. Experience has shown that European ash is rather difficult to bond with conventional adhesives (Knorz et al. 2014). Better bonding properties than those of European ash would therefore be an advantage for tree of heaven as a substitute wood species. In the present tests, the adhesive properties according to DIN EN 302 (2013) were investigated for tree of heaven and European beech. In addition to testing the dry samples (A1), tests of the tensile shear strength after water storage (A5) were also conducted (6-h storage in water at 100°C, 2-h storage in water at 20°C, conditioning of the samples in standard climate until equilibrium MC was reached). No A5 tests were carried out for the nonwaterproof UF adhesive. Overall, tree of heaven showed very good bonding properties. Most of the values determined did not differ from beech (see Figs. 1a and 1b). In the dry state, only the samples bonded with EPI showed lower shear tensile strengths. However, the tests did not show any significant differences compared with European beech (one-way analysis of variance, $P = 0.05$). Significantly higher shear strengths (ν) were only found for European beech when bonded with PRF. Overall, the tensile shear strength was in the range of the determined block shear strength (ν) of 12.75 N/mm$^2$. Owing to the high percentage of wood failure in tree of heaven (EPI 80%, PRF 90%, PUR 75%, UF 80%, MUF 100%), it can be assumed that the strength of the wood is the limiting factor of the determined tensile shear strengths. Overall, the tests showed that the tree of heaven has good bondability. The results are in good agreement with the results reported by Brandner and Schickhofer (2013), although these were determined on the basis of ÖNORM EN 392 (1995).

A tensile shear strength corresponding to that of beech was also demonstrated for tree of heaven in the dry state after wet storage and reconditioning (A5; see Fig. 1b). As the standard tests for adhesives for load-bearing purposes in accordance

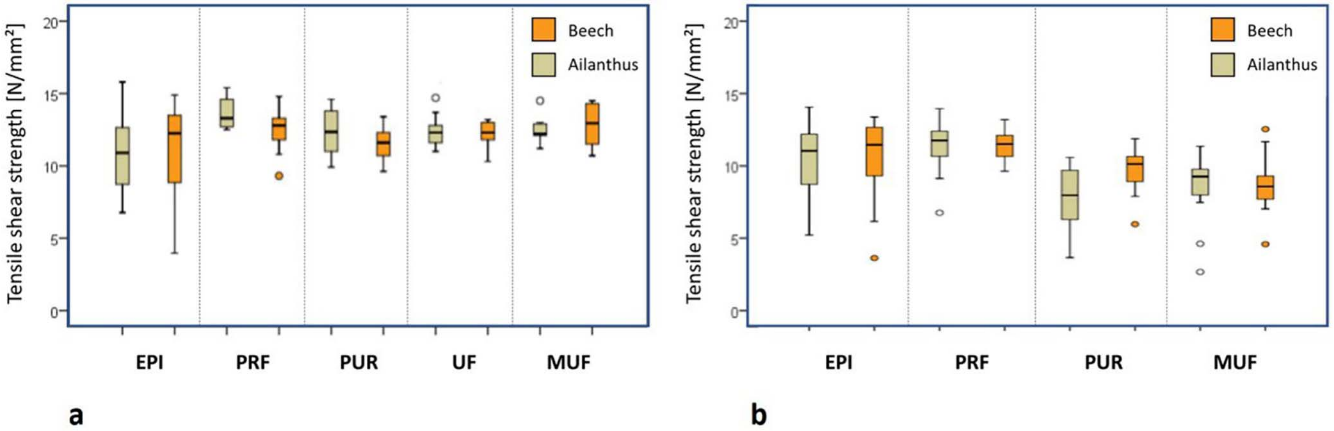

*Figure 1.—Tensile shear strengths tested according to European standard DIN EN 302 (2013) in (a) dry condition (A1, left) and (b) dry condition after water storage and conditioning (A5, right).*

with DIN EN 302-1 (2013) for tensile shear strength are carried out using beech wood, the tests with tree of heaven demonstrate excellent bonding properties. For all adhesives, tensile shear strengths in the range of the level of beech were found. Only for PUR were significantly lower values determined for tree of heaven. It can be concluded that the technological use of tree of heaven solid wood is not restricted by bondability.

