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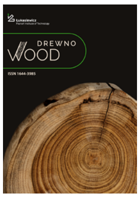

Variability in Vessel Dimensions Across Select Quercus Species: A Comparative Study of Four European and American Species

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Anatomical features of wood cells and their size variations are key elements of wood identification. This research focuses on microscopic differentiation between four Quercus species: two red oaks (*Q. cerris* and *Q. rubra*) and two white oaks (*Q. alba* and *Q. petraea*). More specifically, it studies the variation of vessel width in earlywood and latewood. The results show that in earlywood, *Q. rubra* had the widest vessels (332.27 ± 65.21 µm), followed in descending order by *Q. cerris* (300.27 ± 57.62 µm), *Q. petraea* (286.09 ± 58.83 µm), and *Q. alba* (200.82 ± 43.50 µm). In latewood, *Q. cerris* had the largest vessels (83.89 ± 20.31 µm), with *Q. rubra* having a slightly smaller value (74.05 ± 20.31 µm). *Q. petraea* (35.34 ± 6.11 µm) and *Q. alba* (26.70 µm) retained their order, revealing a consistent pattern between the wood growth phases. The variability in vessel dimensions was also supported by statistical differences among most species combinations in both earlywood and latewood. The investigation of certain vessel traits may serve as a valuable component of studies related to wood properties and species adaptability in the context of climate change.

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Introduction

The examination of both macroscopic and microscopic structures of wood is essential for comprehending its formation process. This fundamental analysis not only facilitates wood identification, but also serves as a cornerstone for understanding the utilization of wood, since anatomical features affect its technological and physical properties (Mai et al., 2022). Macroscopic features can exhibit great variation as a result of different environmental conditions, genetic basis, and stage of wood development (Feuillat, 1997; Ruffinatto et al., 2023).

Anatomical traits vary from species to species and determine the functionality of trees, as they control water transport and storage and influence the tree's mechanical support. Quantitative wood anatomy (QWA) is primarily concerned with the examination of distinct anatomical features within specific regions of a growth ring or larger segments of wood, such as heartwood and sapwood. Furthermore, QWA focuses on the precise measurement of cell types in relation to respective species (Von Arx et al., 2016). It has been noted that anatomical features exert a significant influence on various properties of wood, including shrinkage and density (Nepveu et al., 1996). Woodcock et al. (2022) found

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connections between vessel size diversity and factors related to climate and paleoenvironment transformation, pointing out the importance of the anatomical variation in wood when the evolution of a tree is studied over time. QWA is a scientific field engendering increasing research interest, a fact that has led to the establishment of Q_NET, a site that facilitates the worldwide exchange of knowledge in this area (Von Arx et al., 2021).

The *Quercus* genus, belonging to the family Fagaceae, comprises around 500 species and is distributed across various climates and environments worldwide (Wilis, 1973). Most of them are deciduous trees, except for *Quercus coccifera* L., *Quercus ilex* L. and *Quercus suber* L. *Quercus alba* L. (white oak) has a wide range in the eastern United States and Canada, while *Quercus cerris* L. (Turkey oak) is distributed from southern Europe to Asia. *Quercus rubra* L. (northern red oak) is widely distributed in Canada and the northern United States, whereas *Quercus petraea* Matt. (Cornish oak, durmast oak, Irish oak, sessile oak) occurs widely in Europe, but has been naturalized in the United States for timber production (De Rigo et al., 2016; Eaton et al., 2016; Rogers, 2023; Sander, 2023).

Quercus wood is highly valued. Species of the genus are ring porous broadleaved trees with a flared design, accompanied by wide distinct rays. The wood of *Quercus* species is characterized by its hardness and heaviness. Generally, *Quercus* species are divided into two categories, white oaks and red oaks, which differ in terms of their wood construction. In the case of red oaks, the vessels in the latewood are fewer in number and can be easily counted using a hand magnifier. Moreover, the height of the rays does not exceed 2 cm. The wood from red oaks is heavy and hard, having a basic density within the range 680–800 kg/m^3 measured at a moisture content of 12% (Voulgaridis, 2015; Tsoumis, 2009; Mantanis, 2019).

