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Case Study of Anatomy, Physical and Mechanical Properties of the Sapwood and Heartwood of Random Tree *Platycladus orientalis* (L.) Franco from South-Eastern Poland

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Abstract: Oriental arborvitae is not fully characterized in terms of its microscopic structure or physical or mechanical properties. Moreover, there is a lot of contradictory information in the literature about oriental arborvitae, especially in terms of microscopic structure. Therefore, the sapwood (S) and heartwood (H) of *Platycladus orientalis* (L.) Franco from Central Europe were subjected to examinations. The presence of helical thickenings was found in earlywood tracheids (E). Latewood tracheids (L) were characterized by a similar thickness of radial and tangential walls and a similar diameter in the tangential direction in the sapwood and heartwood zones. In the case of earlywood tracheids, such a similarity was found only in the thickness of the tangential walls. The volume swelling (VS) of sapwood and heartwood after reaching maximum moisture content (MMC) was 12.8% (±0.5%) and 11.2% (±0.5%), respectively. The average velocity of ultrasonic waves along the fibers (υ) for a frequency of 40 kHz was about 6% lower in the heartwood zone than in the sapwood zone. The dynamic modulus of elasticity (MOE_D) was about 8% lower in the heartwood zone than in the sapwood zone. These differences, both in the case of υ and MOE_D, were statistically significant. However, no statistically significant differences were found for the static bending strength (MOR, approx. 90 MPa), modulus of elasticity at static bending (MOE, approx. 4800 MPa), or compression strength parallel to the grain (CS, approx. 47 MPa) in relation to the wood zone (sapwood, heartwood).

Keywords: biota; oriental arborvitae; physical and mechanical properties of wood; swelling; thuja; tracheids; water absorption; wood anatomy

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1. Introduction

Oriental arborvitae is a species native to Asia and commonly known as *Thuja orientalis*. Initially, it belonged to the biota genus [1,2], at a later stage it was included in the thuja genus, and then it was restored to the *Platycladus* genus and returned to the name of biota eastern (*Platycladus orientalis* (L.) Franco) [2,3]. The final assignment in the plant systematics was influenced by the analysis and the identified morphological differences: vertically arranged twigs, uniform coloring of leaves, oval cones, or hook-shaped growths on the husks.

Platycladus orientalis (L.) Franco is an evergreen, coniferous tree, reaching a height of 15 m, and most often reaching heights from 5 m to 10 m [4,5]. The natural area of occurrence of oriental arborvitae is China, Manchuria, Korea, and Japan [6,7]. It appeared there probably thanks to Buddhist priests [2,8]. According to Ridsdale et al. [9], the tree also comes from eastern Russia. It is a popular ornamental species in parks in the southwestern part of the USA (from Texas to California) [4]. It is considered a thermophilic species and is sensitive to frost, which makes it most common in Central Europe in regions with mild winters. However, in order to maintain its ornamental value for a long time, it should be planted in warm and sheltered positions [2]. Wang et al. [7] reported that it occurs in the forest ecosystems in the mountainous area of North China. In Europe, it is most popular in the west and south, where columnar or low-conical varieties are grown [10]. Oriental arborvitae prefers dry habitats with calcium-rich soil [5], and is one of the most important afforesting tree species in some countries, especially for establishing plantations on barren mountains [11]. Due to its tolerance to air pollution, it is also possible to plant in urban conditions [2,3,12].

In Western Europe, oriental arborvitae probably appeared in the 17th or 18th century, and the beginnings of cultivation date back to 1792. The first documented specimen was planted in the Physic Garden in Chelsea [2]. Some authors claim that oriental arborvitae in Central Europe, including Poland, appeared in the 17th century [2,13]. The planting area is often determined by the species' thermophilic nature and the wish to display the ornamental values of the plant. However, it does not always result in high physical or mechanical properties of wood [2].

In its homeland (China), oriental arborvitae has been used for centuries to decorate cemeteries, Buddhist temples, and tombs of sovereigns [2,8,14]. Currently, due to its aesthetic value, it is most often found in parks, gardens, home gardens, and in pots on balconies and terraces [6]. Due to its representative character, it is located at palace gates and at the entrances to estates [4]. Oriental arborvitae wood is mainly used in furniture and model making [6].

Although the species is well known, its wood is not fully characterized in terms of its microscopic structure or physical or mechanical properties. According to Román-Jordán et al. [15], *Platycladus orientalis* (L.) Franco, unlike *Thuja occidentalis*, *Thuja plicta*, or *Thuja standishii*, has torus in bordered pits in its tracheary cells. In the parenchyma cells of the rays (on the cross-fields), taxodioid pits are absent; there are only cupressoid pits. There are one to five pits on a single cross-field. *Platycladus orientalis* has no resin canals. The wood rays are homocellular and uniseriate. According to Gregus [16], *Platycladus orientalis*, unlike species of thuja trees, is characterized by the presence of helical thickenings in the tracheids of the earlywood. On the other hand, the data provided by Román-Jordán et al. [15] indicated that such morphology is not present in oriental arborvitae. Moreover, there are no data relating directly to the physical or mechanical properties of sapwood (S) or heartwood (H). Such analyses are important due to the fact that the sapwood of many tree species is often treated without justification as a waste material and used only for the production of particleboard or for heating purposes [17]. With regard to oriental arborvitae, there are numerous publications on chemical composition. Seeds, cones, leaves, and small twigs are used to obtain extracts and essential oils, and create infusions and ointments for health and care purposes [18–21].

Due to the deficit of wood biomass, new species suitable for industrial processing are sought. However, their physical and mechanical structure needs to be researched in order to find out about the properties determining their potential use. The aim of this research was to find out about selected microscopic features as well as the physical and mechanical properties of *Platycladus orientalis* (L.) Franco from Central Europe. Sapwood and heartwood were tested. The results of the microscopic research were compared with the literature data on oriental arborvitae. In addition, the obtained results of the physical and mechanical tests were compared with the literature data for moderately light wood, i.e., for Scots pine (*Pinus sylvestris* L.), silver fir (*Abies alba* Mill.), and western red cedar (*Thuja plicata* Donn. ex D. Don). It should be assumed that in the case of similar properties, oriental arborvitae wood can be used for similar purposes as the aforementioned species of wood (as a substitute for them).