## Natural durability

*Natural durability without soil contact.*—Before the weathering period, the initial color of the wood was determined, and the following values were found: lightness of the color $L^* = 81.0$; red–green axis value $a^* = 3.6$; yellow–blue axis value $b^* = 21.6$; chroma $C^* = 22.0$; hue angle $h^\circ = 80.6^\circ$. The color was identified in three measurement spots per sample, and a mean value was calculated. The same spots were used for all measurement points within the whole weathering period. The color measurements of the individual samples were determined at intervals of approximately 1 month. This means that 50 color measurements (including the determination of the initial color) were taken during the 4-year weathering period. After only 1 year, all samples had turned gray and showed only slight seasonal fluctuations in color. The color measurement showed the following values at the end of the experiment (after 1,532 days): $L^* = 48.8$; $a^* = 1.3$; $b^* = 2.6$; chroma $C^* = 2.9$; hue angle $h^\circ = 63.3$. The wood color showed a color distance ($\Delta E^*$) of 37.4, became darker ($\Delta L^* = -32.2$), and lost much of its color intensity ($\Delta C^* -19.0$).

The specimens showed crack formation on the faces and on the surface (maximum crack depth 2 mm). The surface hardness was slightly reduced on the weathered surface, whereas the unweathered side showed no change. No wood-destroying organisms (e.g., fungi or insects) were found. A good indicator of the presence of wood-damaging organisms is to check the impact bending strength, according to DIN 52189-1 (1981). For this purpose, appropriate test specimens were cut out of the weathered samples and stored at 20°C and 65 percent RH for 30 days before the tests were conducted. Table 4 shows the comparison of unweathered (data from Table 3) and weathered (1,532 days) samples; no significant difference in strength could be determined.

*Natural durability with ground contact.*—The natural durability in ground contact of tree of heaven was tested in a field test method according to ÖNORM EN 252 (2014). At the first inspection at 6 months, the first signs of fungal infestation appeared. After 1 year of exposure, many of the samples buried in the soil showed clear signs of deterioration. As Grabner (2017) also noted earlier, after 2 years of weathering in the field, the level of infestation in the samples by microorganisms averaged Class 4 (= less durable). About 50 percent of all specimens failed after 3 years of soil contact. Only a few specimens survived a weathering period of 4 or more years. This means that these samples were partially or completely destroyed during the standard impact test when clamped in the impact pendulum or with a very low impact, or already during excavation from the ground or during the subsequent visual inspection. Compared with the reference species, pine sapwood, or other species such as ash or alder, the *Ailanthus* specimens in this study are classified in the lowest durability classes 4 to 5, "less durable" to "not durable," respectively.

*Table 4.—Impact bending test on unaffected tree of heaven (*Ailanthus altissima*) specimens (values from Table 3) and after 1,532 days of weathering, showing number of samples (*N*), mean values (mean), standard deviation (SD), and minimum (min.) and maximum (max.) values.*

| | Units | $N$ | Mean | SD | Min. | Max. |
|---|---|---|---|---|---|---|
| Work of fracture impact bending $I_b$ (samples without weathering, Table 3) | J/mm$^2$ | 78 | 49.91 | 20.28 | 26.8 | 67.01 |
| Work of fracture impact bending $I_b$ (after 1,532 days weathering) | J/mm$^2$ | 30 | 53.11 | 12.61 | 27.51 | 69.64 |

## Pulping and paper properties

Thanks to the high fiber content and the long fibers of tree of heaven, good paper properties have been postulated (Ferreira et al. 2013; Baptista et al. 2014). Nevertheless, the suitability of tree of heaven for pulp and paper production has not yet been sufficiently investigated (Adamik and Brauns 1957, Isenberg 1981).

The results are presented here as mean values for the kappa numbers 19.5 and 20, respectively. Norway spruce: fiber length 2.62 mm, fines content 3.37 percent, fiber width 28.1 µm, and fiber wall thickness 10 µm; tree of heaven: fiber length 0.98 mm, fines content 8.96 percent, fiber width 21.5 µm, and fiber wall thickness 8.9 µm. Tree of heaven thus differs primarily by shorter fibers and by a higher fines content.

In addition, tree of heaven is characterized by a higher degree of grinding at grindings up to 9,000 rpm and thus a higher energy input during raw material pulping. At grindings up to 2,000 rpm, tree of heaven provided similar paper properties in terms of tensile strength and specific bursting resistance to Norway spruce. Overall, the air resistance increased more steeply with tree of heaven than with Norway spruce, which can also be attributed to the higher fines content. Similar results were also observed for the higher kappa number 29.6, where slightly less favorable paper properties were found for tree of heaven than for Norway spruce. Overall, the trial yielded relatively good pulp and paper properties for tree of heaven. However, relatively high freeness is required for this. High freeness means higher energy consumption, longer dewatering times, and thus lower production speeds (Mandlez 2017).