White oaks and red oaks are two large categories which consist of various species. It is possible to distinguish them easily when the whole plant is available; however, when only the wood is available this becomes a challenging problem. White oaks are found to have small and numerous, usually angular latewood pores with thin walls, while red oaks have larger and fewer pores in the latewood, usually round with thick walls. The wood of white oaks is dense and durable and exhibits excellent resistance against decay. This explains its widespread use in sawn wood products, veneer, furniture, flooring, boat construction, firewood, and other applications (Harlow, 1970; Kakaras, 2008).

In comparing red oak species (*Quercus rubra* L. and *Quercus cerris* L.) and white oak species (*Quercus alba* L. and *Quercus petraea* Matt.), it is essential to distinguish their characteristics and uses. *Q. rubra*, commonly known as red oak, has heavy wood with a density of 770 kg/m^3. Its grain is mostly straight, and it features large pores, displaying a yellow-gray heartwood with a reddish tone. *Q. rubra* is valued for its moderate bending strength and modulus of elasticity, as well as its high compressive strength. This species finds applications in flooring, furniture, vehicles, and other interior spaces, with primary marketed products being sawn timber and veneer (Kakaras, 2008). The second red oak species, *Q. cerris*, has a density of 720 kg/m^3 and features a red-to-brown color with medium to large pores (The Wood Database, 2023). However, its wood is not widely used due to its tendency to crack easily. It is primarily utilized for energy production (De Rigo et al., 2016).

In turn, *Q. alba*, commonly known as white oak, has heavy wood with a density of 760 kg/m^3. Its grain is straight, and the color ranges from yellow-brown to yellow-gray with pink shadows. *Q. alba* is characterized by medium bending strength and compressive strength, along with a low modulus of elasticity. It is commonly used for sawn timber and veneer, and it also finds applications in furniture manufacturing, wood crafting, heavy constructions, barrel production, wood carving, and flooring (Kakaras, 2008). Finally, *Q. petraea*, another white oak species, has wood with a density ranging from 670 to 720 kg/m^3. Its heartwood is light yellow-brown, typically straight-grained, and durable. This species is suitable for sawn timber, veneer, barrels, shipbuilding, furniture, wood carving, and flooring (Kakaras, 2008). It should be noted that in *Q. petraea* and *Q. robur*, the transition from earlywood to latewood is reported to be either gradual or abrupt, based on the distribution of vessel size in the radial direction (Feuillat et al., 1997).

The present study aimed to collect and analyze anatomical data from four *Quercus* species, with a specific focus on understanding the variations among them. More specifically, the goal was to measure the vessel dimensions of *Q. alba, Q. cerris, Q. rubra* and *Q. petraea* and examine the differences in their wood structure, so as to facilitate their identification. The null hypothesis asserted that statistical differences among the examined species would be found. This research aspires to provide a detailed examination of the specific anatomical traits exhibited by these *Quercus* species.

Materials and methods

Wood slides from *Q. alba, Q. rubra, Q. cerris,* and *Q petraea* were examined. The *Q. cerris* and *Q. petraea* samples originated from stands in northern Greece, and those of *Q. alba* and *Q. rubra* also from stands in the northeastern United States. Wood disks obtained at breast height for each species were used for the preparation of wood slides. Samples were collected from one or two trees within the same stand, since the primary wood structure remains consistent when trees of the same species and stand are studied. For each sample four to five slides were prepared. Wooden strips were cut from each disk at breast height and with an orientation from pith to bark, with the goal of creating sections from mature wood. From each strip, cubic samples measuring approximately 1 cm × 1 cm × 1 cm were boiled until sinking point. After boiling, the wood specimens were stored in a solution comprising glycerin, alcohol, and water in the proportions 3:2:1 to facilitate softening and increase elasticity.

Slides were cut by means of a microtome from each sample cross-section, and had a thickness of 15 μm. The slides were preserved in distilled water and stained with safranin in a water solution. Afterwards, water was removed by means of continuous rinsings with ethyl alcohol solutions of increasing concentration, followed by final rinsing with xylene to remove all alcohol from the slides. The safranin-stained microscopic sections were fixed on a slide using Canada balsam, and cover-slipped with light pressure applied to hinder air bubble formation and create permanent slides.

