Effect of Thinning Intensity on Fiber Morphology and Crystallinity of Poplar

Bai-Xiang Cui,[a] Jun-Long Liu,[b] Nan Zhou,[c] Wen-Ping Wu,[a] Xue-Hai Tang,[a] Chang-Jun Ding,[d] Shuangyan Zhang,[a,]* and Chuan-Gui Wang [a,]*

Thinning silviculture is a forestry measure that can improve forest ecosystems and stand structure. Thinning can impact the properties and quality of poplar wood. This study investigated the effects of three different thinning intensities on the fiber morphology and crystallinity of poplar wood, providing a theoretical basis for the cultivation and rational processing of poplar plantations. The results indicated significant differences in the proportion of wet heartwood area among different thinning intensities. With increased thinning intensity, the wet heartwood area proportion rose, while it decreased with wood height under the same thinning intensity. Fiber length increased with thinning intensity, reaching a 16% increase at 50% thinning, as well as with sampling height. Fiber width grew with thinning intensity, initially widening, and then narrowing with height. Cell wall thickness first increased and then decreased with thinning intensity, peaking at 50% thinning. The fiber length-width ratio increased with thinning intensity and initially increased then decreased with height. The fiber-diameter-cavity ratio also increased with thinning intensity and height. Crystallinity showed a trend of first increasing and then decreasing with tree height, peaking at breast height, and it was higher in normal wood than in wet heartwood under the same thinning intensity.

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Contact information: a: School of Materials and Chemistry, Anhui Agricultural University, Hefei 230036, China; b: Anhui Academy of Forestry, Hefei, 230031, China; c: KUIP MAKE, Fuyang, 236057, China; d: Research Institute of Forestry Chinese Academy of Forestry, Beijing, 100091, China;
** Corresponding author: zsyhj_2006@163.com, nj230036@163.com*

INTRODUCTION

Poplar is a widely planted fast-growing afforestation tree in China, with a wide distribution range and large stock volume. In China, the area of poplar forests exceeds 10.1 million hectares, with a total volume of 549 million cubic meters, ranking first in the world. It has advantages, such as fast growth and easy survival; therefore it is chosen as the preferred species for fast-growing high-yield forests and industrial timber forests in China. However, poplar also has shortcomings in terms of wood properties. For example, it has lower density and weaker mechanical performance. These could be attributed to its rapid growth rate and the environmental conditions in which it grows, resulting in significant variability and unevenness in its wood. Ma's research (2011) shows that the average annual increment of breast diameter of *Populus* × *euramericana* cv. 'Neva' is 2.5 to 6.0 centimeters, and the annual increment of tree height is 2.0 to 5.0 meters. This can make poplar wood less stable for certain specific uses compared to other tree species. Wet heartwood is also a common issue in poplar trees. Wet heartwood, a wood defect caused by external environmental and genetic factors, is associated with a higher moisture content, darker color, higher extractives content, and alkaline pH compared to both sapwood and normal heartwood. Zhang (2006) observed through scanning electron microscopy that there are bacteria on the pit membrane of wet heartwood. Not only are some of the ray parenchyma cells degraded, but the chain-like structure at the edge of the pit membrane is also degraded. This leads to changes in the physical and chemical properties of the wood, affecting the drying, processing, and plywood quality, and increasing the difficulty of wood processing while reducing its value. Li (2018) analyzed the chemical compositions of heartwood and sapwood of two poplar species, *Populus trinervis* and *Populus kangdingensis*. The results showed that there were obvious differences in the main chemical compositions between heartwood and sapwood of the two poplar species. Improving wet heartwood can enhance the wood's lifespan and quality, reduce the processing difficulties and costs associated with wet heartwood, and increase the wood's economic value and market competitiveness.

Thinning management is an effective silvicultural measure that involves periodically removing some trees to improve stand forest quality and enhance the growth, development, and quality of poplar wood. It refers to the number and proportion of trees removed, as well as the degree of impact on the trees. Moderate thinning can improve light and air circulation within the forest, reduce competition between trees, and enhance tree growth and wood quality (Pitre *et al*. 2007). The research by Cai (2005) indicates that selective thinning improves the mechanical properties of young wetland pine. With increasing thinning intensity, the volume shrinkage rate decreases 14% to 39%. The study by Minghui (2001) suggests that in thinned forests, the length and diameter of tracheids, fiber angle, growth rate, and growth ring width are greater than in unthinned forests. He Ling points out that thinning significantly affects the cellulose content, with an average decrease of 1% to 5% with increasing thinning intensity. Xu's research (2024) took 18-year-old *Populus trinervis* as the test material, set different intensities of thinning treatments, and measured the growth traits and wood traits of the test forest. The results showed that thinning can promote the growth of forest stands and improve the wood properties of forests. It is evident that the assessment of wood quality is closely related to management objectives, with the primary determinant being the intended use of the wood. Therefore, assessing wood quality according to its purpose is of great practical significance for targeted forest cultivation.