2. Materials and Methods

2.1. The Origin and Preparation of Oriental Arborvitae

Oriental arborvitae wood (*Platycladus orientalis* (L.) Franco), growing in Central Europe, i.e., in southeastern Poland, in the area of the Kadzielnia range of the Świętokrzyskie

Mountains, was used for the research. It is the border distribution of this species in Poland. It is worth noting that it is an area with a relatively cool climate for typical oriental arborvitae growing conditions. Its properties in extreme conditions of growth in Poland were examined. The following criteria were adopted to select a representative tree: height and diameter (diameter at breast height—DBH). The trees from which the model tree was selected grew under identical forest site and climatic conditions.

The butt section of the trunk was examined. The diameter at breast height (DBH) with bark was 320 mm (±20 mm), and 280 mm (±20 mm) without bark. After cutting, the wood was kept in a normal climate (temperature 20 °C ± 2 °C, relative humidity 65% ± 5%). The method of preparing samples for individual tests is presented in Figure 1.

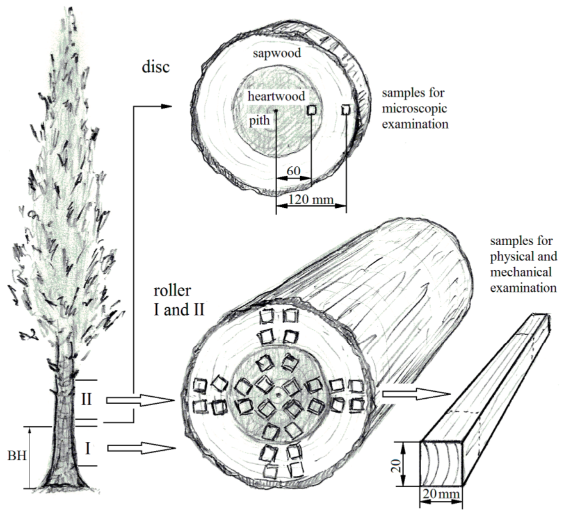

Figure 1. The method of preparing (cutting out) samples for individual examinations.

2.2. Annual Ring Measurements

Annual rings were analyzed on wood discs cut from the breast height (BH) of the tree trunk. The transverse section of the trunk was scanned on an Expression 11000XL scanner (Seiko Epson Corporation, Suwa, Japan). The sanded disks were scanned with a resolution of 3200 dpi and the images were saved as a TIFF (tagged information file format). Using the WinDENDRO^{TM} version 2016a program (Regent Instruments Inc., Quebec, QC, Canada), the measurement paths were designated, along which the system determined the boundaries of annual rings, the width of earlywood and latewood, and subsequently the share of latewood in the sapwood (S) and heartwood (H) zones. Selected tree-ring parameters were determined on the basis of measurements within four measurement paths from the core to the outer zone of the trunk.

2.3. Microscopic Measurements

A number of 10 mm (radial) × 10 mm (tangential) × 15 mm (longitudinal) samples were prepared. Samples were from the sapwood and heartwood, 12 cm and 6 cm (to obtain mature wood zone) from the pith, respectively. The samples were soaked in a mixture of water, 96% ethyl alcohol, and glycerin in the proportion of 1:1:1 ($v/v/v$). After three weeks of soaking in the prepared mixture, the samples were cut with a sledge microtome (Reichert, Vienna, Austria) to the appropriate thickness (15–30 μm). Preparations were stained with 5% safranin solution in 96% ethyl alcohol. The microscopic analysis was performed using an Olympus BX-41 microscope (Olympus Corporation, Tokyo, Japan) equipped with a digital camera and coupled with specialized Cell B analytical software. The following parameters of earlywood (E) and latewood (L) tracheids in the sapwood and heartwood were measured in transverse section images: the thickness of the radial and tangential walls, and the diameter in the radial and tangential directions. The length of earlywood and latewood tracheids in the sapwood and heartwood were measured in tangential section images. A total of 30 measurements were taken for each parameter of tracheids.

2.4. Determination of Physical Properties

The wood moisture content was determined according to ISO 13061-1:2014 [22]. The density was determined using the stereometric method, as required under ISO 13061-2:2014 [23]. Wood samples with the dimensions of 20 mm (radial) × 20 mm (tangential) × 30 mm (longitudinal) were dried at a temperature of 103 °C ± 2 °C until a mass change between two separate measurements not exceeding 0.2% was reached. The tested material was cooled to room temperature (20 °C ± 2 °C) in a desiccator. Samples were soaked in distilled water at 20 °C ± 2 °C. The weight of the samples was determined after 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 7 h, and 24 h and until no further change in weight occurred, i.e., after reaching maximum moisture content (MMC). The obtained results were used to calculate the water absorption (*WA*) and rate of water absorption (V_n) according to Equations (1) and (2), respectively:

$$WA(t) = \frac{m_{\mathrm{s(t)}} - m_{\mathrm{o}}}{m_{\mathrm{o}}} \times 100\ (\%), \tag{1}$$

$$V_n = \frac{W_{i+1} - W_i}{\tau_{i+1} - \tau_i} \left(\% \times h^{-1}\right), \tag{2}$$

where W_i is the change in moisture content upon soaking (%), $W_{i+1} - W_i$ is the change in moisture content (%), τ_{i} is the soaking time *(h)*, $\tau_{\mathrm{i+1}} - \tau_{\mathrm{i}}$ are the time intervals *(h)*, m_{o} is the mass of wood in absolute dry state *(g)*, and $m_{\mathrm{s(t)}}$ is the mass after soaking in water *(g)* for a specific length of time.

Linear swelling was determined according to ISO 13061-15:2017 [24], and volumetric swelling (VS) according to ISO 13061-16:2017 [25]. The same samples were used to determine the swelling of oriental arborvitae wood as to determine the water absorption. The dimensions of the samples were determined after 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 7 h, and 24 h and after reaching MMC. On the basis of the obtained results, the swelling in the radial, tangential, and longitudinal directions, as well as the swelling in volume, were calculated.

