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ORIGINAL PAPER

Responses of radial growth, wood density and fiber traits to planting space in poplar plantations at a lowland site

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Abstract Poplar is raw material for various panel, paper and fiber products. The 12 sample trees of clone Nanlin-895 from four spacings were destructively harvested after thirteen growing seasons to assess the influence of spacing on radial growth and wood properties. Spacing significantly affected tree-ring width and wood basic density ($p < 0.05$) but not fiber traits. The highest diameter and wood basic density at breast height (1.3 m) was in 6 m×6 m and 3 m×8 m spacings, respectively. However, no significant differences in tree-ring width, wood basic density and fiber traits were observed among the four sampling directions in discs taken at 1.3 m for each spacing. Growth rings from the pith and tree heights had significant effects on wood basic density and fiber anatomical characteristics, highlighting obvious temporal-spatial variations. Pearson correlation analysis showed a significantly negative relationship of tree-ring width to wood basic density, fiber length and fiber width, but a significantly positive relationship to hemicellulose. There was no relationship with cellulose and lignin contents. Based on a comprehensive assessment by the TOPSIS method, the 6 m×6 m spacing is recommended for producing wood fiber at similar sites in the future.

Keywords Planting density · Growth ring · Fiber morphology · Chemical composition · Temporal-spatial variation

Introduction

Declining availability of wood supplies and increasing demand have prompted a renewed interest in short rotation woody crops (SRWC) around the world (Zhang et al. 2012; Wang et al. 2016a, b). With global warming however, more short-term waterlogged areas are projected (IPCC 2014), which would lead to unfavorable conditions for tree growth. One option to minimize the effects of waterlogging stress on tree growth and yield is to select species/genotypes capable of tolerating waterlogging. *Populus* spp. and their hybrids, due to characteristics of fast-growth and wide adaptability to various environments, are widely planted in subtropical and temperate regions in both plantation forestry and agroforestry systems (Fang et al. 2004). As the best SRWC species, the total area of poplar plantations has reached 8.54 million ha in China (IPC 2016; Tun et al. 2018), while poplar wood is mainly used as raw materials for various panel, paper and fiber products.

The chemical composition, anatomy, and morphology of raw materials influence paper and fiber products and ultimately determine its quality and appropriate end-use (Neiva et al. 2015). For example, some results indicate that fiber morphology is an important feature of papermaking,

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Table 1 General characteristics of sample trees in different planting spacing of the clone Nanlin-895. Different letters indicate significant differences ($P < 0.05$) by the Tukey test after 13 growing seasons

Planting spacing (m^2)	Height (m)	Diameter at breast height (cm)	Volume (m^3 $tree^{-1}$)
6×6	24.03 ± 1.24^a	27.34 ± 0.62^a	0.60 ± 0.06^a
5×5	23.87 ± 1.10^a	22.86 ± 0.24^b	0.40 ± 0.07^b
4.5×8	24.47 ± 1.02^a	25.33 ± 1.31^a	0.47 ± 0.07^b
3×8	23.43 ± 0.87^a	22.49 ± 0.59^b	0.39 ± 0.06^b

Different letters indicate significant difference among the planting spacings for the same index according to Duncan's test ($p < 0.05$)

especially fiber length (Ohshima et al. 2005; Pirralho et al. 2014). This determines sheet formation, drainage properties, strength and optical properties and is correlated with various physical and mechanical properties of the wood (Young 1994; Ai and Tschirner 2010; Li et al. 2015). In addition, wood basic density (WD) is also considered one of the most important wood properties, and has a major impact on the freight costs, wood mechanical properties, pulp yield per unit mass of wood, and paper quality (Francis et al. 2006; Santos et al. 2012). It is also generally accepted that the tree volume growth (biomass accumulation) and chemical composition (e.g., cellulose, hemicellulose, and lignin) together determine the pulp yield and pulping costs (Palenik and Stupińska 2005; Mokfienski et al. 2008; Bose et al. 2009; Silva et al. 2009; Santos et al. 2012; Guo et al. 2020).