However, research on the influence of thinning intensity on the fiber morphology and crystallinity of poplar trees is limited. This article takes poplar as the experimental material, and studies the impact of thinning intensity on the proportion of wet heartwood, fiber morphology, and crystallinity of the poplar tree. The aim is to provide a theoretical basis for the cultivation and rational processing and utilization of *Populus* plantations.

EXPERIMENTAL

Materials

This study focuses on poplar (American black poplar) trees planted at a density of 3 m × 9 m and examines three different treatments applied to them. The thinning time was six years. Three different thinning intensities were designed: 50% thinning (cut down one tree for every other tree), 30% thinning (cut down one tree for every three trees), and 20% thinning (cut small trees, leave large ones). The thinning intensity of sample trees is shown in Fig. 1. Poplar trees materials were sourced from Xinguanzhou Forest Farm, Daguan District, Anqing City, Anhui Province (116°54’36" E, 30°26’24" N). For each treatment method three trees were selected for a total of twelve trees following GB/T 2677.20 (1995) standard. In the direction perpendicular to the ground, the procedure was to measure the maximum widths of the tree crown in the east-west and north-south directions, and record the crown amplitudes in the east-west and north-south directions. The collecting information is shown in Table 1.

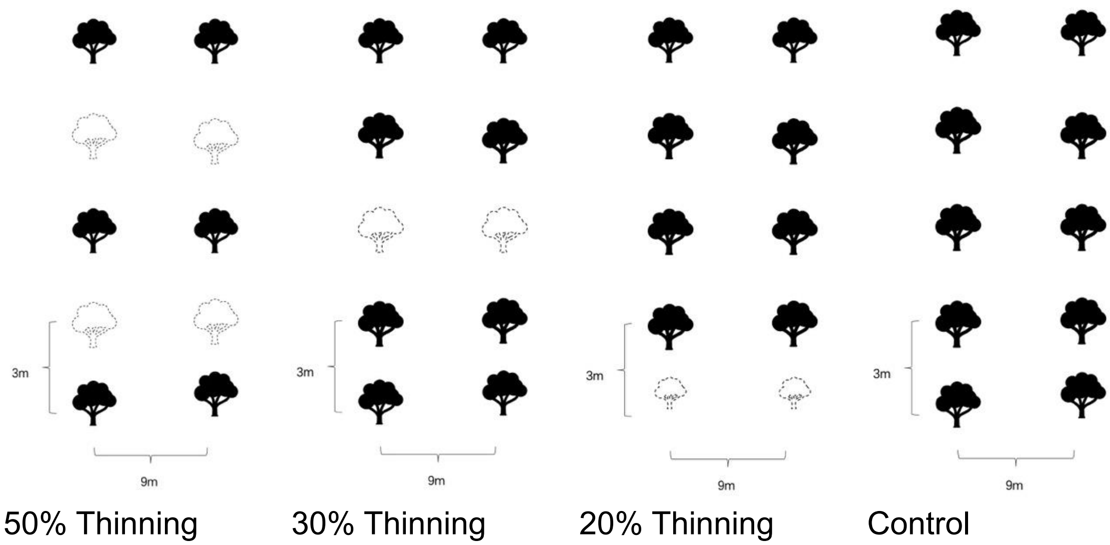


Fig. 1. Schematic diagram of thinning treatment

Table 1. Average Tree Height, Branch Number, and Diameter in Experimental Groups

Thinning Intensity (%)	Tree Height (m)/ average value	Height Under the First Branch (m)/ average value	Number of Branches (pcs) /average value	Diameter at Breast Height (cm) /average value
50	23.8	5.2	19	36.1
30	22.6	3.6	14	34.8
20	22.3	4.6	12	30.8
Control	22.3	5.0	16	29.1

Methods

Sample

From the base, 10-cm-thick disks were cut out at 0 m, 1.3 m, 3.3 m, 5.3 m, and 7.3 m of the sample. Each sample yielded five disks in total, and the disc interception part is shown in Fig. 2. The cut disks were polished with a sanding machine (H4600) and placed into the C3530 scanner for scanning.