The results prove that tree of heaven can be considered a potentially interesting raw material for pulp and paper production. Whether the good pulp and paper properties justify the higher grinding degrees depends specifically on the respective product properties of the desired papers in production. No general statement about the trials is therefore possible, and it remains to be investigated whether the adaptation of the pulping conditions to tree of heaven does not lead to further improvements. The work of Demirbaş (1998) shows that longer cooking times, higher cooking temperatures, and adapted chemical conditions lead to better results.

## Fiber- and particleboard production

In the milling processes with the laboratory refiner for fiberboard production, no differences were found in the measured energy consumption between tree of heaven and Norway spruce in pulp production. In the particleboards produced, there were no significant differences in thickness swelling (TS) for tree of heaven ($t$ test, $P = 0.05$): Norway spruce TS = 23.1 ± 2.10 percent and tree of heaven TS =

23.0 ± 2.96 percent. On the other hand, the tests on the fiberboards showed a lower TS for tree of heaven (TS = 30.6%) than for Norway spruce (TS = 40.9%). The relatively high TS values can be explained by the absence of a hydrophobic agent in the laboratory production of the boards.

The measurement of the internal bond strength (IB) of the particleboards showed significantly higher values ($P = 0.05$) for tree of heaven (IB = 1.22 ± 0.35 N/mm$^2$) than for Norway spruce (IB = 0.80 ± 0.18 N/mm$^2$). Analogous to the investigations on the manufactured particleboards, significantly higher values ($P = 0.05$) were also found for the fiberboards for tree of heaven (IB = 0.60 ± 0.20 N/mm$^2$) than for Norway spruce (IB = 0.19 ± 0.13 N/mm$^2$) despite a relatively high scatter of the measured values.

The target density of 650 kg/m$^3$ was achieved neither for tree of heaven ($\rho = 608 \pm 30$ kg/m$^3$) nor for Norway spruce ($\rho = 597 \pm 34$ kg/m$^3$). However, the statistical evaluation of the density values did not reveal any significant differences between the two wood species ($t$ test, $P = 0.05$). The glue contents were also approximately the same for all panel types. The differences found in the board properties can therefore not be attributed to a variation in density or different glue contents.

Regarding the bending strength of the tested particleboards, it should be mentioned that only single-layer boards were produced in the laboratory. Industrially produced particleboards usually have a three-layer structure and have bending properties related to the needlelike geometry with a high aspect ratio of the face sheet material. The results presented here therefore allow only a comparison of the laboratory panels with each other. The bending strength of Norway spruce ($\sigma_b = 7.37 \pm 1.89$ N/mm$^2$) was slightly higher than that of tree of heaven ($\sigma_b = 6.97 \pm 1.59$ N/mm$^2$). Similarly, slightly higher values for the bending MOE were found for Norway spruce (MOE = 1,355 ± 274 N/mm$^2$) than for tree of heaven (MOE = 1,115 ± 218 N/mm$^2$). The slightly lower bending values of tree of heaven are probably due to the greater amount of cubic chip material. The Norway spruce fibers are comparatively long and it is assumed that they result in particles with a higher aspect ratio. However, a $t$ test performed showed a significant difference only for the MOE ($P = 0.05$).

In contrast to the particleboards, no significant difference was found for the bending properties of the fiberboards made of Norway spruce ($\sigma_b = 13.2 \pm 0.12$ N/mm$^2$; MOE = 1,596 ± 297 N/mm$^2$) and tree of heaven ($\sigma_b = 13.9 \pm 2.44$ N/mm$^2$; MOE = 1,525 ± 317 N/mm$^2$; $t$ test, $P = 0.05$).

Because of the increasing competition between material and energy use, alternative raw material sources are being sought for the production of wood-based materials. As a result, wood from short-rotation plantations is increasingly becoming the focus of the wood industry. Its fast growth and low requirements make tree of heaven a potential source of raw material for the industry. Its suitability for the production of fiberboard and particleboard has not been sufficiently investigated, even given the present results. However, the results confirm the study by Elbadawi et al. (2015) in which tree of heaven (*Ailanthus excelsa* Roxb.) was processed into particleboard. From the research conducted so far, it can be concluded that the tree of heaven species should be considered as a potential raw material resource for wood panel production. Whether these results can be directly transferred to industrially produced wood-based materials still needs to be investigated.

## Conclusions

The tree of heaven is a very aggressive invasive neophyte. The tree presents a major challenge for forestry in Central Europe. However, in some locations and stands, even with the use of strong control measures, it is no longer possible to prevent this tree from becoming established. With climate change continuing, an increase in the stock volume of tree of heaven in Central Europe is to be expected. Therefore, this study deals with the wood technology potential of this tree for the timber industry.

