Suitability of an Ornamental Tree, *Sorbus alnifolia*, as a Source of Industrial Wood: Properties and the Juvenile to Mature Transition

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Ornamental trees are being promoted to supplement wood for industrial applications in China. To determine the wood utilization potential of an ornamental tree species, *Sorbus alnifolia*, this study investigated the radial variation of anatomical characteristics of its wood cross-section. The results showed that *S. alnifolia* is porous with high cell wall percentage, fiber percentage, and vessel percentage, small fiber and vessel sizes, and low vessel frequency. The transition age between juvenile wood and mature wood is 7 to 11 years for vessels, 12 to 16 years for axial parenchyma, and 18 to 24 years for fibers. Mature wood exhibits a higher percentage of cell walls, thicker fiber walls, and a lower percentage of vessels than juvenile wood. This result implies that wood is easy to dry, has strong permeability, good physical and mechanical properties, and a high fiber yield.

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INTRODUCTION

In China, there are considerable supplies of ornamental tree species. *Sorbus alnifolia* (Sieb. & Zucc.) K. Koch is a precious ornamental tree species with a beautiful crown shape, smooth bark, highly ornamental golden leaves, and red fruits in autumn (Tang *et al.* 2019). *Sorbus alnifolia* is also an important fruit tree species, with rich nutrients and various dietary and health functions in its fruits (Kwon *et al.* 1994). China is currently developing a large area of fruit orchards and landscape forest utilizing *S. alnifolia* (Dong *et al.* 2023). During intensive cultivation, *S. alnifolia* begins to bear fruit at 15 years of age, and 30 years is the peak period of fruit bearing (Zou and Zou 2006). After the peak fruiting period, its fruit yield decreases year by year. *Sorbus alnifolia* wood harvested through thinning and renewal has the potential to be used for furniture, construction, and interior decoration. However, due to insufficient understanding of its wood properties, it is less commonly used in industry.

Wood is a heterogeneous material. Heterogeneous properties are the main barrier to wood processing and use in industry (Jozsa and Middleton 1999). Wood is a collection of various cells produced by the division of apical meristem and cambium (Zink-Sharp 2004). For hardwood, the cell types are mainly vessels, fibers, and rays, and some also include axial parenchyma and fiber tracheids, which exhibit the unique ordered arrangement of the tree species. The cylindrical column formed by the apical meristem around the pith in the early stages of tree growth is called juvenile wood, also known as core wood or pith wood (Burdon *et al.* 2004). It is generally believed that compared to mature wood, juvenile wood has smaller cells with thinner walls and narrower diameters. Mature wood near the bark has large fibers, thick cell walls, and low lumen diameters (Savero *et al.* 2024). Wood with smaller lumen diameters, thicker fiber walls, and higher fiber cell wall ratios has higher density (Couto *et al.* 2023) and compressive strength (Chukwunonso *et al.* 2019). Therefore, the physical and mechanical properties of juvenile wood are worse than those of mature wood, with reduced natural durability and drying quality (Bao *et al.* 2001). However, Vidaurre *et al*. (2011) believe that the difference between juvenile and mature wood is not significant in hardwood compared to softwood, and juvenile wood can be used as a substitute for mature wood. Therefore, it is important to master the anatomical characteristics of wood and determine the age at which juvenile wood transforms into mature wood. Investigation of the radial variation pattern of wood properties is beneficial for selection and prediction of wood quality, formulation of logging periods, and improvement of wood processing and utilization (Butterfield 2003).

Juvenile and mature wood can distinguish ring numbers from pith (Zobel and van Buijtenen 1989). In fact, the true reflection of the biological progression from juvenility to maturity is anatomical characteristics that make up wood (Heliñska-Raczkowska and Fabisiak 1999). Liu *et al.* (2020) reported that the transition between juvenile and mature wood was between 7 and 8 years based on patterns of radial variation in earlywood fiber length. A differentiation of juvenile wood from mature wood is to set a threshold for cell characteristics, which has advantages for addressing product performance. However, the disadvantage of applying single property threshold values for juvenile and mature wood is that they apply only to certain limited product performance attributes. Fos *et al*. (2023) reported that the transition from juvenile wood to mature wood begins in the 5th year of growth based on radial variation in anatomical characteristics of *Paulownia elongata x fortunei* hybrid *Cotevisa* 2 wood. Savero *et al*. (2024) reported that the clearest transition from juvenile to mature wood in six Korean oak species was observed in radial variation in earlywood vessel diameter and fiber length with maturation ages ranging from 19 to 44 years. In summary, the transition of wood properties from juvenile wood to mature wood is a tree growth pattern, but there are differences in transition patterns among different genera and species.