2.5. Determination of Wood Properties Using Ultrasound

The UMT-1 ultrasound tester (Unipan, Warsaw, Poland) was used in the tests to determine the properties of the wood. The tests were carried out with the use of samples with dimensions of 20 mm (radial) × 20 mm (tangential) × 300 mm (longitudinal) and in the air-dry state (i.e., determined wood moisture content). Test heads (transmitter and receiver) with a frequency of 40 kHz were used. Before starting the test, the output parameters of the device were set as follows: transmission signal power 40 dB, trigger level 2, transmission 12 Hz, gain with a voltage of 60 V, and delay time of 8.94 µs. Then, the heads were placed on the front surfaces of the samples covered with ultrasound gel. The ultrasounds were passed along the fibers of the test material in pulses every 12 Hz and the time of passage through the wood was read. The velocity of ultrasonic waves along the fibers (υ) was calculated using Equation (3):

$$\upsilon = \frac{L}{t - t_o} \left(m \times s^{-1}\right), \tag{3}$$

where L is the sample length (m), t is the time of passing through of the wave read from the computer screen (s), and t_o is the lag time (s).

The dynamic modulus of elasticity ($\mathrm{MOE_D}$), described also as the sonic MOE [26], along the fibers was determined and calculated according to Equation (4):

$$MOE_D = \upsilon^2 \times \rho \times \frac{(1 + \mu_o)\ \times\ (1 - 2 \times \mu_o)}{(1 - \mu_o)}\ (MPa), \tag{4}$$

where ρ is the wood density (kg $\times$ m^{-3}) and μ_o is the reduced Poisson's ratio for wood (μ_o = 0.3).

2.6. Mechanical Wood Properties

The determination of the strength of wood for static bending (MOR) and the modulus of elasticity for static bending (MOE) was carried out according to ISO 13061-3:2014 [27] and ISO 13061-4: 2014 [28], respectively. The same samples were used for the study, which were used to determine the properties of the wood with the use of ultrasound. MOR and MOE testing was performed using an Instron® testing machine, model 3369 (Norwood, MA, USA), coupled with the INSTRON SERIES IX/S computer software. After the completed tests, the failure appearance was analyzed and classified according to the ASTM D 143-94:2000 [29] standard.

The determination of the compression strength parallel to the grain (CS) was carried out according to the ISO 13061-17:2017 [30] standard. The test was performed using an Instron® testing machine, model 3382 (Norwood, MA, USA), coupled with the INSTRON SERIES IX/S computer software. After the test was completed, the failures analysis was performed and the damage was classified according to the ASTM D 143-94:2000 [29].

2.7. Statistical Analysis

Statistical analyses were performed using STATISTICA version 12 software (TIBCO Software Inc., Palo Alto, CA, USA). The statistical analysis of the results was based on the *t*-test or ANOVA (Fischer's F-test), with a significance level (p) of 0.05.

3. Results

3.1. Macroscopic Features

Oriental arborvitae is a pink-brown colored heartwood species; the sapwood is whitish, or white-gray (Figure 2). The heartwood is not evenly colored; there are often lighter and darker streaks with a gentle, pastel transition, which is similar to the wood of the western red cedar (*Thuja plicata* Donn. ex D. Don) [31]. In oriental arborvitae wood no resin is present; however, in the heartwood there may be a leakage of essential oils, which was observed in the tested trunk (Figure 2a). Due to their presence, the freshly sawn wood has an intense, aromatic incense-like fragrance. The smell persists for a long time and can therefore be an auxiliary hallmark. The wood is straight grained. Annual rings are clearly visible and clearly defined on all sections. Their cross-sectional shape deviates from perfectly circular and shows slight waves. Knots do not form whorls. The shape of knots on the tangential section is similar to circular, and their color is darker than the surrounding wood.

(a) (b) (c)

Figure 2. Macroscopic images of oriental arborvitae: (**a**) transverse, (**b**) radial, and (**c**) tangential sections.

The age of the oriental arborvitae was 46 years and was determined on the basis of annual rings at the base of the trunk (Figure 3). In the oriental arborvitae the sapwood was 4 cm to 6 cm wide, which is similar to the western red cedar (*Thuja plicata* Donn. Ex D. Don), in which the sapwood ranges from 2 cm to 5 cm [31]. The sapwood in the oriental arborvitae had 15 annual rings and thus in the butt part it had a significant share in relation to the width of the 46-year-old trunk, amounting to approx. 35%. The width of the annual rings in the sapwood and heartwood zones was 2.61 mm (±1.19 mm) and 2.88 mm (±1.15 mm), respectively, and the differences were not statistically significant (t-test, $p > 0.05$). The share of latewood in the sapwood zone was 55% (±12%), and 49% (±11%) in the heartwood zone, and the differences were statistically significant (t-test, $p \leq 0.05$). This shows that the share of latewood can determine the differences between the properties of oriental arborvitae sapwood and heartwood.

Figure 3. Transverse section of oriental arborvitae across the entire diameter of the tree trunk.

3.2. Microscopic Features

Figure 4 shows the microscopic structure of oriental arborvitae sapwood on the transverse (a), radial (c), and tangential (e) sections. In Figure 4 there are also pictures of the heartwood transverse (b), radial (d), and tangential (f) sections. The transverse sections (Figure 4a,b) showed thin-walled earlywood tracheids and thick-walled latewood tracheids. In the parenchyma cells of the wood rays, the presence of cupressoid pits was found (Figure 4c,d). There were two to five pits on a single cross-field. The wood rays were homogeneous. On the tangential section (Figure 4e,f), uniseriate rays without resin canals were visible.