As long as the tree is available in larger quantities and diameters, there is nothing to prevent its solid wood from being used. Its mechanical and optical properties are similar to those of the native ash. For a broader use of sawn timber, a special drying program must be developed for kiln drying, as the drying properties differ greatly from those of other ring-porous hardwood species. The drying program for ash is only partially suitable. The observed higher drying stresses in the tree of heaven, however, might become less and similar to ash in managed forests. The possible technological use of solid wood in nonload-bearing applications, as well as for load-bearing timber structures, therefore depends primarily on an adequate supply of roundwood, but not on technical or technological limitations.

The investigations of the pulp and paper properties as well as the particleboard and fiberboard have shown that tree of heaven could be a potentially interesting raw material for the pulp and paper and wood industries. Further investigations on a larger scale would be necessary to continue trials at the industrial level. Influences on the roundwood quality caused by forest management need to be considered.

## Acknowledgments

The authors are grateful for research funding from the Federal Ministries BML, Austria for research project no. 100995. We also thank Holzcluster Steiermark GmbH, namely DI (FH) Erhart Pretterhofer, for successful cooperation in the project, Kompetenzzentrum Holz GmbH, specifically Dr. Stefan Pinkl, for conducting refiner experiments, and Mondi Frantschach GmbH, namely Dr. Elisabeth Schwaiger, for conducting the trials to assess the paper properties of tree of heaven. The authors also thank Walter Gangl of Österreichische Bundesforste for providing the tree material and for organizing the felling and production of the sawn timber as well as Johannes Wallisch for sample preparation. Many thanks to Marlene Freudenthaler and David Obernosterer for performing mechanical tests.

An earlier research project no. 815162 was thankfully financed by the Holz.Bau Forschungs GmbH and carried out in collaboration with the Institute of Timber Engineering and Wood Technology at Graz University of Technology, the Esterházy Betriebe GmbH, the Rutan Holzindustrie GmbH, and the Holzcluster Steiermark GmbH and funded by the Austrian Research Promotion Agency.

## Literature Cited

Adamik, K. and F. E. Brauns. 1957. *Ailanthus glandulosa* (tree of heaven) as a pulpwood, part II. *TAPPI J.* 40(7):522–527.

Alden, H. A. 1995. *Ailanthus altissima*, Simarubaceae, Tree-of-Heaven. *In:* Hardwoods of North America. General Technical Report FPL-GTR-83. USDA Forest Products Laboratory, Madison, Wisconsin. 136 pp.

American Society of Testing and Materials (ASTM). 1992. Standard methods of testing small clear specimens of timber. ASTM D 143-83. Wood. ASTM, West Conshohocken, Pennsylvania.

Ammer, C., A. Fichtner, A. Fischer, M. M. Gossner, P. Meyer, R. Seidl, F. M. Thomas, P. Annighöfer, J. Kreyling, B. Ohse, U. Berger, E. Feldmann, K.-H. Häberle, K. Heer, S. Heinrich, S. and F. Huth. Arbeitsgruppe invasive Neobiota. 2014. Gebietsfremde Problempflanzen (invasive Neophyten) bei Bauvorhaben. Flyer der Arbeitsgruppe invasive Neobiota, Schweiz. https://www.ur.ch/_docn/111001/AGIN-Flyer_Neophyten_bei_Bauvorhaben.pdf. Accessed, January 2025.

Baptista, P., A. Paula Costa, R. Simões, and M. E. Amaral. 2014. *Ailanthus altissima*: An alternative fiber source for papermaking. *Ind. Crops Prod*. 52:32–37.

Berki, D. 2014. Eigenschaften und Verwendung des Holzes des Götterbaums (*Ailanthus altissima*) Visuelle Bewertung vom Götterbaum im Vergleich zu fünf ringporigen Holzarten. Master's thesis. BOKU-Universität für Bodenkultur, Vienna. 90 pp.

Blab, A. 2002. Die „Aliens" kommen! Problematik der Einschleppung, Einfuhr und Ausbringung von nicht-heimischen Arten. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft Wien, Vienna.