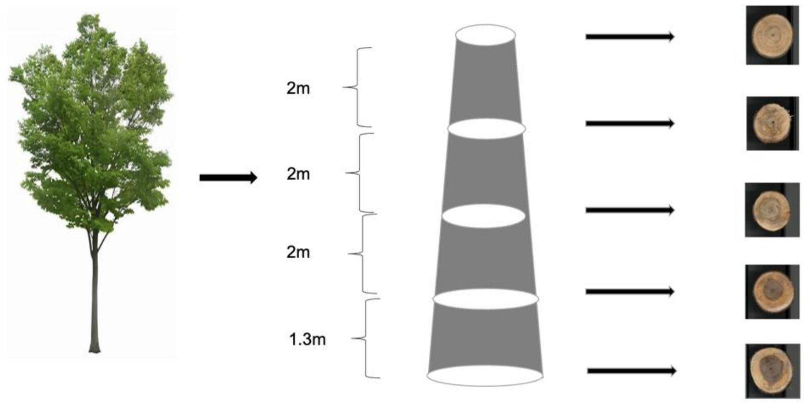


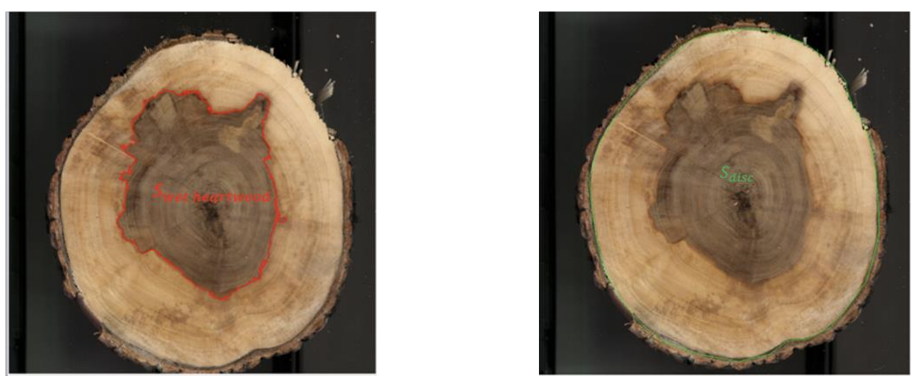
Fig. 2. Wood disc sampling

Percentage of wet heartwood area

The scanned images were analyzed using the Image-Pro Plus (V6.0) software to outline the wet heartwood and measure the wet heartwood area and disc area, as shown in Fig. 3. The proportion of wet heartwood was calculated according to Eq. 1,

$$C = \frac{S_{wet\ heartwood}}{S_{disc}} \times 100\% \tag{1}$$

where C is proportion of wet heartwood (%), $S_{wet\ heartwood}$ is wet heartwood area (mm^2), and S_{disc} is disc area (mm^2).



(a) Wet heartwood area **(b)** Disc area

Fig. 3. Wood disc sampling

Fiber Morphometry

Sample

From the prepared wood discs, a 5-cm center strip was cut out. The central strip was split into matchstick-sized pieces and the wet heartwood was separated from the normal wood for further analysis.

Determination of fiber morphology

The preparation of fibers from the wet heartwood and normal wood of poplar were done using the Franklin method (1945). Equal volumes of glacial acetic acid and 30% H_2O_2 solution were mixed thoroughly. The mixture was added into a test tube until the small stick was completely immersed. The test tube was sealed and placed into a large beaker with a certain amount of distilled water. The beaker was covered completely with plastic wrap and heated in a water bath at 60 to 70 °C until the small stick in the test tube turned completely white and the solution became colorless and transparent. Heating was stopped when many loose fibers were visible to the naked eye upon slight shaking of the test tube. After the test tube cooled down, the fibers in the test tube were washed repeatedly with distilled water until there was no obvious pungent odor and no or few tiny particles were visible to the naked eye.

Enough distilled water was added into the test tubes so that the fibers could be evenly distributed. Using dissecting needles, the fibers were transferred onto glass slides. After adding 1 to 2 drops of distilled water, the slide was covered with a coverslip. An upright fluorescence microscope (Model Eclipse Ni-U) was used and measured at 2x, 20x, and 40x magnifications. Fiber morphology tests on at least 100 fibers per group were conducted at optical and digital zooms. The fiber length, fiber width, lumen diameter, and wall thickness were determined. The experimental procedure is shown in Fig. 4.

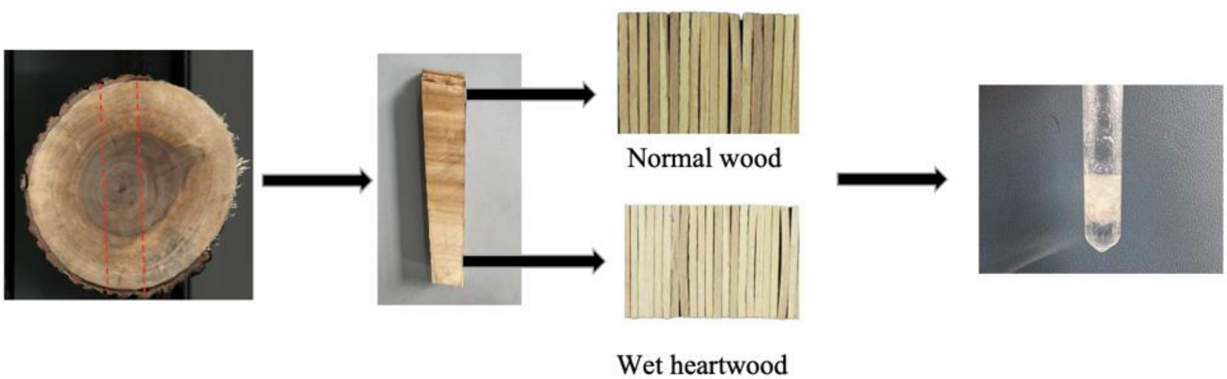


Fig. 4. Measurement of fiber morphology

Crystallinity

X-ray diffraction can provide information about the crystalline and amorphous regions in a material by analyzing the diffraction patterns. The intensity of the diffraction peaks corresponding to the crystalline regions can be used to calculate the crystallinity.