So far, there have been few studies on the anatomical characteristics of *S. alnifolia* wood, and research on radial variation and maturation age is also limited. Additional information on the age of maturity is crucial to ensuring wood quality and enhancing the economic value of high-value applications. Therefore, the goals of this study were to: (1) determine anatomical characteristics in the cross-section of *S. alnifolia* wood; (2) analyze the variation in anatomical characteristics from pith to bark; (3) determine the transitional age between juvenile and adult wood; and (4) compare anatomical characteristics between juvenile and mature wood.

EXPERIMENTAL

Materials

Three *S. alnifolia* trees were sampled from Longyuwan Forest Farm, located in the hinterland of Funiu Mountain, 165 km southwest of Luoyang City, China. The forest farm is situated between 111 ° 40 '-111 ° 50' E and 33 ° 39 '-33 ° 43' N, with an altitude of 1083

m. In 1997, it was designated as a national nature reserve. The height and diameter at breast height of the sample trees was measured using a Laser Range Finder (2200B, Onick Outdoor Optics Inc., USA) and a measuring tape, respectively. From each sample tree, an increment core was drilled at breast height (1.3 m) in the south direction from bark to pith. Tree age was checked by counting rings from the increment core. The characteristics of the sampled trees are shown in Table 1.

Table 1. Characteristics of the Sampled *Sorbus alnifolia* Trees in Relation to the Analysis of Radial Variation in Wood Anatomy

Tree Number	Tree Age (years)	Tree Diameter at Breast Height (cm)	Tree Height (m)	Height of the Lowest Branch (m)
1	37	24.0	18.6	13.5
2	38	25.4	21.7	15.6
3	36	23.6	17.2	15.6

Methods in Wood Anatomy

The collected increment cores were softened with ethylenediamine. Then 13-μm-thick transverse sections were cut using a Lycra slicer. The sections were stained with safranin and photographed using a digital imaging system (Mshot-MD50, Microshot Technology Limited, Guangzhou, China). An image computer analysis system (TDY, version 5.2, Beijing Tian Di Yu Technology Co., Ltd., Beijing, China) was used to measure ring-by-ring anatomical features. An average of 60 cells for each tissue type were measured per tree ring. The cell wall percentage was calculated from the cell wall area percentage of all cell types in the cross section microscopic images of each tree ring. The percentage of each cell type was calculated from all cell areas (including wall and lumen) percentage of the type in the cross section of each tree ring.

Data Analysis

Statistical analyses were performed using SPSS (Version 24.0, International Business Machines Corporation, Armonk, NY, USA), including mean, maximum, minimum, standard deviation (SD), and coefficient of variation (CV) of anatomical characteristics. Partial correlation analysis was used to examine the correlation between anatomical characteristics. Two-segmented linear regression models were used to evaluate the transition from juvenile to mature wood, in terms of ring number, for anatomical characteristics. Differences in anatomical characteristics between juvenile and mature wood were studied using variance analysis, and the significance of differences was tested using Duncan's Multiple Range Test.

RESULTS AND DISCUSSION

Cell Wall Percentage (CP)

The cross-section from pith to bark of *S. alnifolia* is shown in Fig. 1. The width of tree rings varies greatly. As reported in many species (Bao *et al.* 2001), early formed wood has a larger ring width than later formed wood. This is related to the period of wood formation, cell size, proportion, and arrangement of different components (Plomion *et al.* 2001). The CP is the smallest near the pith, then shows an increasing trend from the pith to the bark, especially in the first 10 years where the rate of increase is relatively high (Fig.

2). The CP shows an average value of close to 50% and a maximum of 63.7% (Table 2), which means that mature wood has a high density (Fortunel *et al.* 2014), and excellent physical-mechanical properties of wood (Akyildiz and Kol 2010).