Each slide was examined using a Nikon Eclipse 50i microscope, and the samples were photographed with a Nikon DS-Fi1-L2 camera attached to the microscope, under 40x magnification (Fig. 1). Four photos were taken from each cross-sectional slide, capturing different areas of the section in a clockwise direction, with the objective of measuring the dimensions of a total of 60–80 earlywood and 60–80 latewood vessels. Two measurements were taken for each pore, the first corresponding to the largest diameter and the second perpendicular to the first, and their mean value was subsequently calculated for purposes of statistical analysis.

Statistical analysis of the results was performed using IBM SPSS software, version 23 (IBM, 2015) and R (R-Core Team 2023). Analysis of variance was used to identify statistical differences among group means, and Bonferroni's post hoc test was used for pairwise comparisons. All tests were performed at the $\alpha = 0.05$ significance level. Finally, the effect size was determined by means of partial eta squared (η^2_p).

Results

1. Earlywood vessel width

A total of 268 earlywood pore cavities were examined on the prepared slides (Table 1 and Fig. 2). Investigation of the distributions of earlywood vessels reveals interesting patterns. Analysis of variance results indicate statistically significant differences among the four species ($F = 57.883$, $df = 3$, $p < 0.001$) as well as a high η^2_p effect size value of 0.397 (Table 1). The post hoc tests revealed that the earlywood vessel widths of *Q. cerris* and *Q. rubra* did not differ significantly, in contrast to all other species combinations.

The species with the highest vessel width were *Q. rubra* (332.27 ± 65.21 μm) and *Q. cerris* (300.27 ± 57.62 μm), followed by *Q. petraea* (286.09 ± 58.83 μm) and *Q. alba* (200.82 ± 43.50 μm). It should be noted that earlywood vessel variability is large: the mean vessel width for *Q. rubra* is more than 50% larger than for *Q. alba* (Fig. 3). This data provides a detailed picture of the earlywood vessel dimensions, highlighting the significant variability inherent in this aspect of wood anatomy. Furthermore, a wider range of values is found in *Q. rubra*, and a narrower range in *Q. alba*. In all cases the statistical error lies within the range 5.66–8.42 μm, suggesting statistical accuracy.

2. Latewood vessel width

A total of 197 latewood pore cavities were examined on the prepared slides (Fig. 4). Analysis of variance results indicated statistically significant differences among all four species ($F = 100.255$, $df = 3$, $p < 0.001$) as well as a high η^2_p effect size value of 0.609 (Table 2).

Fig. 1. The microscope equipment used for the measurements

Table 1. Descriptive statistics of earlywood vessel width for the examined *Quercus* species

	N	Mean	SD	s.e.	Range	95% CI Mean
Q. rubra	60	332.27 ^{b}	65.21	8.42	293.53	315.43–349.12
Q. cerris	71	300.27 ^{b}	57.62	6.84	231.07	286.63–313.91
Q. petraea	78	286.09 ^{c}	58.83	6.66	253.81	272.82–299.35
Q. alba	59	200.82 ^{a}	43.50	5.66	158.62	189.49–212.16