From the prepared center strip cut, wet heartwood and normal wood samples were prepared, crushed into powder less than 60-mesh size, and an infrared spectroscopy and X-ray diffraction (XRD) tests (XD6,) were performed. After preparing the samples using a high-throughput tissue grinder, the powdered samples were placed into the sample holder groove and leveled. Testing was conducted using an X-ray diffractometer with an X-ray wavelength of 0.154 nm, a tube voltage of 36 kV, a tube current of 20 mA, a scanning range of 10° ≤ 2θ ≤ 40°, a scanning rate of 5°/min, stepwise scanning with a step size of 0.02°. The formula used for calculating crystallinity was as follows,

$$X_c = \frac{I_{002} - I_{am}}{I_{002}} \times 100\% \tag{2}$$

where X_c represents the crystallinity of the material (%); I_{am} is the intensity of the diffraction peak at $2\theta = 17°$ in the amorphous region; and I_{002} is the intensity of the diffraction peak at $2\theta = 22.5°$ in the crystalline region.

RESULTS AND DISCUSSION

Wet Heartwood Area Ratio of Poplar

The proportions of wet heartwood area in poplar wood at different levels of thinning intensities are shown in Fig. 5. At the same height, the proportion of wet heartwood area increased with the increase in thinning intensity. At 0 m, the proportion with a 50% thinning intensity was 46.5%, compared to 34.6% in untreated poplar trees, an increase of about 34.3%. This is related to crown width. According to Liu's research (2010), thinning measures enable trees to better access sunlight, water, and nutrients, promoting crown width development, which leads to rapid tree growth and more wet heartwood; thus, increased thinning intensity results in larger crown widths, faster growth, greater biomass accumulation, and a larger proportion of wet heartwood area. Table 3 indicates that crown width under different thinning intensities increases with the intensity of thinning. As the thinning intensity increases, the crown width of poplar trees also increases, consistent with the trend of thinning intensity and the proportion of wet heartwood area. Liu's research results (2010) also show that with the increase of thinning intensity, the crown width of poplar also increases.

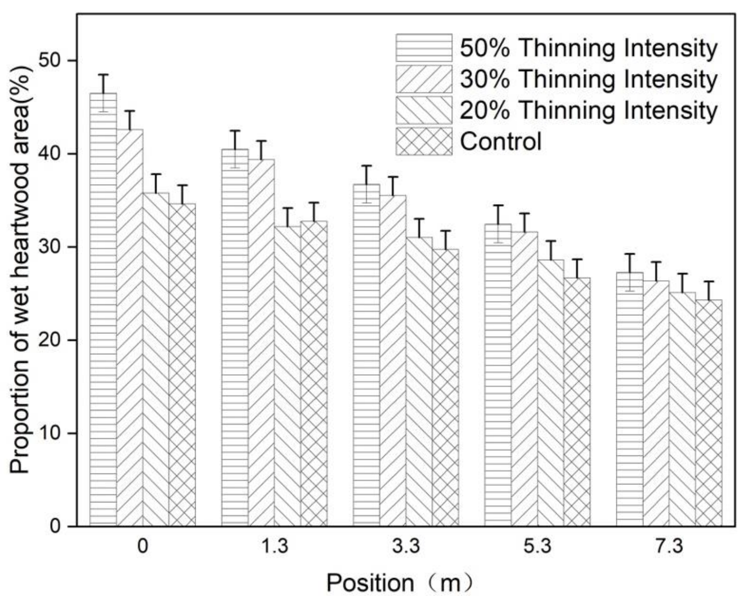


Fig. 5. Proportion of wet heartwood at different tree positions and within different thinning intensity

At the same thinning intensity, the proportion of wet heartwood area decreased with increasing height, as shown in Table 4. At a height of 0 m under a 50% thinning intensity, the proportion of wet heartwood area was 46.5%, compared to 27.2% at 7.3 m, representing a decrease of 41.4%. The reason for the decrease in the proportion of wet heartwood areas with increasing tree height may be attributed to the distribution of wood tissue. The increase in tree height leads to a greater proportion of normal wood tissue in the outer layer, causing a decrease in the proportion of wet heartwood, while inner wet heartwood gradually dries and transforms into normal wood tissue as trees grow, further reducing the wet heartwood area proportion. As indicated in Table 3, the proportion of untreated poplar wet heartwood area decreased 29.6% from 0 m to 7.3 m. However, with an increase in thinning intensity, the reduction in the proportion of poplar wet heartwood area increased. Among these, the reduction was greatest at a thinning intensity of 50%, reaching 41.4%. This indicates that thinning intensity treatments help reduce the proportion of wet heartwood area in poplar at various heights.

Table 3. Effect of Thinning Intensity on Wet Heartwood Area and Crown Width.