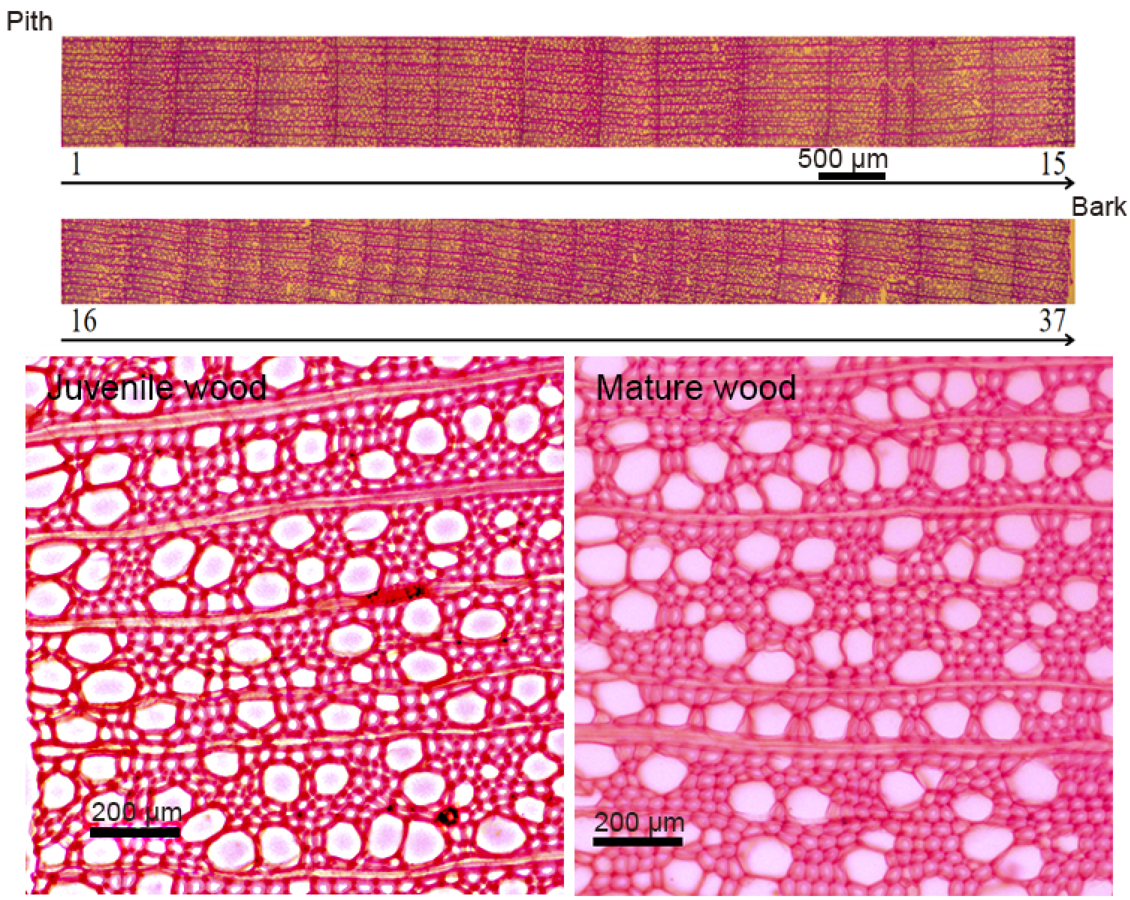

Fig. 1. Cross section microscopic images of the wood from pith to bark of *Sorbus alnifolia*

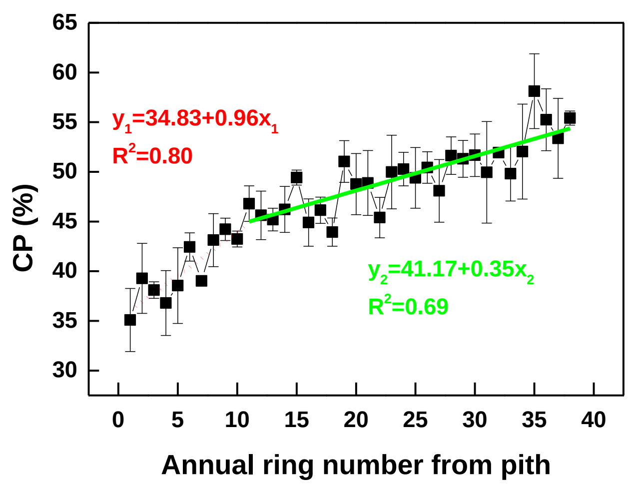

Fig. 2. Observed (mean) and two segment-fitted cell wall percentage (CP) trends *vs.* annual ring number in the wood of *Sorbus alnifolia*. Bars show standard error. The green, solid lines represent the first segment (juvenile wood). The red, dashed lines represent the first segment (mature wood).

The segmented regression showed that the transition age from juvenile to mature wood is 11 years for CP. The fitting effect was good for both juvenile and mature wood (Fig. 2). The CP difference between juvenile and mature wood was significant ($p = 0.00$), with the average value approaching 50% in mature wood and about 40% in juvenile wood (Table 3). A high CP is generally associated with a high fiber percentage (FP) and a low tissue proportion of thin-walled cells, such as a high vessel percentage (VP). There was a significant positive correlation between CP and FP (Table 4). CP was also significantly correlated with axial parenchyma tissue percentage (AP) and axial parenchyma cell double wall thickness (AT). The AP was less than 1% (Table 2). Such results imply that there will be little impact on wood processing and utilization (Zobel and van Buijtenen 1989).