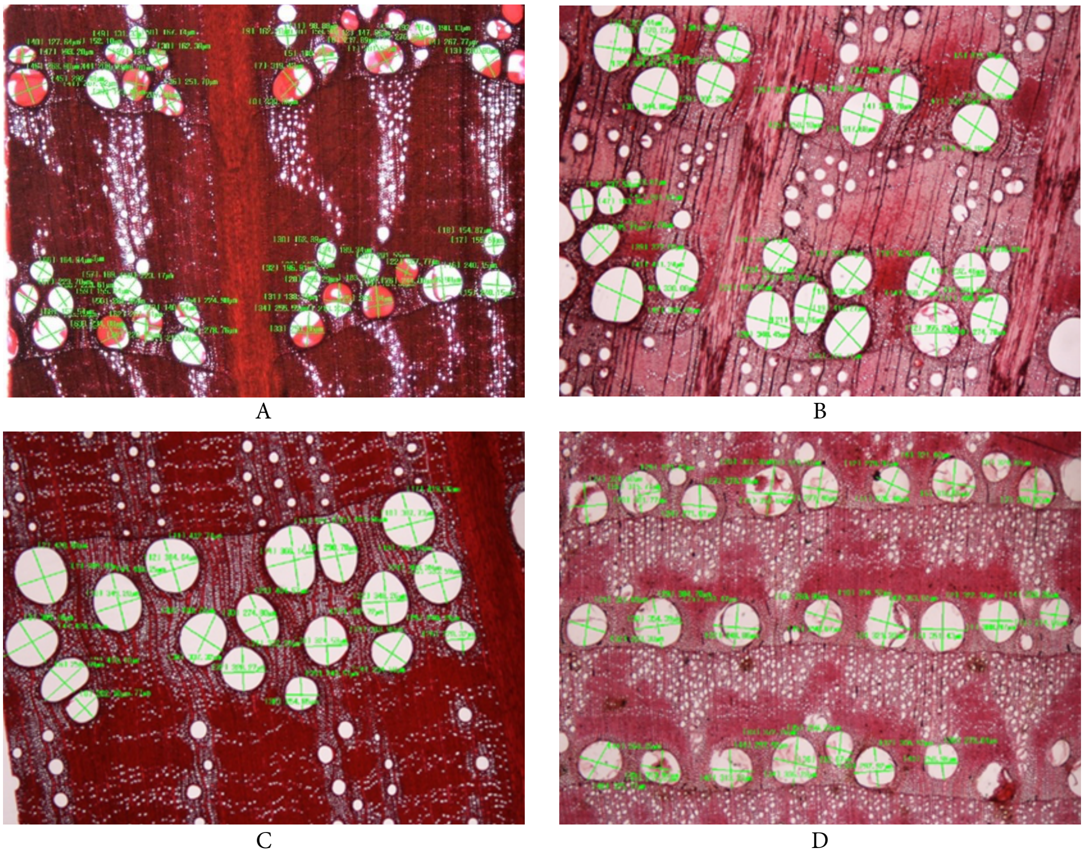

Fig. 2. Transverse earlywood sections of the examined *Quercus* species. A. *Q. alba*, B. *Q.cerris*, C. *Q. rubra*, D. *Q. petraea*

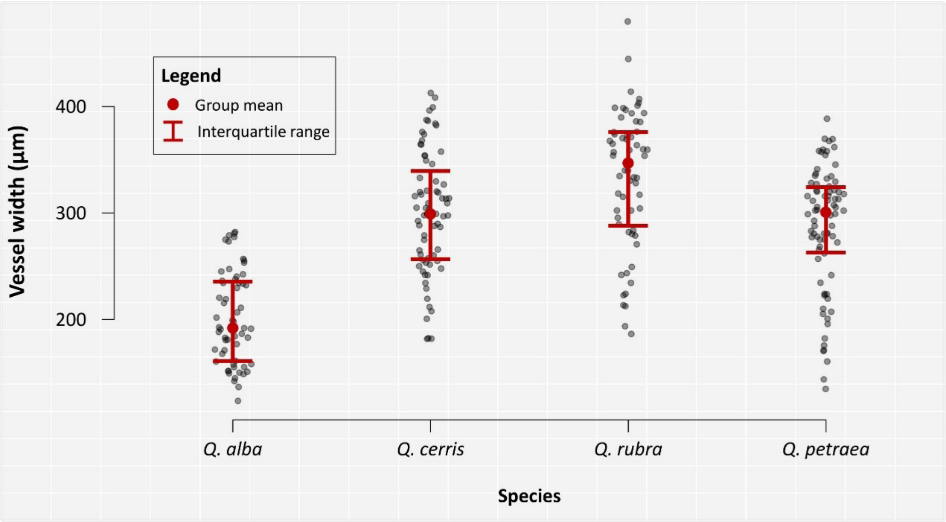

Fig. 3. Earlywood vessel width distribution of the examined *Quercus* species

Table 2. Descriptive statistics of latewood vessel width for the examined *Quercus* species

	N	Mean	SD	s.e.	Range	95% CI Mean
Q. cerris	63	83.89 ^{b}	20.31	2.56	84.41	78.77–88.99
Q. rubra	42	74.05 ^{c}	23.04	3.55	96.20	66.87–81.23
Q. petraea	45	46.97 ^{d}	7.04	1.05	26.70	44.86–49.08
Q. alba	47	35.34 ^{a}	6.11	0.89	30.61	33.55–37.13