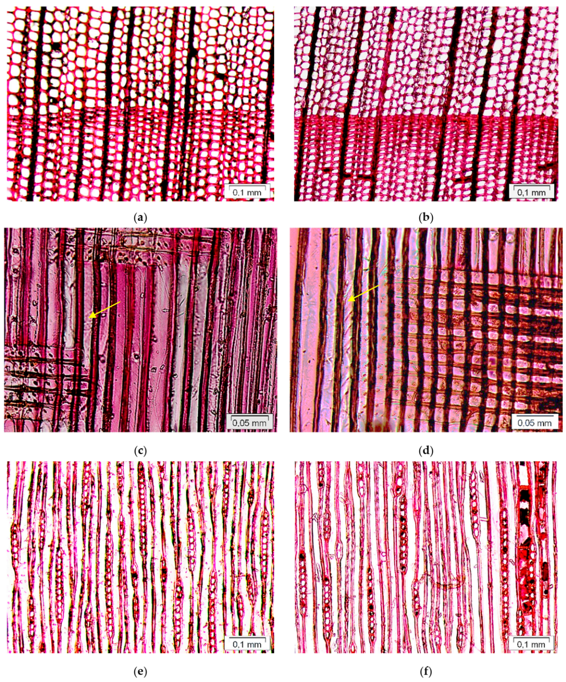

Figure 4. The microscopic structure of oriental arborvitae wood: (**a**) sapwood transverse section, (**b**) heartwood transverse section, (**c**) sapwood radial section, (**d**) heartwood radial section, (**e**) sapwood tangential section, and (**f**) heartwood tangential section.

In the bordered pits in the radial walls of the earlywood tracheids was a well-defined torus (Figure 5). Its presence was also indicated by Román-Jordán et al. [15]. It is one of the anatomical features that distinguishes oriental arborvitae from thuja, i.e., *Thuja occidentalis*, *Thuja plicata*, and *Thuja standishii*. In the work by the same authors, the lack of helical thickenings in tracheids was indicated. On the other hand, Gregus [16] reported that *Platycladus orientalis* is characterized by the presence of helical thickenings in the tracheids of earlywood, which was also presented in a graphic form. Our results confirmed the presence of helical thickenings in the tracheids of earlywood both in the sapwood and heartwood zones. The thickenings were placed at an angle of approximately 45% to the cell axis (Figure 4c,d).

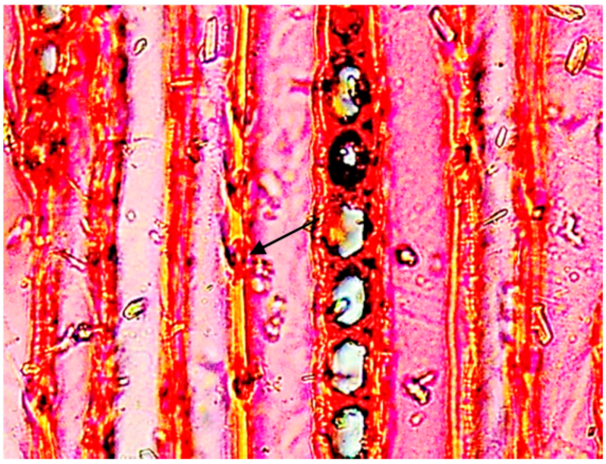

Figure 5. Tracheid pitting in radial walls with torus (earlywood in sapwood zone, tangential section).

Softwood xylem is mainly composed of longitudinal tracheids (90–95%), has a smaller amount of ray parenchyma (5–10%), and has ray tracheids and epithelial cells surrounding resin canals [32]. For this reason, mainly tracheids are tested [33–36]. Regardless of the direction of measurement, it can be observed that the thickness of the latewood tracheids (L) was about 40% greater than the thickness of the earlywood tracheids (E). These relationships were observed in the sapwood (S) and heartwood (H) zones (Table 1). In the sapwood, latewood tracheids (S_L) had a diameter approx. 30% smaller than that of the earlywood tracheids (S_E). On the other hand, in the heartwood, latewood tracheids (H_L) had a diameter approx. 20% smaller than that of the earlywood tracheids (H_E). Considering the measuring direction, it should be noted that the diameter of the tracheids in the radial direction was smaller than the diameter of the tracheids in the tangential direction. The radially flattened tracheids are a characteristic feature of softwood [37,38].

In the oriental arborvitae wood the tracheids were much shorter (2400 µm–2700 µm) than in silver fir (3400 µm–4600 µm) or western red cedar (3600 µm–5400 µm), but comparable to Scots pine tracheids, for which the average length of the tracheids is 3100 µm, in the range of 1800 µm–4500 µm [38]. Latewood tracheids were approx. 7% shorter than earlywood tracheids, but these differences were not statistically significant (*t*-test, $p > 0.05$). These relations were observed in the sapwood and heartwood. Due to their significant diameter, the tracheids of earlywood in the sapwood had a slenderness of approx. 120, and the other ones approx. 150. Tracheids formed in the first part of the vegetation period (spring) are usually shorter than those formed in the summer, irrespective of the location of the annual increment at the stem transverse section [39,40]. Taylor and Moore [41] concluded that in loblolly pine, earlywood tracheids are not consistently longer or shorter than latewood tracheids. In juvenile wood, first-formed earlywood tracheids were the shortest, but in mature wood the first-formed earlywood and the last-formed latewood tracheids were of the same length. Mäkinen et al. [42] showed that in the transition and mature wood (compared to juvenile wood) of Scots pine (*Pinus sylvestris* L.), the increase in tracheid length was more gradual from earlywood to latewood, and no significant differences were found between earlywood and latewood. In Norway spruce (*Picea abies* (L.) Karst.), tracheids were only 2–4% longer (non-significant) in latewood than in earlywood. The authors stated that in general, tracheid length is highly variable within annual rings and the variation can differ from ring to ring even within the same tree. Fabisiak et al. [43] examined the radial variation for tracheid lengths of Norway spruce (*Picea abies* (L.) Karst.), European larch (*Larix decidua* Mill.), and Scots pine (*Pinus sylvestris* L.). The authors showed that in the mature wood zone the tracheid length was stabilized at a certain level, showing slight fluctuations. The differences in the tracheid length of earlywood and latewood in the examined annual rings were also determined, and it was established that for the majority of annual rings they were statistically significant ($p < 0.05$). It should be assumed that the habitat and climatic conditions had a significant influence on the dimensions of the tracheids of the oriental arborvitae. In the area of the Kadzielnia range of the Świętokrzyskie Mountains, a significant drop in temperature is recorded in September (by approx. 5 °C compared to August), which may result in a slowing down of the growing season and changes in the microscopic structure of wood. Relationships between wood structure and environmental factors are well known [44–46].