Table 2. Descriptive Statistics in the Cross-section of the Wood Anatomical Characteristics of *Sorbus alnifolia*

Characteristics	Minimum	Maximum	Mean	SD	CV
CP (%)	31.67	63.66	47.49	6.28	0.60
FP (%)	34.41	61.48	48.28	5.66	0.54
VP (%)	20.66	46.43	33.11	5.12	0.49
RP (%)	11.69	24.90	17.78	2.86	0.27
AP (%)	0.11	4.26	0.98	0.85	0.08
FT (μm)	0.39	3.82	2.26	0.76	0.07
FD (μm)	1.72	9.53	5.50	1.85	0.18
VT (μm)	1.52	12.92	3.67	1.69	0.16
VD (μm)	21.17	129.16	47.80	18.52	0.77
VF (mm^{-2})	12.45	34.33	19.57	4.46	0.43
AT (μm)	0.55	2.53	1.38	0.37	0.04
AD (μm)	3.04	15.39	8.57	2.40	0.23

Note: AD = axial parenchyma cell lumen radial diameter; AP = axial parenchyma tissue percentage; AT = axial parenchyma cell double wall thickness; CP = cell wall percentage; CV = coefficient of variation; FD =fiber lumen radial diameter; FP = fiber percentage; FT = fiber wall thickness; RP = ray percentage; SD = standard deviation; VD = vessel lumen radial diameter; VF = vessel frequency; VP = vessel percentage; VT = vessel double wall thickness

Table 3. Differences in the Cross-section of the Juvenile and Mature Wood Anatomical Characteristics of *Sorbus alnifolia*

Characteristics	Juvenile Wood	Mature Wood	p -value
CP (%)	39.988 ± 3.08	49.68 ± 3.45	0.00
FP (%)	47.51 ± 2.81	48.69 ± 2.88	0.27
VP (%)	35.17 ± 1.56	33.14 ± 3.35	0.01
RP (%)	17.02 ± 1.87	17.91 ± 1.22	0.09
AP (%)	0.48 ± 0.16	1.22 ± 0.67	0.00
FT (μm)	1.95 ± 0.47	2.70 ± 0.79	0.00
FD (μm)	5.50 ± 1.64	5.59 ± 1.76	0.87
VT (μm)	3.77 ± 0.94	3.53 ± 0.83	0.52
VD (μm)	46.40 ± 6.87	48.05 ± 13.04	0.75
VF (mm^{-2})	20.69 ± 3.20	18.81 ± 3.88	0.18
AT (μm)	8.03 ± 1.66	8.70 ± 2.05	0.35
AD (μm)	1.51 ± 0.26	1.29 ± 0.36	0.04

Note: means ± standard deviation. AD = axial parenchyma cell lumen radial diameter; AP = axial parenchyma tissue percentage; AT = axial parenchyma cell double wall thickness; CP = cell wall percentage; FD =fiber lumen radial diameter; FP = fiber percentage; FT = fiber wall thickness; RP = ray percentage; SD = standard deviation; VD = vessel lumen radial diameter; VF = vessel frequency; VP = vessel percentage; VT = vessel double wall thickness

Table 4. Correlation Among the Wood Anatomical Characteristics of *Sorbus alnifolia*

	FP	VP	RP	AP	FT	FD	VT	VF	VD	AT	AD
CP	0.37*	-0.56**	0.28	0.68**	0.41*	-0.01	0.04	0.27	-0.24	-0.39*	0.18
FP		-0.84**	-0.35*	0.59**	0.43**	0.24	-0.02	0.07	-0.17	-0.45**	-0.01
VP			-0.15	-0.76**	-0.62**	-0.29	-0.01	-0.18	0.23	0.35*	-0.27
RP				0.08	0.21	0.05	0.06	0.11	0.03	0.13	0.34*
AP					0.48**	0.22	-0.02	0.41*	-0.31	-0.44**	0.29
FT						0.60**	0.06	0.12	-0.18	-0.01	0.33*
FD							0.16	0.23	-0.17	0.21	0.33
VT								0.66**	0.11	0.10	-0.18
VF									-0.07	-0.24	0.02
VD										-0.03	-0.45**
AT											0.46**

Note: AD = axial parenchyma cell lumen radial diameter; AP = axial parenchyma tissue percentage; AT = axial parenchyma cell double wall thickness; CP = cell wall percentage; FD =fiber lumen radial diameter; FP = fiber percentage; FT = fiber wall thickness; RP = ray percentage; SD = standard deviation; VD = vessel lumen radial diameter; VF = vessel frequency; VP = vessel percentage; VT = vessel double wall thickness. * = significant at the 5% level; ** = significant at the 1% level