Bockel, S., I. Mayer, J. Konnerth, S. Harling, P. Niemz, C. Swaboda, M. Beyer, N. Bieri, G. Weiland, and F. Pichelin. 2019. The role of wood extractives in structural hardwood bonding and their influence on different adhesive systems. *International Journal of Adhesion and Adhesives*. 91:43–53. https://doi.org/10.1016/j.ijadhadh.2019.03.001

Brandner, R. and G. Schickhofer. 2008. Ermittlung von physikalischen und mechanischen Kenngrößen von 'clear wood' und 'construction timber'. Forschungsbericht, Institut für Holzbau und Holztechnologie, Technische Universität Graz, Kompetenzzentrum Holz.Bau Forschungs GmbH, Graz. [in German.] Verlag der Technischen Universität Graz, Graz, Austria. www.ub.tugraz.at/Verlag

Brandner, R. and G. Schickhofer. 2010. Tree-of-Heaven (*Ailanthus altissima*): Enormous and wide potential neglected by the western civilisation. *In*: WCTE 2010 Conference Proceedings, Vol. 2. WCTE World Conference on Timber Engineering, June 20–24, 2010, Riva del Garda, Italy. pp. 1576–1582.

Brandner, R. and G. Schickhofer. 2013. The mechanical potential of the Tree-of-Heaven (*Ailanthus altissima*). *Holztechnologie* 54:5–11.

Changjiu, Y., J. Hulai, L. Xiaoxiu, L. Hui, and W. Mang. 2000. Study on the drying method of *Ailanthus altissima* Swingle. [In Chinese.] *Forestry Sci. Technol*. 25(5):43–45.

Demirbaş, A. 1998. Aqueous glycerol delignification of wood chips and ground wood. *Bioresour. Technol*. 63:179–185.

Deutsches Institut für Normung (DIN). 1975. Prüfung von Holz–Bestimmung der Rohdichte. DIN 52182. DIN, Berlin.

Deutsches Institut für Normung (DIN). 1976. Prüfung von Holz–Bestimmung der Druckfestigkeit parallel zur Faser. DIN 52185. DIN, Berlin.

Deutsches Institut für Normung (DIN) 1977. Prüfung von Holz–Bestimmung des Feuchtigkeitsgehalts. DIN 52183. DIN, Berlin.

Deutsches Institut für Normung (DIN) 1978. Prüfung von Holz–Biegeversuch. DIN 52186. DIN, Berlin.

Deutsches Institut für Normung (DIN). 1979. Prüfung von Holz–Bestimmung der Zugfestigkeit parallel zur Faser. DIN 52188. DIN, Berlin.

Deutsches Institut für Normung (DIN). 1979. Prüfung von Holz; Bestimmung der Scherfestigkeit in Faserrichtung. DIN 52187. DIN, Berlin.

Deutsches Institut für Normung (DIN). 1979. Prüfung von Holz–Druckversuch quer zur Faserrichtung. DIN 52192. DIN, Berlin.

Deutsches Institut für Normung (DIN). 1981. Prüfung von Holz; Schlagbiegeversuch; Bestimmung der Bruchschlagarbeit DIN 52189-1. DIN, Berlin.

Deutsches Institut für Normung (DIN) 1993. Particleboards and fibreboards; determination of swelling in thickness after immersion in water. DIN EN 317. DIN, Berlin.

Deutsches Institut für Normung (DIN). 2013. Adhesives for load-bearing timber structures—Test methods—Part 1: Determination of longitudinal tensile shear strength. DIN EN 302-1. DIN, Berlin.

Elbadawi, M., Z. Osman, T. Paridah, T. Nasroun, and W. Kantiner. 2015. Mechanical and physical properties of particleboards made from *Ailanthus* wood and UF resin fortified by Acacias tannins blend. *J. Mater. Environ. Sci.* 6(4):1016–1021.

Essl, F. 2007. Verbreitung, Status und Vergesellschaftung von Pinus strobus in Österreich. In: Floristisch-soziologischen Arbeitsgemeinschaft e.V., coord.: Tuexenia - Mitteilungen der Floristisch-soziologischen Arbeitsgemeinschaft. Avec la collaboration de Hansjörg Küster (27), pp. 59–72.

European Union (EU). 2019. Regulation (EU) No. 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. EU, Brussels, Belgium.

Ferreira, P. J. T., J. A. F. Gamelas, M. G. V. S. Carvalho, G. V. Duarte, J. M. P. L. Canhoto, and R. Passas. 2013. Evaluation of the papermaking potential of *Ailanthus altissima*. *Ind. Crops Prod*. 42:538–542.

Frenes, J. 2021. Beurteilung von Bekämpfungs- und Förderungsmaßnahmen des Götterbaums in Südtirol. Master's thesis. BOKU-Universität für Bodenkultur, Vienna. 151 pp.