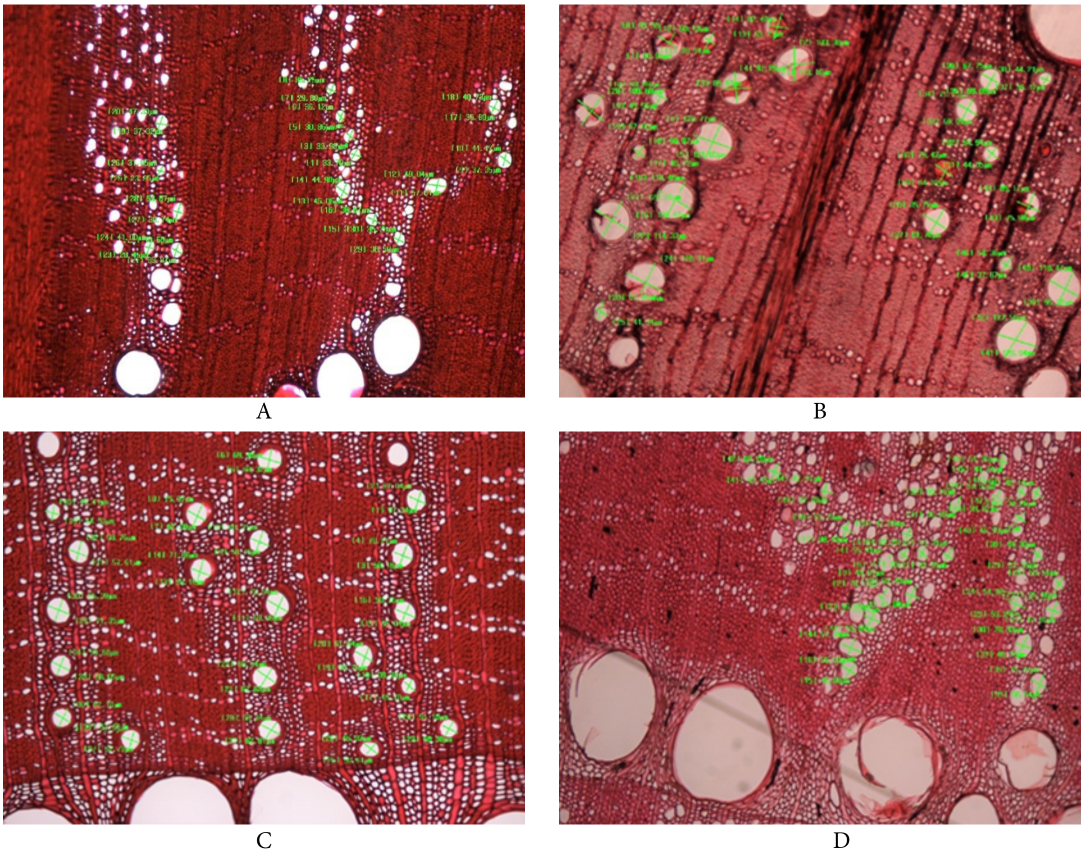

Fig. 4. Transverse latewood sections of Quercus species with the conducted measurements. A. *Q. alba*, B. *Q. cerris*, C. *Q. rubra*, D. *Q. petraea*