Fiber

The average FP of *S. alnifolia* is close to 50% (Table 2), indicating the wood's potential to achieve high pulse yield (Stokke and Manwiller 1994). However, FP variability is high (CV = 0.54), with a maximum value of 61.5% and a minimum value of only 34.4%. Like CP, FP shows an overall upward trend from pith to bark, but it appears to have decreased slightly in the first 10 years and fluctuated greatly around 46% (Fig. 2A). Segmented regression shows that the transition age from juvenile to mature wood is 11 years for FP. The radial trend of FP is complex with low linear fitting in juvenile wood and good fitting in mature wood (R^2 = 0.44). Analysis of variance shows that there was no significant FP difference between juvenile wood and mature wood (p = 0.27, Table 3).

Both fiber wall thickness (FT) and fiber lumen radial diameter (FD) decrease slightly with increasing ring age, and then increase in some years. Segmented regression indicates that the transition age occurred at 24 and 18 years, respectively (Fig. 4 A, B). This means that as the wood matures, fiber size increases with age, but it fluctuates greatly. Similar results were also found in *Acacia mangium* (Xu *et al.* 2005). The average FT of *S. alnifolia* is 2.26 μm, which is close to the FT of the fruit tree species *Nephelium iappaceum*, but less than *Syzygium malaccense* and *Durio zibethinus* (Aiso *et al*. 2017). Mature wood has a significantly higher FT than juvenile wood (Table 3). Increased FT can improve wood's mechanical strength, such as compressive strength and flexural strength. At the same time, thicker walls may also affect wood density and texture. Wood with thicker cell walls and wider cell diameters typically exhibits higher quality (Barnett and Jeronimidis 2003).

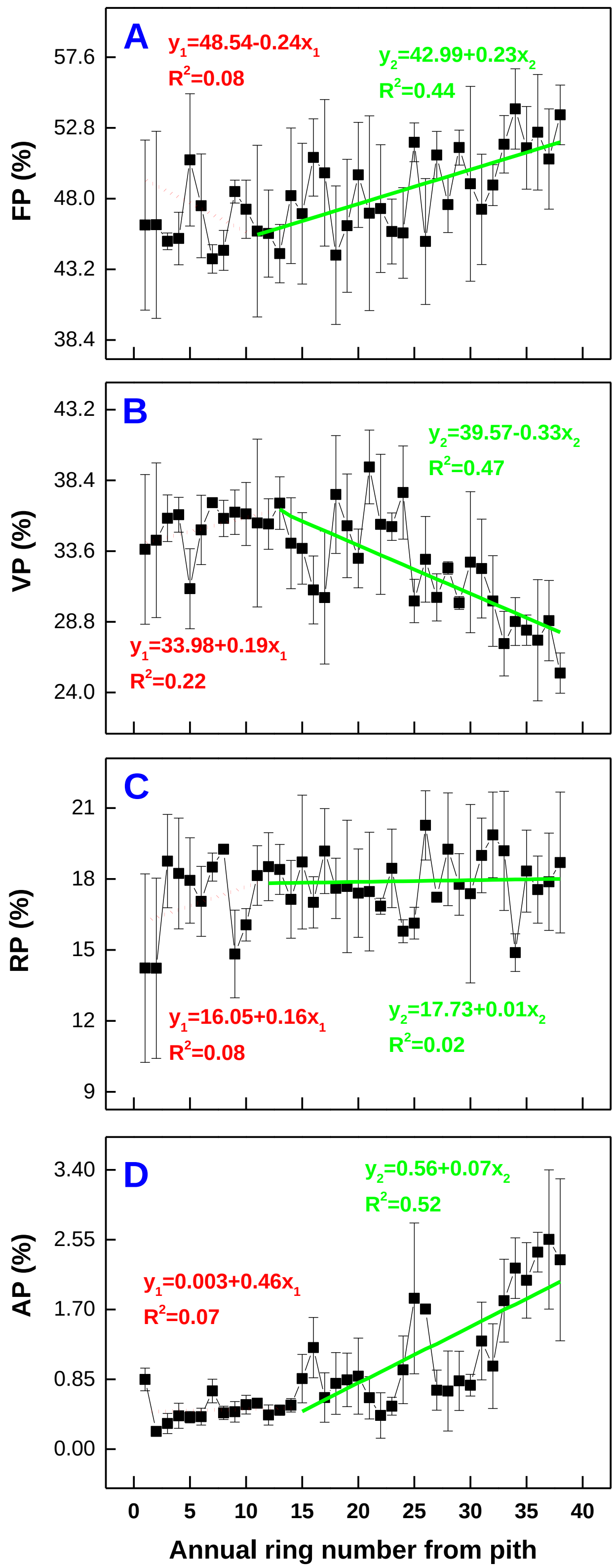

Fig. 3. Observed (mean) and two segment-fitted tissue percentage trends *vs.* annual ring number in the wood of *Sorbus alnifolia*. Bars show standard error. The green, solid lines represent the first segment (juvenile wood). The red, dashed lines represent the first segment (mature wood). AP represents axial parenchyma tissue percentage; FP represents fiber percentage; RP represents ray percentage; VP represents vessel percentage.