A statistical analysis of the significance of the differences between the examined dimensions of the oriental arborvitae wood tracheids is presented in Table 2. Earlywood tracheids from the sapwood zone (S_E) and earlywood tracheids from the heartwood zone (H_E) had similar thickness of the tangential walls. On the other hand, the latewood tracheids in the sapwood (S_L) and heartwood (H_L) zones were characterized by a similar thickness of radial and tangential walls and a diameter in the tangential direction (*t*-test, $p > 0.05$). The present studies indicate that the structure of oriental arborvitae wood is homogeneous and uniform, which is desirable for wooden structures that require wood uniformity, alike to *Thuja occidentalis* L. [36].

Table 1. Dimensions of the oriental arborvitae tracheids; ±(SD).

Zone	Tracheids	Symbol	Dimensions				
			Thickness (µm)		Diameter (µm)		Length (µm)
			Radial Wall	Tangential Wall	Radial Direction	Tangential Direction	
Sapwood (S)	Earlywood (E)	S_E	3.47 (±0.28)	3.52 (±0.29)	21.66 (±1.99)	24.59 (±2.15)	2661.28 (±190.67)
	Latewood (L)	S_L	4.61 (±0.40)	4.88 (±0.44)	14.30 (±1.49)	17.32 (±1.74)	2454.98 (±225.45)
Heartwood (H)	E	H_E	3.06 (±0.36)	3.62 (±0.46)	14.09 (±1.33)	22.18 (±2.16)	2586.88 (±191.46)
	L	H_L	4.70 (±0.59)	4.86 (±0.69)	10.95 (±1.29)	17.18 (±1.61)	2397.15 (±228.65)

3.3. Wood Density

The average moisture content of oriental arborvitae sapwood was about 8.5% (±0.2%), and that of heartwood about 9.5% (±0.3%). The average density of the tested wood in the air-dry state (i.e., determined wood moisture content) for sapwood and heartwood was 467 kg·m^{-3} (±4 kg·m^{-3}) and 501 kg·m^{-3} (±3 kg·m^{-3}), respectively, and these differences were statistically significant (*t*-test, $p \leq 0.05$). Converting the density of the oriental arborvitae to that in a completely dry state, it was 448 kg·m^{-3} (±5 kg·m^{-3}) and 473 kg·m^{-3} (±3 kg·m^{-3}) for S and H, respectively, and these differences were statistically significant (*t*-test, $p \leq 0.05$). The coefficient of variation for both sapwood and heartwood was quite low (below 5%), indicating a relatively homogeneous set of examined wood. For example, according to the research by Sekhar and Negi [47], carried out on 250 logs from 50 different types of wood, the coefficient of density variation within a single wood species in the air-dry state is, on average, approx. 6%. According to literature data, in terms of density, oriental arborvitae wood can be classified into the fifth group, i.e., moderately light wood (also including pine, fir, and cedar) [38,48].

Table 2. Statistical analysis of the significance of the differences between the studied dimensions of oriental arborvitae wood (t-test, $p \leq 0.05$).

Zone	Statistical Measures			
	t	***p***	***t***	***p***
	Tracheid Dimensions			
	Thickness of Radial Wall		**Thickness of Tangential Wall**	
S_E vs. S_L	−11.6249	0.000000	−12.5296	0.000000
S_E vs. H_E	4.3539	0.000079	−0.5957	0.554222
S_L vs. H_L	−0.6884	0.494066	−0.2545	0.800212
H_E vs. H_L	−11.4233	0.000000	−7.1828	0.000000
	Diameter in Radial Direction		Diameter in Tangential Direction	
S_E vs. S_L	16.4265	0.000000	12.8856	0.000000
S_E vs. H_E	16.1781	0.000000	4.1345	0.000127
S_L vs. H_L	8.6332	0.000000	0.2942	0.769918
H_E vs. H_L	8.3205	0.000000	9.5057	0.000000

3.4. Water Absorption

Absorption in solid wood is rarely tested, but it is more and more often a criterion for the qualitative assessment of woody materials, and is also considered to be of practical importance for the susceptibility of wood to penetration by various protective agents [49]. Figure 6 shows the curves of the soaking rate of the sapwood and heartwood in oriental arborvitae during the first 7 h of soaking. For the first 3 h of soaking, the heartwood exhibited a faster soaking rate than the sapwood. After this time, both wood zones reached a similar absorption rate of approx. 4.0%/h after 3 h, and approx. 2.0%/h after 5 h, respectively. On the other hand, after 24 h, the rate of soaking of both sapwood and heartwood was about 0.5%/h. The samples subjected to the soaking test were previously dried, and most likely during this process the pits were closed by toruses (in sapwood as well), which directly translated into the impeded soaking of this wood zone. This is important information from a practical point of view: The sapwood of oriental arborvitae will be difficult to impregnate after drying.

According to the obtained results, presented in Figure 7, the sapwood after the first hour of soaking exhibited lower water absorption (WA) than the heartwood. After 24 h, WA was not significantly changed. The share of latewood in the sapwood zone was higher than in the heartwood zone and the differences were statistically significant (t-test, $p \leq 0.05$). Thus, the heartwood had a higher share of earlywood, which absorbed more water in the first stage of soaking. In subsequent stages, the presence of extractive compounds limited the moisture content of the heartwood [38,48,50]. The obtained WA values after 24 h of soaking were lower than those from the literature for Scots pine (98% for sapwood, 78% for heartwood) [48]. The WA of Scots pine sapwood, determined by Can and Sivrikaya [49] on samples of dimensions of 20 mm × 20 mm × 10 mm, was approx. 90% after 24 h of water soaking. The samples were conditioned to 12% moisture content before water soaking. Thus, this suggests that the water content in wood depends not only on its structure, but also on the conditions of the test.