Grabner, M. 2017. WerkHolz. Eigenschaften und historische Nutzung 60 mitteleuropäischer Baum- und Straucharten. Verlag Dr. Kessel, Remagen, Germany. 160 pp.

Gurtner, D., M. Conedera, A. Rigling, and J. Wunder. 2015. Der Götterbaum dringt in die Wälder nördlich der Alpen vor. WALD und HOLZ–Zeitschrift für Wald, Waldwirtschaft, Holzmarkt und Holzverwendung, Freiburg, Germany. July. pp. 22–24.

Härtel, O. 1955. *Ailanthus glandulosa*, eine Würdigung seiner Holzeigenschaften. Zentralbl. Gesamte Forstwesen. 73/74(2):95–97.

Hecker, U. 2001. Bäume und Sträucher. 3. Aufl. Munich: BLV Verlagsgesellschaft, Munich. pp. 388–389.

Hölbling, M. 1989. Beitrag zur Kenntnis einiger physikalischer und technologischer Eigenschaften des Götterbaumes (*Ailanthus altissima*). Master's thesis. BOKU-Universität für Bodenkultur, Vienna.

Hu, S. Y. 1979. *Ailanthus*. Arnoldia. 39(2):29–50.

Hubo, C., E. Jumpertz, M. Krott, L. Nockemann, A. Steinmann, and I. Bräuer. 2007. Grundlagen für die Entwicklung einer nationalen Strategie gegen invasive gebietsfremde Arten. Bundesamt für Naturschutz, BfN-Skripten, Bonn. 213:1–370.

Isenberg, I. H. 1981. Pulpwoods of the United States and Canada–Volume II–Hardwoods. Revised by M. L. Harder and L. Louden. The Institute of Paper Chemistry, Appleton, Wisconsin. 168 pp.

International Organization for Standardization (ISO). 1999. Pulps—Determination of drainability—Part 1: Schopper–Riegler method. ISO 5267-1. ISO, Geneva.

International Organization for Standardization (ISO). 2001. Paper—Determination of bursting strength. ISO 2758-2001. ISO, Geneva.

International Organization for Standardization (ISO). 2002. Pulps—Laboratory beating—Part 2: PFI mill method. ISO 5264-2, ISO, Geneva.

International Organization for Standardization (ISO). 2003. Paper and board—Determination of air permeance and air resistance (medium range). Part 5: Gurley method. ISO 5636-5. ISO, Geneva.

International Organization for Standardization (ISO). 2004. Preparation of laboratory sheets for physical testing. Part 2: Rapid–Köthen method. ISO 5269-2. ISO, Geneva.

International Organization for Standardization (ISO). 2004. Paper and board—Determination of CIE whiteness, D65/10 degrees (outdoor daylight). ISO 11475. ISO, Geneva.

International Organization for Standardization (ISO). 2005. Paper and board—Determination of tensile properties—Part 3: Constant rate of elongation method (100 mm/min). ISO 1924-3. ISO, Geneva.

International Organization for Standardization (ISO). 2012. Paper and board—Determination of grammage. ISO 536-2012. ISO, Geneva.

Jörg, E. 2017. Mechanische Bekämpfung des Götterbaumes im TWW-Objekt 5090. Amt für Landwirtschaft und Natur des Kantons, Bern, Switzerland.

Knapp, L. B. and C. D. Canham. 2000. Invasion of an old-growth forest in New York by *Ailanthus altissima*: Sapling growth and recruitment in canopy gaps. *J. Torrey Bot. Soc*. 127(4):307–315.

Knorz, M., M. Schmidt, S. Torno, and J. W. G. van de Kuilen. 2014. Structural bonding of ash (*Fraxinus excelsior* L.): Resistance to delamination and performance in shearing tests. *Eur. J. Wood Wood Prod*. 72(3):297–309.

Kollmann, F. 1951. Technologie des Holzes und der Holzwerkstoffe. Springer-Verlag, Berlin.

Kowarik, I. and R. Böcker. 1984. Zur Verbreitung, Vergesellschaftung und Einbürgerung des Götterbaumes (*Ailanthus altissima* [Mill.] Swingle) in Mitteleuropa. *In:* Mitteilungen der Floristisch-soziologischen Arbeitsgemeinschaft. Band Nr.4. H. Dierschke (Ed.). Tuxenia, Göttingen, Germany. pp. 9–29.

Kowarik, I. and W. Rabitsch. 2010. Biologische Invasionen: Neophyten und Neozoen in Mitteleuropa (2., wesentlich erweiterte Auflage). Ulmer, Stuttgart, Germany.