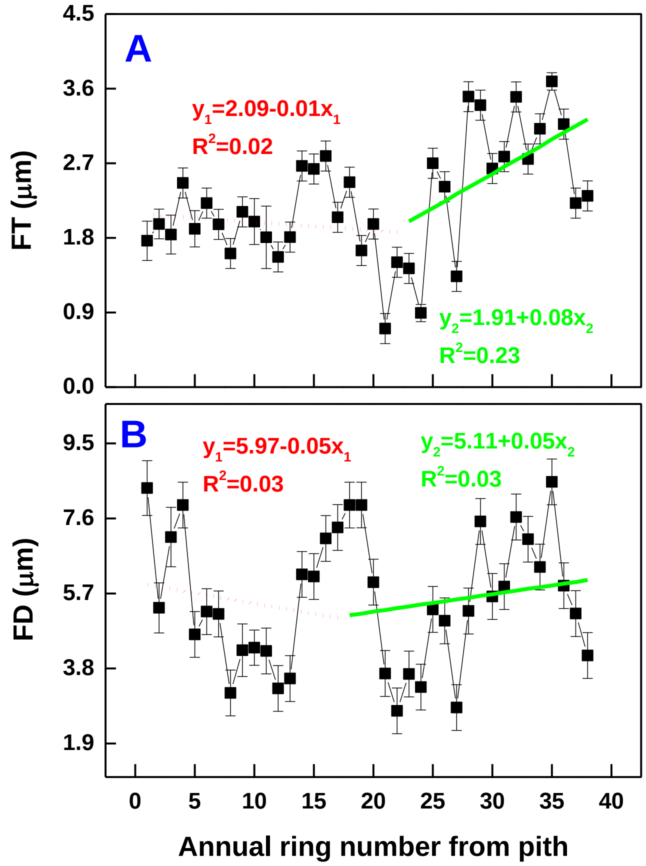

Fig. 4. Observed (mean) and two segment-fitted fiber wall thickness (FT) and fiber lumen radial diameter (FD) trends *vs.* annual ring number in the wood of *Sorbus alnifolia*. Bars show standard error. The green, solid lines represent the first segment (juvenile wood). The red, dashed lines represent the first segment (mature wood).

Vessel

S. alnifolia wood is porous, with VP ranging from 20.7% to 46.4% (Table 2). The pores are mostly single, and no pore clusters have been observed (Fig. 1). Occasionally pore chains are seen, which is similar to others (Zhang *et al.* 2006). Distribution, arrangement, size, and number of vessels directly affect wood uniformity and infiltration treatment (Emaminasab *et al.* 2017), and paper properties (Sari *et al.* 2012). According to Fig. 3B, VP first increased slightly and then decreased from pith to bark. Segmented regression showed that the transition age was 13 years, and VP of mature wood was significantly lower than that of juvenile wood ($p = 0.01$, Table 3). However, the linear fit was not good, indicating obvious fluctuations.

Vessels mainly serve as conduits for water transport during tree growth. Sperry (2003) believes that vessel double wall thickness (VT) is related to the strength of the vessel wall, and the wall can provide protection and support for vessels. However, under high tension conditions in the water column, VT resistance to container deformation appears unlikely (Carlquist 2001). From Fig. 5A, it can be observed that the VT variation shows a first decreasing and then slightly increasing trend from pith to bark. Segmented regression indicates that the transition age is 7 years. However, the VT difference between juvenile and mature wood is not significant (Table 2).