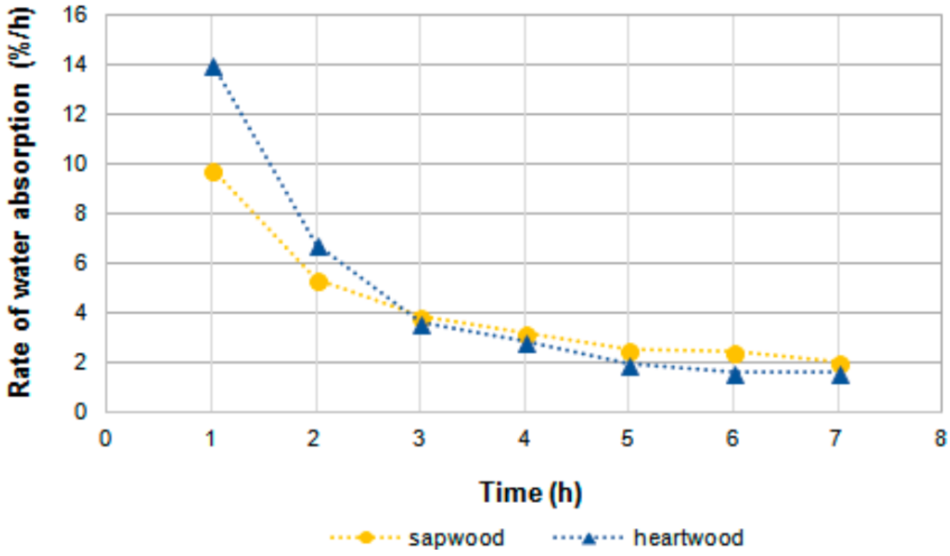

Figure 6. Rate of water absorption of oriental arborvitae wood.

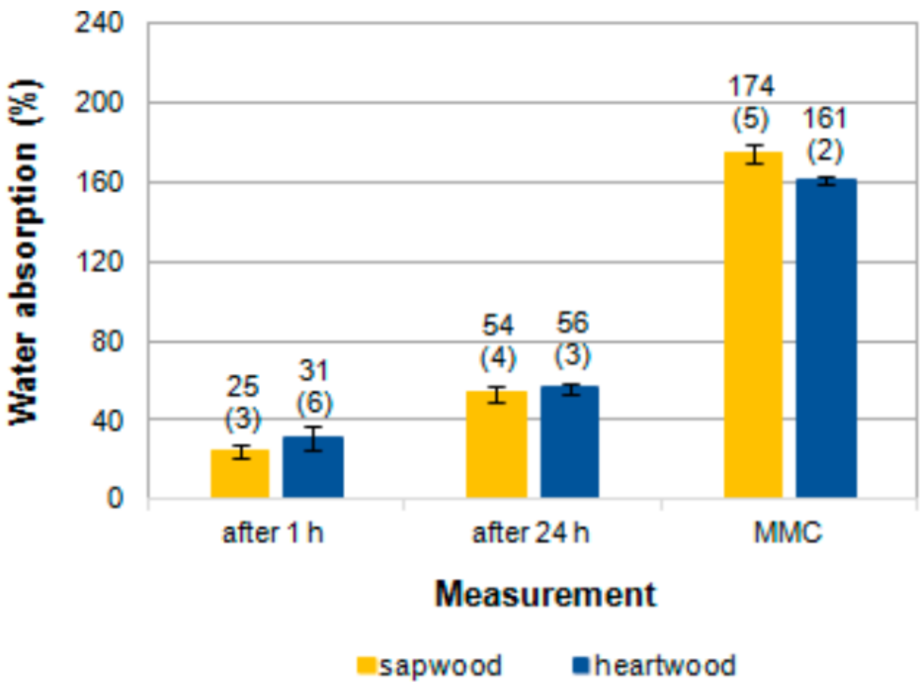

Figure 7. Water absorption (WA) of the sapwood and heartwood of oriental arborvitae; ±(SD).

The maximum moisture content (MMC) of oriental arborvitae sapwood was higher than that of the heartwood, and these differences were statistically significant (*t*-test, $p \leq 0.05$). In general, it can be concluded that the MMC of sapwood was seven times higher than WA after 1 h of water soaking, and three times higher than WA after 24 h of soaking in water. The MMC of heartwood was five times higher than WA after 1 h of water soaking, and three times higher than WA after 24 h of soaking in water.

3.5. Linear and Volumetric Swelling

Figure 8 shows the linear swelling of the sapwood and heartwood of oriental arborvitae in the radial, tangential, and longitudinal directions during the first 7 h of soaking in water in one-hour increments. The heartwood was characterized by greater swelling, both in the radial and tangential directions, than the sapwood. However, in the longitudinal direction, a slightly greater swelling of the sapwood was initially noticed. After 3 h of soaking in water, the swelling of the sapwood and heartwood were at similar levels of approx. 0.5%. The higher heartwood radial and tangential linear swelling within first stage of soaking, when compared to the sapwood, were observed most likely due to the higher share of earlywood, which absorbed more water than latewood [38,50]. Some authors stated that the wood rays are a particularly important contributory factor in the wood swelling process [51,52]. The activity of rays decreases from the outer to the inner sapwood and eventually completely stops in the heartwood as parenchyma cells die [53].

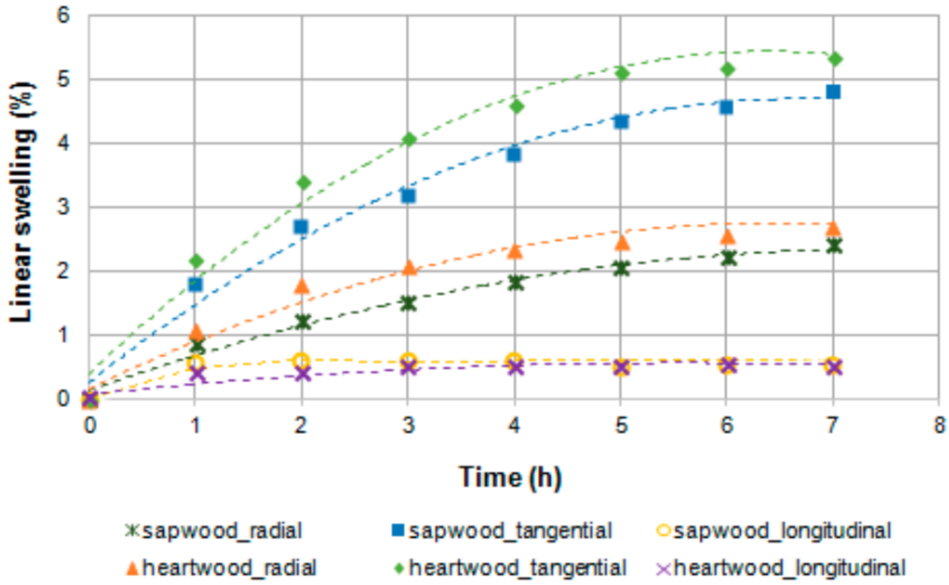

Figure 8. Swelling in the radial, tangential, and longitudinal directions of the sapwood and heartwood of oriental arborvitae.