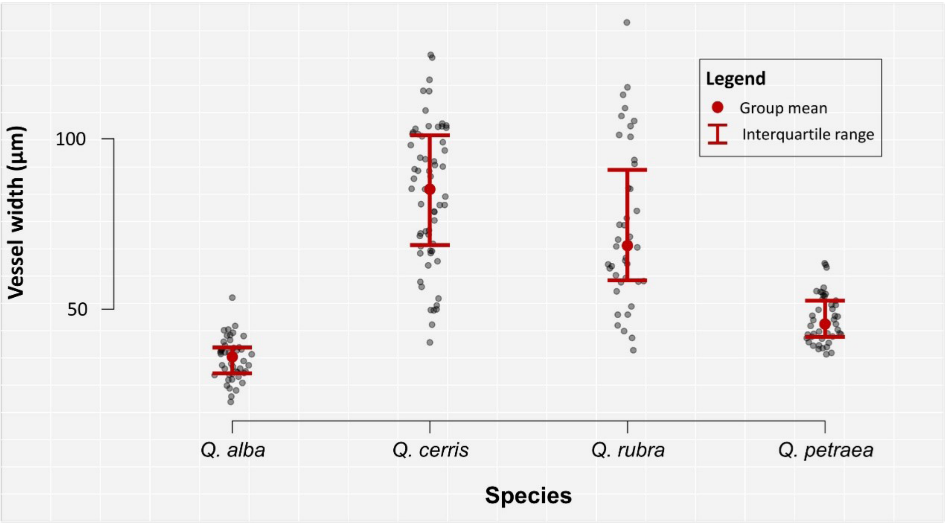

Fig. 5. Latewood vessel width distribution of the examined *Quercus* species

The post hoc tests revealed that latewood pore width was highest in *Q. cerris* (83.89 ± 20.31 μm), followed by *Q. rubra* (74.05 ± 20.31 μm), *Q. petraea* (46.97 ± 7.04 μm) and *Q. alba* (35.34 ± 6.11 μm). *Q. rubra* again exhibited the widest range of values (96.20 μm), and *Q. petraea* the narrowest (26.70 μm) (Fig. 5). The standard error of the means for the examined species ranged from 0.89 to 3.55 μm, which confirms the robustness of the findings.

Discussion

The presented results offer valuable insights into the anatomical differences among the studied *Quercus* species, particularly regarding vessel dimensions in both earlywood and latewood. In earlywood, *Q. rubra* exhibited the widest vessels, followed in descending order by *Q. cerris*, *Q. petraea*, and *Q. alba*. In latewood, *Q. cerris* had the largest pores, with *Q. rubra* having a slightly smaller value. *Q. petraea* and *Q. alba* retained their order, indicating a consistent pattern between the two wood growth stages. Notably, *Q. rubra* produced the broadest range of vessel sizes in both earlywood and latewood, indicating significant variability. By contrast, *Q. alba* exhibited a narrower spread in earlywood, while *Q. petraea* had a limited range of vessel sizes in latewood. However, Feuillat et al. (1997a) found no significant differences in earlywood vessels between *Q. petraea* and *Q. robur*, with regard to either their diameter or their shape.

Furthermore, an interesting observation was made regarding the spatial arrangement of pores. *Q. petraea* was distinguished by having vessels predominantly arranged in a single row, covering a substantial portion of the sample area. In contrast, the other three species exhibited a dispersed pattern, forming groups within the samples. This finding aligns with previous research by Feuillat et al. (1997), emphasizing the distinct anatomical characteristics of *Q. robur* and *Q. petraea*, especially in terms of vessel rows and their proportionate area within the total sample. Moreover, Feuillat and Keller (1997) noted a strong correlation between the structural features of these species and ring width, particularly in earlywood, although this relationship was influenced by residue variability.

In terms of vessel shapes, most species displayed an oval morphology, with *Q. petraea* vessels appearing slightly less oval and more circular. It should be noted that vessel shapes can vary between immature and mature wood, a phenomenon documented by Zasada & Zahner (1969). While previous studies, such as that of Sharma et al. (2011), have investigated anatomical variations among *Quercus* species, focusing primarily on diffuse porous species, there remains an opportunity to expand research in this area. A promising avenue for future exploration might involve examining the relationship between wood density and vessel width, a suggestion made by Rao et al. (1997). Collecting additional data in this context may further enhance our understanding of the intricate interplay between wood density and vessel characteristics within these *Quercus* species.

Conclusions

The present study gives valuable quantitative information about the variability of vessel sizes in earlywood and latewood among four *Quercus* species. Statistically significant differences were detected among the species in both earlywood and latewood. In earlywood, *Q. rubra* had the widest vessels (332.27 ± 65.21 μm), followed in descending order by *Q. cerris* (300.27 ± 57.62 μm), *Q. petraea* (286.09 ± 58.83 μm), and *Q. alba* (200.82 ± 43.50 μm). In latewood, *Q. cerris* exhibited the largest vessels (83.89 ± 20.31 μm), followed by *Q. rubra* (74.05 ± 20.31 μm), *Q. petraea* (35.34 ± 6.11 μm) and *Q. alba* (26.70 μm). While the use of similar data as a wood identification attribute cannot be excluded, more potential fields of research can be suggested. These include wood quality and utilization, where vessel size and arrangement may be linked to properties such as the density and mechanical properties of wood. Another potential implementation is the correlation of vessel size dimensions and climate adaptation, exploring links between plants' responses to climate change.

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