Thinning Intensity (%)	50	30	20	Control
Wet heartwood area and decrease in the amplitude (%)	41.4	38.1	29.8	29.6
Crown Width (m)	7.3	6.9	6.7	6.4

Table 4. Proportion of Wet Heartwood at Different Thinning Intensities

Position	50% Thinning Intensity	30% Thinning Intensity	20% Thinning Intensity	Control
0 m	46.5%	42.6%	35.8%	34.6%
1.3 m	40.5%	39.4%	32.2%	32.8%
3.3 m	36.7%	35.5%	31.0%	29.7%
5.3 m	32.4%	31.6%	28.6%	26.7%
7.3 m	27.2%	26.4%	25.1%	24.3%

Impact of Thinning Intensity on the Fiber Morphology Characteristics of Poplar Wood

The fiber morphology of wood is closely associated with the physical, mechanical, and processing properties of wood. Trevisan (2013) conducted experiments on 18-year-old *Eucalyptus grandis* and found that thinning affects the length of wood fibers. With the increase in thinning intensity, there is no obvious change rule for fiber length. Zhang (2010) measured and analyzed the fiber morphological characteristics of two eucalyptus clones under different stand densities and found that stand density significantly affects fiber width and length-width ratio. Guo's research (2001) on the wood fiber morphology of *Fraxinus mandshurica* shows that the fiber length increases with the increase in thinning intensity. Thinning reduces the fiber diameter and length of *Populus ussuriensis* and *Pinus elliottii*. The characteristics of fiber morphology are also notably correlated with the quality of pulp.

Fiber length is the most crucial parameter in fiber morphology. It has a substantial impact on the flexural mechanical properties of wood. It is also an important factor affecting the performance of fiberboard and paper quality. The fiber length is positively correlated with the degree of cross-linking. The longer the fiber length, the stronger will be the fiber cross-linking between fiberboard and paper manufacturing, the higher the tensile strength of paper, and the higher the static bending strength of fiberboard.

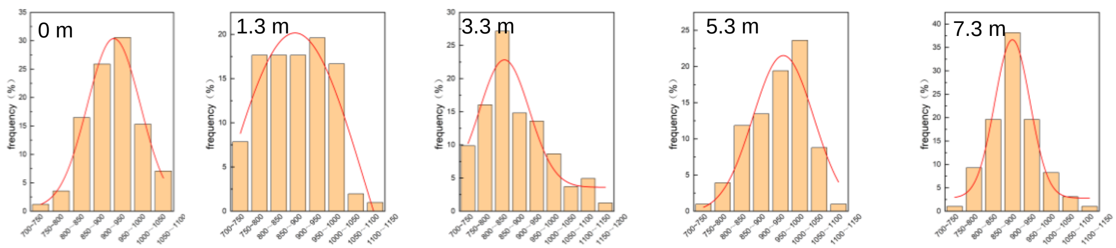
Table 5 shows the fiber morphology at different thinning intensities. The table indicates that at the same thinning intensity and height, the fiber length, width, and wall thickness of normal wood are all greater than those of wet heartwood. The reason for this phenomenon may be that during the growth process of trees, normal wood is formed on the outer part of the trunk, undergoing a relatively longer period of growth and wood formation. This means that the wood fibers of normal wood have more time and space to develop and mature, thus typically having longer fiber length, greater fiber width, and thicker cell walls.