Owing to the interest of the forest industry and the large carbon stock in poplar plantations, numerous studies on suitable silvicultural techniques for poplar plantations have been carried out to get optimum yield and wood quality (Pinno et al. 2010; Benomar et al. 2012; Yang et al. 2015; Nelson et al. 2018). In practice, choosing planting spacing as an easily controlled variable is important in the silviculture of the plantation to achieve maximum biomass production, reasonable biomass partitioning, and high wood quality (Tun et al. 2018; Fang et al. 2021), when suitable genotypes are selected for a specific site. However, poplar has been widely characterized as a low-density and low strength genus (Mátyás and Peszlen 1997; Balatinecz et al. 2001), and wood from short rotation plantations is utilized as raw material for fiber board and oriented strand board as well as for the pulp and paper industry (Balatinecz et al. 2001). Previous studies have confirmed that there are significant variations in WD, fiber morphology and chemical composition among poplar clones (Fang and Yang 2003; Fang et al. 2004, 2021), while the responses of these traits to silvicultural practices (especially spacing) were less available. Moreover, most studies of wood properties were carried out with mixed samples, ignoring the change of these traits in radial and vertical directions among tree-rings (Bose et al. 2009; Ai and Tschirner 2010; Yue et al. 2019).The influence of uneven growth of annual rings on wood density and fiber traits is particularly poorly understood (DeBell et al. 2002; Fang and Yang 2003; Fang et al. 2004; Zhang et al. 2012). Our previous study concluded that there was significant variations in tree volumes among plantations with different spacings (Zhang et al. 2020). Therefore, a comprehensive understanding of the effect of planting space on radial growth, wood density and fiber traits is vital for improving wood production and wood quality of poplar plantations. The objective of this study is to compare the differences in radial growth, WD, fiber morphology and cellulose, hemicellulose and lignin contents under different spacings, with a specific focus on the temporal-spatial variation of these properties. Results from this study would provide useful information for optimizing management of poplar plantations for high productivity and wood quality at lowland sites.

Materials and methods

Study site and plantation establishment

The study was conducted at Sihong Forest Farm, Jiangsu Province, China (33°16' N, 118°18' E). Soils at this site were formed of fine sediments of Hongze Lake and have a clay loam texture with average fertility (Yan et al. 2015). The mean annual water table is approximately 0.8 m below the surface, with a waterlogging period of 1–2 months during the growing season. Detailed climate conditions are described by Zhang et al. (2020).

Clone Nanlin-895, a hybrid of clone I-69 (*Populus deltoides* Bartr. cv. 'Lux') × clone I-45 (*P.* × *euramericana* (Dode) Guinier cv. 'I-45/51'), was used as research material due to its good growth performance and adaptability at the site. A randomized block design was adopted to establish the spacing experiment with three replications. The plantations were established in March 2007 with one-year-old rooted cuttings at four levels of spacing (6 m × 6 m, 4.5 m × 8 m, 5 m × 5 m, and 3 m × 8 m) and the north–south direction is the spacing between rows, while the east–west direction is the spacing between plants. A total of 12 plots were established, ranging from 1200 to 1800 m^2 to allow 50 trees per plot for each treatment. The 6 m × 6 m and 5 m × 5 m spacings were square configurations, while the 4.5 m × 8 m and 3 m × 8 m spacings were rectangular. The plantations of 6 m × 6 m and 4.5 m × 8 m spacing have the same planting density (278 ind. ha^{-1}), while the plantations with 5 m × 5 m (400 ind. ha^{-1}) and 3.5 m × 8 m (417 ind. ha^{-1}) spacings were regarded as having similar planting density.