Kowarik, I. and I. Säumel. 2007. Biological flora of Central Europe: *Ailanthus altissima* (Mill.). *Persp. Plant Ecol. Evol. Syst.* 8:207–237. https://doi.org/10.1016/j.ppe¬es.2007.03.002

Kowarik, I. and I. Säumel. 2013. *Ailanthus altissima*. *In:* Enzyklopädie der Holzgewächse. 63. Erg.Lfg. Deutschland A., Roloff H., Weisgerber U., M. Lang, and B. Stimm (Eds.):: Wiley-VCH Verlag, Weinheim, Germany. 24 pp.

Li, X., Y. Li, S. Ma, Q. Zhao, J. Wu, L. Duan, Y. Xie, and S. Wang. 2021. Traditional uses, phytochemistry, and pharmacology of *Ailanthus altissima* (Mill.) Swingle bark: A comprehensive review. *J. Ethnopharmacol*. 275. https://doi.org/10.1016/J.JEP.2021.114121

Ließ, N. 2007. Der Baum des Himmels? *Ailanthus altissima* (Mill.) Swingle. Monitoring und Evaluierung von Kontrollmethoden im Nationalpark Donau-Auen (Österreich). Master's thesis. Eberswalde—Hochschule für nachhaltige Entwicklung, Eberswalde, Germany. p. 121).

Liu, C., D. Du, H. Li, Y. Hu, Y. Xu, J. Tian, J. G. Tao, and J. Tao. 2016. Interlaminar failure behavior of GLARE laminates under short-beam three-point-bending load. *Composites B* 97: 361e367. http://dx.doi.org/10.1016/j.compositesb.2016.05.003

Liu, Z. 1990. Physical and mechanical properties study of *Ailanthus*. [In Chinese]. *Henan Forestry Sci. Technol*. 3:15–17.

Lodge, D. M. 1993. Biological invasions: Lessons for ecology. *Trends Ecol. Evol*. 8:133–137. https://doi.org/10.1016/0169-5347(93)90025-K

Mandlez, D. 2017. Fraktionierte Mahlung zur Optimierung der Papiereigenschaften und des Energieverbrauches. Master's thesis. Graz University of Technology, Graz, Austria.

Meints, T., A. Teischinger, R. Stingl, and C. Hansmann. 2017. Wood colour of central European wood species: CIELAB characterisation and colour intensification. *Eur. J Wood Wood Prod*. 75(4):499–509. https://doi.org/10.1007/s00107-016-1108-0

Meyer, F. 1982. Bäume in der Stadt. 2. Aufl. Ulmer Eugen Verlag, Stuttgart, Germany.

Miao, X., H. Chen, Q. Lang, Z. Bi, X. Zheng, and J. Pu. 2014. Characterization of *Ailanthus altissima* veneer modified by urea–formaldehyde pre-polymer with compression drying. *Bioresources* 9(4):5928–5939.

Miller, J. H. 1990. *Ailanthus altissima* (Mill.) Swingle. *In*: Silvics of North America. R. M. Burns and B. H. Honkala (Eds.) US Department of Agriculture, Forest Service, Washington, D.C. pp. 101–104.

More, D. and J. White. 2005. Die Kosmos Enzyklopädie der Bäume. Kosmos Verlag, Stuttgart, Germany.

Moslemi, A.A. and S. G. Bhagwat. 1969. Physical and mechanical properties of the wood of Tree-of-Heaven. *Wood Fiber* 1:319–323.

Narayanamurti, D. and K. Singh. 1962. Boards from *Ailanthus altissima*. *India Pulp Paper* 17:167–168.

Nehring, S., I. Kowarik, W. Rabitsch, and F. Essl. 2013. Naturschutzfachliche Invasivitätsbewertungen für in Deutschland wildlebende gebietsfremde Gefäßpflanzen. Bundesamt für Naturschutz. BfN-Skripten 352. BfN-Skripten, Bonn.

Nobis, M. 2008. Ausbreitung gebietsfremder Arten: Invasive Neophyten auch im Wald? *Z. Wald Wald. Holzm. Holzv.* 8:46–49.