Table 5. Fiber Morphology at Different Thinning Intensities

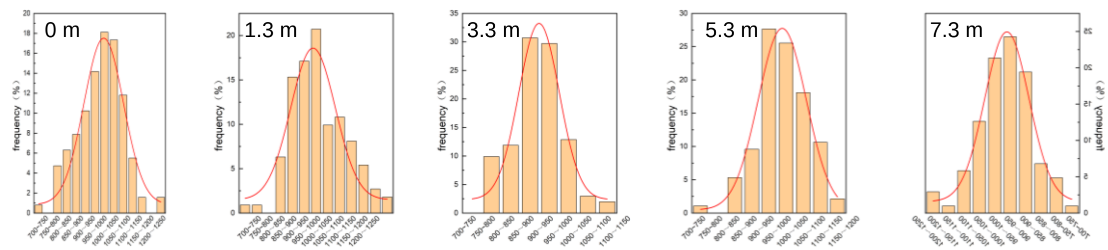
Thinning Intensity (%)	Position (m)		Length (μm)		Wide (μm)	Biwall Thickness (μm)	Aspect Ratio	Cavity Diameter Ratio
			Range	Average				
50	0	WH	504.25 ~ 1427.77	969.90	19.68	9.68	49.28	8.43
		NW	940.87 ~ 1297.83	1278.65	20.43	10.43	62.59	7.58
	1.3	WH	601.44~1198.33	981.68	19.58	9.58	50.14	5.22
		NW	590.43 ~ 2150.44	1299.58	20.22	10.22	64.27	6.80
	3.3	WH	707.43 ~ 1184.43	847.23	19.8	9.80	42.79	4.07
		NW	601.21~1327.28	911.64	20.07	10.07	45.42	9.92
	5.3	WH	542.46 ~ 1378.93	841.66	18.92	8.92	44.49	8.39
		NW	851.11 ~ 1890.38	1012.72	19.39	9.39	52.23	7.75
	7.3	WH	650.47 ~ 1366.16	803.45	17.75	7.75	45.26	8.15
		NW	771.11~1578.29	907.44	18.15	8.15	50.00	4.85
30	0	WH	501.99~1162.18	935.41	17.85	7.85	52.40	5.1
		NW	615.21 ~ 1593.81	1118.32	18.1	8.10	61.79	5.96
	1.3	WH	509.11 ~ 1575.45	976.54	19.96	9.96	48.92	6.23
		NW	738.83~1893.78	1281.12	20.23	10.23	63.33	5.75
	3.3	WH	485.89 ~ 1162.91	835.44	19.75	9.75	42.30	6.51
		NW	678.11~1098.28	871.28	20.51	10.51	42.48	2.82
	5.3	WH	615.22 ~ 1593.88	888.46	18.82	8.82	47.21	4.36
		NW	822.18~1782.11	981.23	19.36	9.36	50.68	2.91
	7.3	WH	535.91 ~ 1072.67	865.90	17.91	7.91	48.35	3.16
		NW	722.18~1872.33	918.23	18.16	8.16	50.56	4.76
20	0	WH	501.99~1162.18	797.59	17.76	7.76	44.91	5.29
		NW	608.91 ~ 1413.81	1143.46	18.29	8.29	62.52	3.61
	1.3	WH	534.19 ~ 1566.45	880.12	16.61	6.61	52.99	5.05
		NW	738.83~1893.78	1214.68	18.05	8.05	67.30	2.98
	3.3	WH	485.89 ~ 1162.91	857.89	16.98	6.98	50.52	4.21
		NW	778.19~1021.28	902.35	17.21	7.21	52.43	2.54
	5.3	WH	601.23 ~ 1473.81	802.68	17.54	7.54	45.76	3.44
		NW	821.00~1782.81	1096.79	18.44	8.44	59.48	1.76
	7.3	WH	535.91 ~ 1072.67	709.23	16.76	6.76	42.32	2.38
		NW	722.18~1872.33	918.23	17.38	7.38	52.83	4.27
Control	0	WH	501.99~1162.18	735.42	16.28	6.28	45.17	4.9
		NW	615.21 ~ 1593.81	1032.44	18.9	8.90	54.63	5.57
	1.3	WH	509.11 ~ 1575.45	976.54	15.57	5.57	62.72	5.73
		NW	738.83~1893.78	1181.12	17.73	7.73	66.62	3.15
	3.3	WH	485.89 ~ 1162.91	835.44	16.15	6.15	51.73	3.33
		NW	678.19~1098.28	871.28	18.33	8.33	47.53	1.83
	5.3	WH	615.22 ~ 1593.88	888.46	15.83	5.83	56.13	2.7
		NW	822.18~1782.11	981.23	17.7	7.70	55.44	3.94
	7.3	WH	535.91 ~ 1072.67	865.90	16.94	6.94	51.12	2.42
		NW	722.18~1872.33	918.23	18.42	8.42	49.85	8.68

*Note: WH stands for wet heartwood, and NW stands for normal wood

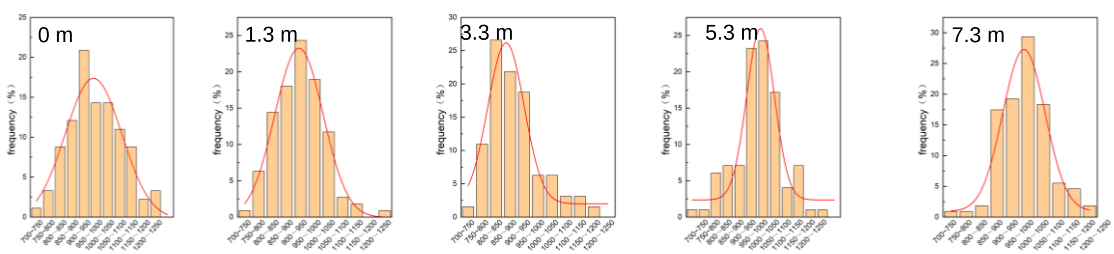
At the same thinning intensity, fiber length, width, and wall thickness show a trend of initially increasing and then decreasing, reaching their maximum values at 1.3 m. The reason for this phenomenon may be that trees receive more nutrients and water supply and experience fewer growth restrictions during their growth process. These environmental conditions enable the wood to develop more fully at breast height, providing wood fibers with more time and space to grow and form, thus typically resulting in longer fiber length, greater fiber width, and thicker cell walls. At the same location and height, fiber length shows an increasing trend with the increase of thinning intensity, reaching its maximum at a 50% thinning intensity. For instance, at 0 m under a 50% thinning intensity, the fiber length of wet heartwood was 970 μm, compared to 735 μm for untreated wet heartwood at the same location, representing an increase of 31.9%. The fiber length distribution frequency plot in Fig. 6 also illustrates that the fiber length increased after thinning treatment compared to untreated fibers.