Figure 9 summarizes the linear swelling separately for sapwood and heartwood in the radial, tangential, and longitudinal directions after 1 h and 24 h, and at maximum moisture content (MMC). The radial swelling after the first hour for heartwood was greater than for sapwood. After 24 h, the sapwood showed higher swelling compared to the heartwood. This trend continued until the achievement of the MMC. Similar relationships occurred for swelling in the tangential direction. The sapwood and heartwood of the oriental arborvitae exhibited comparable swelling along the fibers, regardless of the soaking time. The oriental arborvitae wood, after reaching MMC, was characterized by linear swelling similar to Scots pine (radial 3.3–4.0%, tangential 7.5–8.0%, and longitudinal 0.4%) and silver fir (radial 2.9–3.8%, tangential 7.2–7.6%, and longitudinal 0.1%), especially in the radial and tangential directions. Western red cedar (radial 1.8–2.4%, tangential 4.5–5.0%, and longitudinal 0.2%) is characterized by lower values of linear swelling [38].

The volumetric swelling (VS) of oriental arborvitae sapwood and heartwood after 1 h and 24 h of soaking and after reaching maximum moisture content (MMC), is shown in Figure 10. After the first hour, the VS of the sapwood was lower than the VS of the heartwood. However, after 24 h, at MMC, these relationships inverted. This was most likely due to the fact that sapwood free from heart-forming substances, but containing smaller amounts of extractives, is subsequently more open to moisture absorption, which results in larger dimensional changes [50]. Considering the VS of oriental arborvitae wood after reaching MMC, it should be stated that the species is more similar to Scots pine (11.2–12.4%) than to silver fir (10.2–11.5%). The literature data for the VS of western red cedar indicate much lower values in the range between 6.5% and 7.6% [38].

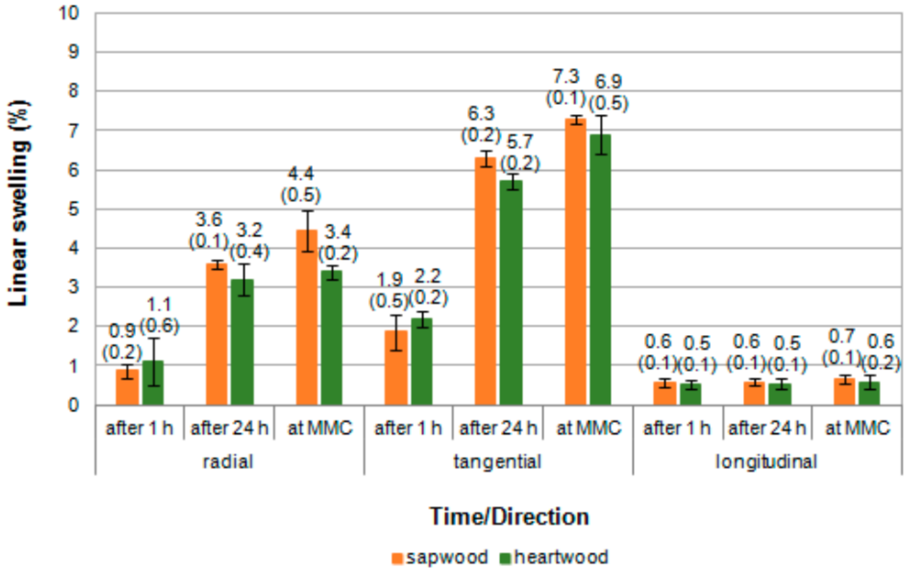

Figure 9. Swelling in the radial, tangential, and longitudinal directions of the sapwood and heartwood of oriental arborvitae after 1 h and 24 h, and at maximum moisture content (MMC); ±(SD).

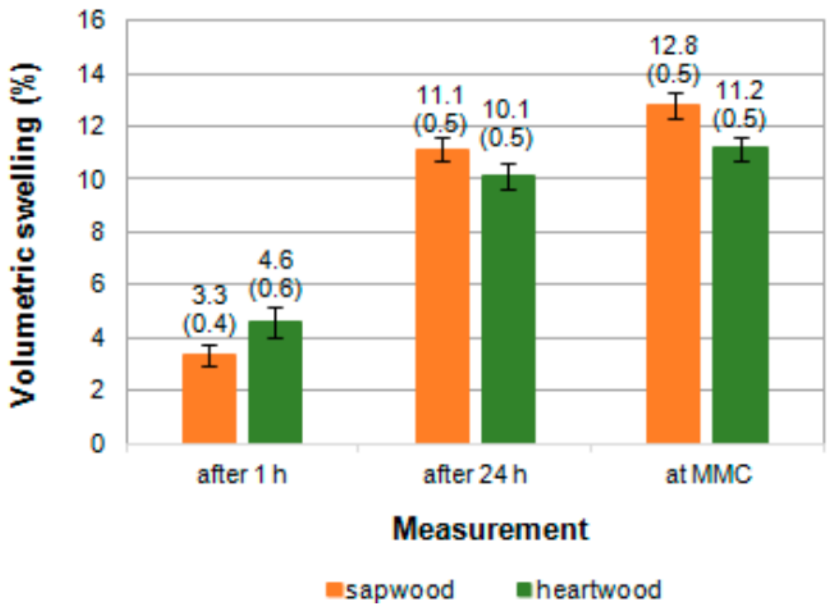

Figure 10. Volumetric swelling (VS) of the sapwood and heartwood of oriental arborvitae; ±(SD).