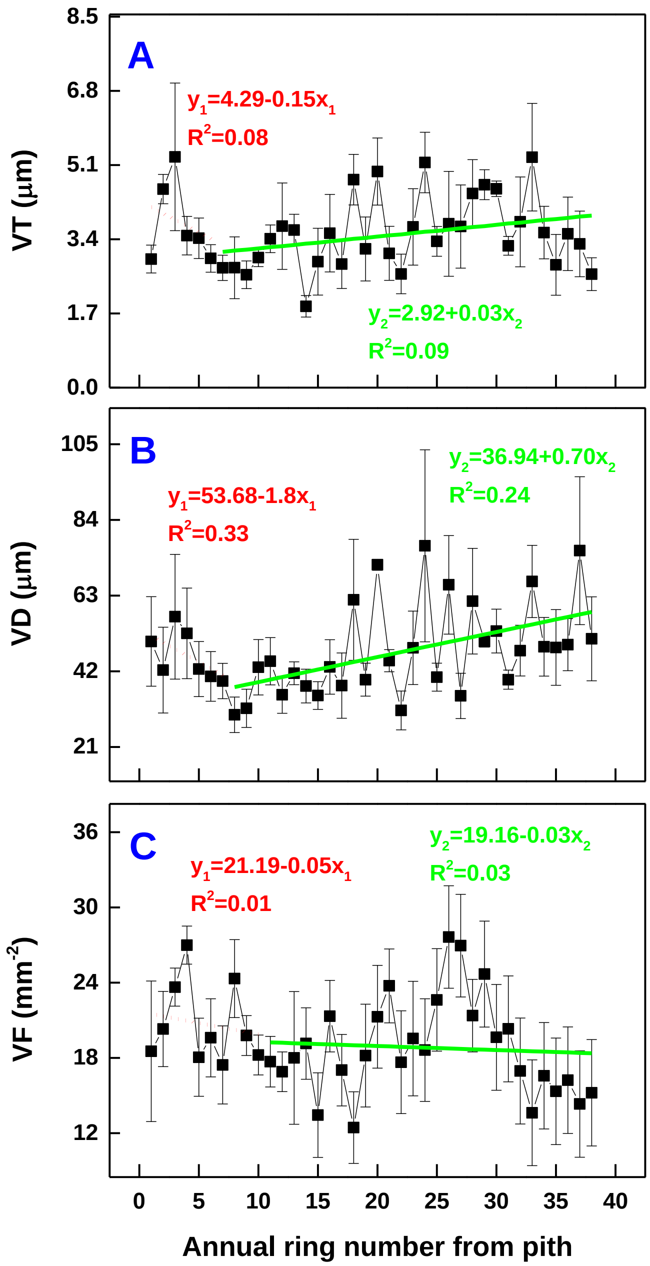

Fig. 5. Observed (mean) and two segment-fitted vessel size and vessel frequency (VF) trends *vs.* annual ring number in the wood of *Sorbus alnifolia*. Bars show standard error. The green, solid lines represent the first segment (juvenile wood). The red, dashed lines represent the first segment (mature wood). VD represents vessel lumen radial diameter. VT represents vessel double wall thickness.

The vessel lumen radial diameter (VD) in *S. alnifolia* wood is less than 100 μm (Table 2), which belongs to small vessels (IAWA Committee 1989). The size is less than in the wood of three fruit tree species (*S. malaccense*, *N. iappaceum*, and *D. zibethinus*, Aiso *et al*. 2017), but higher than in the wood of the other fruit tree species (Passialis and Grigoriou 1999). Variations in the anatomical characteristics listed in Table 2 indicate that VD has the highest variability, reaching 0.77. The variation pattern of VD with growth ring age is basically the same as that of VT, and the transition age between juvenile and mature wood is 9 years, which is close to the transition age of VT, but the fluctuation of change is smaller (Fig. 5B). Radial variation in VD can lead to uneven texture and color on the wood surface, affecting the appearance quality of wood. Variations in VD may affect wood processing performance. For example, wood with larger VD may be more prone to burrs and tearing during sawing and planning processes (Barnett and Jeronimidis 2003).

Similar to VD, vessel frequency (VF) is a sensitive measure in ecological study. One would expect vessel density to be roughly inverse to VD (Heliñska-Raczkowska and Fabisiak 1999; Carlquist 2001). Such a relationship was confirmed in *S. alnifolia* wood, although the correlation was not significant. VF decreases from pith to bark (Fig. 5C). Segmented regression shows that the transition age between mature and juvenile wood occurs in 11 years, and there is a significant difference in VF between juvenile and mature wood (Table 3). However, the VF fitting was not good with large fluctuations. Average VF in *S. alnifolia* wood is less than 20 mm^{-2} (Table 2) and less than in Rosaceae wood (Olvera *et al*. 2008). Usually, lower VF can lead to higher mechanical strength, as the vessel itself is more fragile than the surrounding wood tissue (Santini *et al.* 2013).