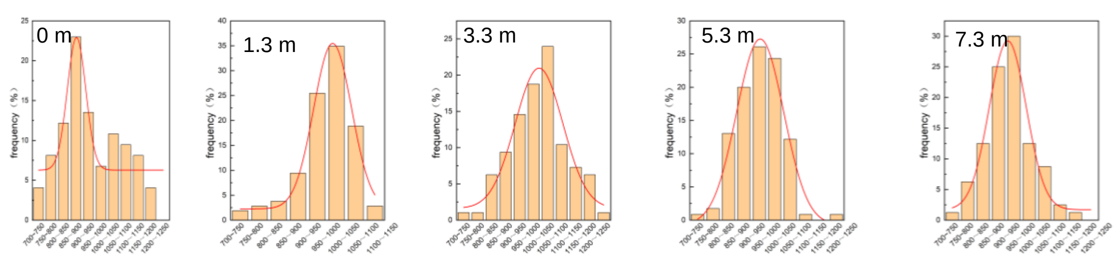
(a-1) Length frequency distribution of 50% thinning intensity in wet heartwood fibers



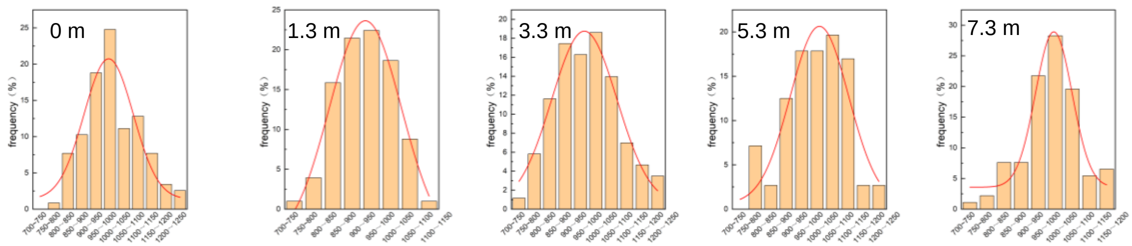
(a-2) Length frequency distribution of 50% thinning intensity in normal wood fibers



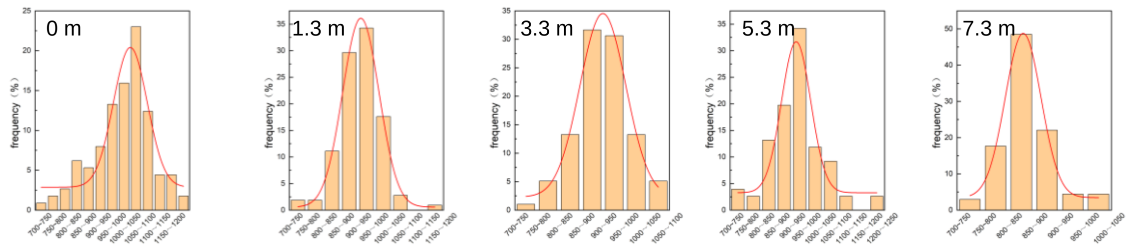
(b-1) Length frequency distribution of 30% thinning intensity in wet heartwood fibers



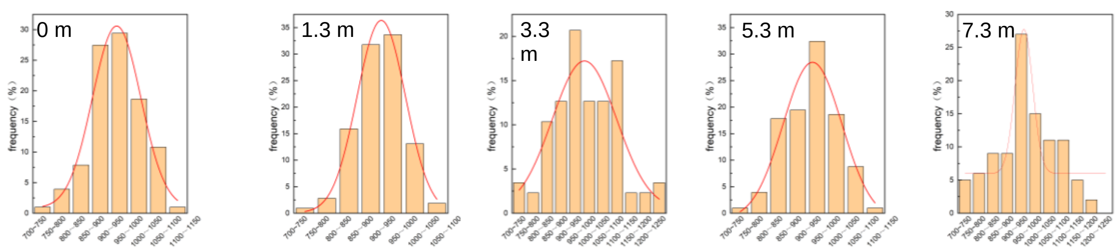
(b-2) Length frequency distribution of 30% thinning intensity in normal wood fibers



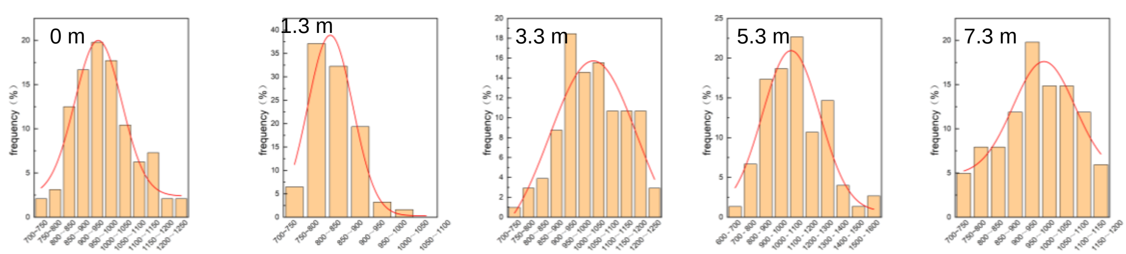
(c-1) Length frequency distribution of 20% thinning intensity in wet heartwood fibers