3.6. Properties Examined with Ultrasound

It is generally accepted that the velocity of ultrasonic waves is inversely proportional to the density of wood, i.e., the lower the density, the higher the wave velocity, and this is especially apparent when extreme cases are compared [54,55]. However, the positive influence of density on the wave velocity is usually suppressed by other factors like material stiffness, micro- and macrostructure of wood, chemical composition, etc. This phenomenon was confirmed by the obtained results. The average velocity of ultrasonic waves (υ) in sapwood (air-dry density) was 3802 $m{\cdot}s^{-1}$ ($\pm$151 $m{\cdot}s^{-1}$), whereas the average velocity in heartwood was 3588 $m{\cdot}s^{-1}$ ($\pm$163 $m{\cdot}s^{-1}$), and these differences were statistically significant (t-test, $p \leq 0.05$). In addition, in heartwood, blocking and slowing down the passage of ultrasound waves could have been caused by local leakage of essential oils. The velocity of ultrasonic waves in the investigated oriental arborvitae was comparable to the literature data for western red cedar, in which the wave velocity was 4000 $m{\cdot}s^{-1}$.

Western red cedar was characterized by a slightly higher wave velocity, but this was due to the lower density of the tested wood, which was about 400 kg·m^{-3} [56,57]. The average density of the oriental arborvitae sapwood and heartwood was 467 kg·m^{-3} (±4 kg·m^{-3}) and 501 kg·m^{-3} (±3 kg·m^{-3}), respectively. Compared to the literature data [58,59] for Scots pine (4760 m·s^{-1}) and fir (4890 m·s^{-1}), the oriental arborvitae wood exhibited a much lower velocity of ultrasonic waves, but similar densities (ρ_{pine} = 520 kg·m^{-3}, ρ_{fir} = 450 kg·m^{-3}). This could be due to the presence of moisture in the tested samples, defects in the wood, or its structure. The changes in the speed-of-sound propagation are largely influenced by anatomical factors. Compared to other conifers, oriental arborvitae has the shortest tracheids.

The dynamic modulus of elasticity along the fibers (MOE_D) of the oriental arborvitae was higher for the sapwood (5430 MPa ± 340 MPa) than for the heartwood (4996 MPa ± 457 MPa), and these differences were statistically significant (*t*-test, $p \leq 0.05$). Compared to the data in the literature [56,57], the MOE_D of western red cedar was higher and reached 6500 MPa for the wood with a density of 400 kg·m^{-3}.

3.7. Mechanical Properties

No significant differences in the modulus of rupture (MOR) of oriental arborvitae wood depending on the zone—either sapwood or heartwood—were found. The MOR was approx. 90 MPa, which was two times higher than that of western red cedar (Table 3) and comparable to the mean MOR of Scots pine and silver fir [38]. The modulus of elasticity (MOE) of the sapwood and heartwood had a similar level of approx. 4800 MPa, and was about 1.5 times lower than the MOE of western red cedar and about 2.5 times lower than the average MOE values of Scots pine and silver fir. Most likely, it resulted from the differences in anatomical structure (i.e., length of wood fibers) and density between the studied species. The analysis of sapwood and heartwood failures, based on ASTM D 143-94:2000 [29], shows that they were splintering (fibrous) tension.

Table 3. Mechanical properties of oriental arborvitae wood compared with the properties of other species according to Wagenführ [38]; (min–mean–max).

Wood Species	Zone	MOR (MPa)	MOE (MPa)	CS (MPa)
Oriental arborvitae (*Platycladus orientalis* (L.) Franco)	S	79-88-96	4500-4700-5200	40-46-49
	H	80-90-97	4500-4900-5500	44-48-51
Scots pine (*Pinus sylvestris* L.)		41-100-205	6900-12000-20100	35-55-94
Silver fir (*Abies alba* Mill.)		47-73-118	6600-11000-17200	31-47-59
Western red cedar (*Thuja plicata* Donn. ex D. Don)		48-55	7400-8300	29-35

Compression strength along the fibers (CS) of oriental arborvitae sapwood and heartwood reached 46 MPa (±3 MPa) and 48 MPa (±2 MPa), respectively, and these differences were not statistically significant (*t*-test, $p > 0.05$). Table 3 shows a comparison of the obtained results for CS of oriental arborvitae with the literature data for Scots pine, silver fir, and western red cedar. The analysis indicated that the studied species have a CS comparable to the mean CS values of Scots pine and silver fir, but about 40% higher than the CS of western red cedar. After the completed CS tests, the failure appearance was analyzed and classified according to the ASTM D 143-94:2000 [29] standard as wedge split and shearing (the plane of rupture makes an angle of more than 45° with the top of the specimen). These are typical images of damage in air-dry, straight-grained wood of medium density [60]. On the basis of the obtained strength results, it can be concluded that oriental arborvitae wood is suitable for use in construction or furniture because of its similarity to pine or fir in terms of static bending strength and compression strength along the fibers.

4. Conclusions

Oriental arborvitae wood is a moderately light wood. The average density of the sapwood and heartwood (in the air-dry state) was, respectively, 467 kg·m^{-3} (±4 kg·m^{-3}) and 501 kg·m^{-3} (±3 kg·m^{-3}), and these differences were statistically significant (*t*-test, $p \leq 0.05$). In oriental arborvitae wood there is no resin, but in the heartwood there may be leakages of essential oils, the presence of which gives the freshly sawn wood an intense, aromatic, incense-like fragrance. The oriental arborvitae wood had only cupressoid pits on the cross-fields. The bordered pits in the radial walls of the earlywood tracheids had a torus. There were helical thickenings in the earlywood tracheids. The thickness of the latewood tracheids was about 40% greater than the thickness of the earlywood tracheids. There was no significant variation in tracheid length depending on the wood zone (sapwood, heartwood, earlywood, latewood). The sapwood after the first hour of soaking was characterized by less water absorption than the heartwood. On the other hand, after 24 h, the water absorption was at a similar level, i.e., approx. 55%. The maximum moisture content of the oriental arborvitae sapwood was higher than that of the heartwood, and these differences were statistically significant. After the first hour, the volumetric swelling of the sapwood was smaller than that of the heartwood, but after 24 h of soaking in water, at maximum moisture content these relationships were opposite. Significant differentiation of the properties of oriental arborvitae wood, tested with ultrasound and depending on the wood zone (sapwood, heartwood), was demonstrated. The oriental arborvitae wood was characterized by a bending strength and compression strength parallel to the grain similar to literature values for Scots pine and fir wood.

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