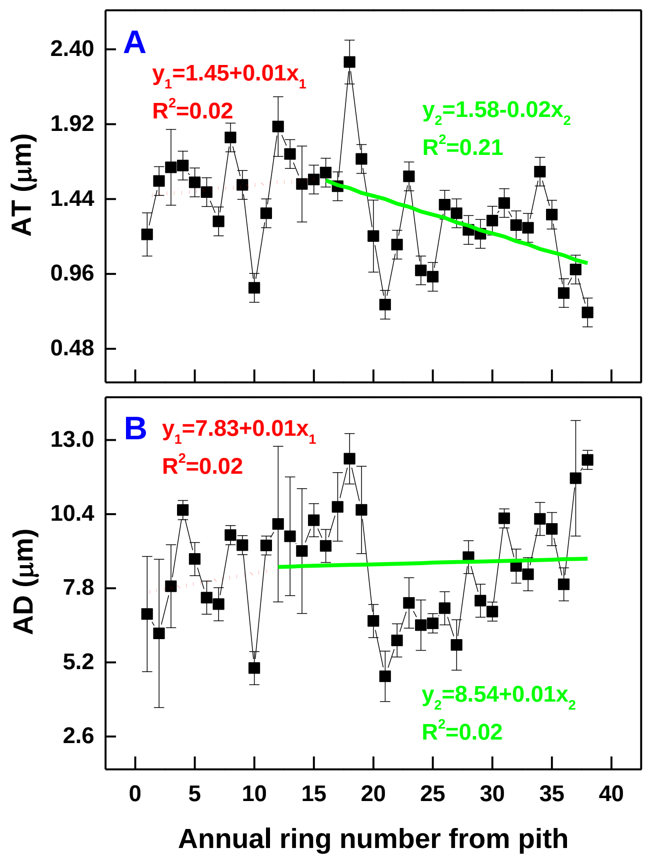

Fig. 6. Observed (mean) and two segment-fitted axial parenchyma cell size trends *vs.* annual ring number in the wood of *Sorbus alnifolia*. Bars show standard error. The green, solid lines represent the first segment (juvenile wood). The red, dashed lines represent the first segment (mature wood). AD represent axial parenchyma cell lumen radial diameter; AT represent axial parenchyma cell double wall thickness.

Axial Parenchyma

From pith to bark, wood initially had a higher AP, which remained relatively unchanged for many years and showed an increasing trend around 15 years (Fig. 3D).

Segmented regression showed that the transition age between mature and juvenile wood was 16 years. The linear fitting degree of the juvenile wood AP is not high, which may be due to the abnormally high AP near the pith ring of the wood. However, the fitting effect of mature wood is better ($R^2 = 0.52$).

Both AT and axial parenchyma cell lumen radial diameter (AD) initially showed a slight increase from the pith outside, then suddenly increased and reached their maximum value in 18 years (Fig. 6 A, B). However, segmented regression found that the transition age of AT and AD between mature and juvenile wood was not 18 years, but 16 and 12 years, respectively. Moreover, the linear fit degree of AT and AD is not high. The sudden increase in 18 years may have been a response to sudden changes in environmental factors (Morris *et al.* 2016), such as increasing hydraulic conductivity (Aritsara *et al.* 2020).

Ray

Wood ray is the only horizontally arranged tissue that is mainly used for horizontal transportation and nutrient storage in standing trees. The size and distribution of wood rays not only affect the appearance of wood, such as texture and luster, but also its behavior during drying and processing. For example, redundant rays can lead to more uniform drying and reduce the likelihood of cracking (Xue *et al.* 2018). The ray percentage (RP) is relatively mild, with no particularly obvious increase or decrease trend from pith to bark, but fluctuates greatly (Fig. 3C), similar to *Catalpa bungei* (Liu *et al.* 2020).

CONCLUSIONS

1. *Sorbus alnifolia* wood is porous, and redundant vessel elements make it relatively easy to dry, increasing its permeability, but reducing mechanical properties and causing problems with linting sheets. The cell wall percentage (CP) and fiber percentage (FP) are relatively high, with axial parenchyma tissue percentage (AP) less than 1%, indicating that wood has good physical and mechanical properties and a higher fiber yield. Fibre and vessel sizes are relatively small, and vessel frequency (VF) is low. *S. alnifolia* wood fibers can be mixed with large fibers to produce specific paper products.
2. Anatomical characteristics of *S. alnifolia* wood show different patterns of radial variation. The transition age of vessel between juvenile wood and mature wood is 7 to 11 years. Compared to vessels, the transition age of axial parenchyma is delayed 5 years, and the transition age of fibers is delayed 10 to 15 years. Radial changes in CP, FP, VP, and VD show a significant transition from juvenile wood to mature wood, with CP being the most reliable indicator for estimating the transition from juvenile wood to mature wood. Mature wood exhibits higher CP, thicker fiber walls, and lower VP than juvenile wood.

This study will provide valuable insights into afforestation treatments and optimal harvest times for the production of higher quality wood from *S. alnifolia*. Further research is needed on natural durability, as well as physical, and mechanical properties to enhance understanding of the quality of water chestnut wood.

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