(c-2) Length frequency distribution of 20% thinning intensity in normal wood fibers



(d-1) Length frequency distribution of control in wet heartwood fibers



(d-2) Length frequency distribution of control in normal wood fibers

Fig. 6. Fiber length distribution frequency

Fiber width is the second characteristic of fiber morphology. The variation pattern of fiber width is similar to that of fiber length after thinning is higher than that before treatment and fiber width is widest at a thinning intensity of 50%. The thickness of wood cell walls reflects the amount of substance in the cells. Thicker cell walls indicate more substance in the cells, resulting in higher density and strength of wood. The cell walls of thinned wood are thicker than those of untreated wood, with the thickest cell walls observed at a thinning intensity of 50%. Fiber cell wall thickness decreases with the increase in height. The cell lumen-to-wall ratio increases with the increase in tree height. The fiber aspect ratio follows a pattern similar to fiber length. As thinning intensity increases, the fiber aspect ratio also increases. The cell lumen-to-wall ratio increases with the increase in thinning intensity. It can reflect the relative thickness of the fibers. This ratio is related to the shrinkage properties of wood; the larger the lumen-to-wall ratio, the greater the shrinkage.

Crystallinity

Crystallinity refers to the percentage of the crystalline cellulose zone relative to all of the cellulose. Research by Li (2003) shows that with the increase of crystallinity, the tensile strength of the fiber, the elastic modulus, *etc*. also increases.

Table 6 shows the crystallinity of wetwood and normal wood at different thinning intensities for various parts. The crystallinity of wet heartwood is greater than that of normal wood under the same thinning intensity, which is because of the wet heartwood contains more water and resin, which affects the crystallinity of wet heartwood greater than that of normal wood under the same thinning intensity. Cellulose in wood has a certain crystalline structure. When the crystallinity is high, the cellulose molecules are arranged more regularly and tightly. Because the molecular structure of the crystalline region is relatively stable and is not prone to large deformations when affected by changes in the external environment (such as changes in humidity and temperature), wood with a higher crystallinity has relatively better shrinkage resistance. It can be seen from the data that the crystallinity of the wood after thinning treatment was higher than that of the untreated wood and the crystallinity was the highest at 30% thinning, indicating that the thinning treatment is conducive to improving the dry shrinkage quality of wood and the 30% thinning is the best option. The higher the crystallinity of the wood, the higher the flexural strength of the wood, the better the mechanical properties of the wood, so the thinning treatment can also improve the mechanical properties of the wood, and the best was achieved at 30% thinning intensity. From Table 6, different thinning intensities had a certain effect on the crystallinity of poplar wood, and the crystallinity increased at 50% thinning and 30% thinning intensity. The crystallinity was the highest at 30% thinning intensity, and the mechanical and physical properties of wood were the best at this time. It shows that after a certain degree of thinning, the quality of wood can be improved and that contributes to the optimal use of wood.

Table 6. Crystallinity at Different Heights and Thinning Intensities

Position (m) / Thinning Intensity (%)		Crystallinity				
		0	1.3	3.3	5.3	7.3
50%	NH	52.8	54.6	54.0	49.5	49.2
	WW	55.3	58.0	51.2	47.4	48.4
30%	NH	50.3	54.6	54.2	50.8	49.9
	WW	52.3	55.2	56.1	50.1	47.0
20%	NH	53.8	50.9	51.0	52.9	49.2
	WW	55.3	52.2	53.1	50.1	47.0
Control	NH	50.8	51.0	47.2	44.4	44.7
	WW	54.2	54.8	50.0	49.0	48.1

* Note：WH stands for wet heartwood, and NW stands for normal wood

CONCLUSIONS

1. With the increase of thinning intensity, the proportion of wet heartwood area of poplar wood increased.
2. The fiber length increased with the increase of thinning intensity. At 50% thinning, fiber length increased by 16%, and the fiber length increased with the increase of sampling height. The fiber width increased with the increase of thinning strength, and first widened and then narrowed with the increase of height. The double-walled thickness of cells increased first and then decreased with the increase of thinning intensity, and the thickest was at 50% thinning intensity. The fiber length-width ratio increased with the increase of thinning intensity, and increased first and then decreased with the increase of height. The fiber-diameter-cavity ratio increased with thinning intensity and increased with height.
3. At the same thinning intensity, the crystallinity exhibited a trend of initially increasing and then decreasing with the height of the poplar trees, reaching its maximum at breast height. The crystallinity of normal wood under the same thinning intensity was greater than that of wet heartwood. Under a thinning intensity of 30%, the crystallinity was greater than that under other thinning intensities.

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