Österreichisches Normungsinstitut (ÖNORM). 1995. Glued laminated timber—Shear test glue lines; German version. ÖNORM EN 392. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2005. Wood-based panels; determination of modulus of elasticity in bending and of bending strength; German version. ÖNORM EN 310. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM) 2005. Particleboards and fibreboards; determination of tensile strength perpendicular to the plane of the board; German version. ÖNORM EN 319. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2010. Wood flooring and parquet—Determination of resistance to indentation—Test method; German version. ÖNORM EN 1534. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2010. Sawn timber—Method of assessment of case-hardening; German version. ÖNORM EN/TS 14464. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM) 2014. Field test method for determining the relative protective effectiveness of a wood preservative in ground contact; German version. ÖNORM EN 252. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2020. Paints and varnishes—Coating materials and coating systems for exterior wood—Part 3: Natural weathering test; German version. ÖNORM EN 927-3. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2020. Paints and varnishes—Natural weathering of coatings—Exposure and assessment; German version. ÖNORM EN ISO 2810. ÖNORM, Vienna.

Österreichisches Normungsinstitut (ÖNORM). 2020. Farbmetrik—Teil 4: CIE 1976 L*a*b* Farbenraum (Colorimetry—Part 4: CIE 1976 L*a*b* colour space); German version. ÖNORM EN ISO/CIE 11664-4. ÖNORM, Vienna.

Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV). 2016. Neophytenmanagement—Behandlung invasiver gebietsfremder Pflanzenarten. ÖWAV-Arbeitsbehelf 49. ÖWAV, Wasser Abfall Regelwerk, Vienna. 28 pp.

Panayotov, P., K. Kalmukov, and M. Panayotov. 2011. Biological and wood properties of *Ailanthus altissima* (Mill.) Swingle. *Forestry Ideas* 17(2[42]):122–130.

Schmidt, O. and S. Heinrichs. 2015. Potenziale und Risiken eingeführter Baumarten—Baumartenportraits mit naturschutzfachlicher Bewertung. Göttinger Forstwissenschaften, Band 7, Universitätsverlag Göttingen, Göttingen, Germany. pp. 47–65.

Sell, J. 1989. Eigenschaften und Kenngrössen von Holzarten. Lignum, Zürich, Switzerland.

Shah, B. 1997. The checkered career of *Ailanthus altissima*. *Arnoldia* 57(3): 21–27.

Siegrist, M. and O. Holdenrieder. 2016. Die Verticillium-Welke—eine Option zur Bekämpfung des Götterbaumes in der Schweiz? *Schweiz. Z. Forstwesen* 167: 249–257.

Stingl, R., H. Hasenauer, M. Klopf, and C. Hansmann. 2013. Innovationsscheck plus SIMU Trade "Götterbaum und Robinie". Report of Kompetenzzentrum Holz GmbH, Linz, Austria.

Stretenovic, A., U. Müller, W. Gindl, and A. Teischinger. 2004. New shear assay for the simultaneous determination of shear strength and shear modulus in solid wood: Finite element modelling and experimental results. *Wood Fiber Sci*. 36(3):302–310.

Swingle, W. T. 1916. The early European history and the botanical name of the Tree of Heaven, *Ailanthus altissima*. *J. Wash. Acad. Sci*. 6(14): 490–498.

Teischinger, A., M. L. Zukal, T. Meints, C. Hansmann, and R. Stingl. 2012. Colour characterization of various hardwoods. *In:* The 5th Conference on Hardwood Research and Utilization in Europe. Proceedings of Hardwood Science and Technology, R. Németh and A. Teischinger (Eds.), University of West Hungary Press, Sopron. pp. 180–188.

Udvardy, L. 2004. Götterbaum (*Ailanthus altissima* (Mill.) Swingle). *In:* Invasive Pflanzen, TermészetBÚVÁR Alapítvány. Verlag, Budapest. pp. 143–155.

Verkasalo, E. and J.-M. Liban. 2002. MOE and MOR in static bending of small clear specimens of Scots pine, Norway spruce and European fir from Finland and France and their prediction for the comparison of wood quality. *Pap. Ja Puu* 84(5):332–340.

Vor, T., H. Spellmann, A. Bolte, and C. Ammer. 2015. Potenziale und Risiken eingeführter Baumarten: Baumartenportraits mit naturschutzfachlicher Bewertung (Nr. 7). Göttingen University Press, Göttingen, Germany. https://doi.org/10.17875/gup2015-843

Wunder, J., S. Knüsel, L. Dorren, M. Schwarz, F. Bourrier, and M. Conedera. 2018. Götterbaum und Paulownie: die ‚neuen Wilden'im Schweizer Wald? *Schweiz. Z. Forstwesen*. 169(2):69–76. https://doi.org/10.3188/szf.2018.0069

Wunder, J., M. Nobis, and M. Conedera. 2014. Der Götterbaum—eine Gefahr für den Schweizer Wald? *Z. Wald Wald. Holzm. Holz.* June. 40–43.