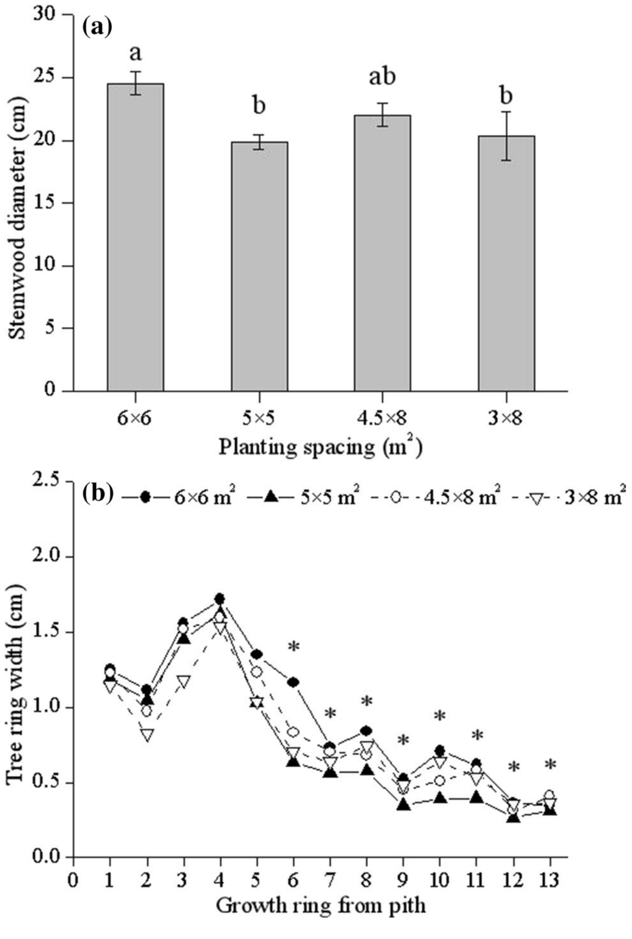


Fig. 1 **a** Variations in stemwood DBH after 13 growing seasons; **b** variations in tree-ring width under four spacings; Means with the same letters were not significantly different in Tukey test at $\alpha = 0.05$. * represents a significant difference among different spacings in the same ring age ($p < 0.05$)

Sample tree selection and destructive sampling

Height (H in m) and diameter at breast height (1.3 m above ground, DBH in cm) of all trees were measured in each plot; one sample tree of each plot was selected, based on the plot means of DBH and H (Table 1). A total of 12 sample trees were harvested October 2018. For each tree, five sample discs 50 mm thick were collected at ground level and at 1.3, and 5.6, 11.6 and 17.6 m (the last three representing about 25%, 50%, and 75% of the total height, respectively). The discs were sanded to increase visualization of growth rings for measuring tree-ring width (TRW) (Menezes et al. 2003; Fang et al. 2021).

After measuring TRW, 20-mm radial strips were sampled in four directions (south, north, east and west) from 1.3 m discs, while the radial strips from the discs at ground level, 5.6, 11.6 and 17.6 m were only collected in the south direction. These sampled strips were used to measure the WD, fiber length (FL), fiber width (FW), FL/FW ratios, and the contents of cellulose, hemicellulose, and lignin.

TRW and wood basic density

Tree-ring width (TRW) was measured to the nearest 0.01 mm using a caliper. TRWs for all discs at 1.3 m were measured in four directions, while the TRWs were only measured in the south direction for the discs at ground level, 5.6, 11.6 and 17.6 m height. Based on the sampled strips, wood basic density (WD) for each annual tree-ring was determined by the maximum moisture content method (Smith 1954; Fang et al. 2021).

Anatomical characteristics of fiber

For the measurement of length (FL) and width (FW), a mixed sample of each annual ring, including early wood and late wood after measuring the WD, was taken. The samples were softened in a boiling 1: 1 (v/v) mixture of acetic acid and hydrogen peroxide for one hour and then rinsed with distilled water (Wu et al. 2013). An appropriate amount of distilled water and solarbio (staining reagent) was added, and shaken until the fibers separated. A drop of paraffin was placed on a glass slide and a dissecting needle used to transfer fibers to the slide and covered with a cover glass for a temporary mount. Fifty intact fibers of each sample were measured using a Leica digital microscope (DM 5000B, USA) based on imaging analysis of Qwin V3 software. The FW were determined at mid-length to the nearest 0.01 μm.

Cellulose, hemicellulose and lignin

For the discs at 1.3 m, two growth rings were combined into one sample from the pith outwards, whereas the outermost three rings were mixed into one sample (288 samples). However, only a mixed sample was collected from each disc at ground level, 5.6, 11.6, and 17.6 m (48 samples). A total of 336 samples were pulverized through a 270-mesh sieve to measure the cellulose, hemicellulose and lignin. The cellulose content was determined according to the anthrone colorimetric method (Wang and Huang 2006), while hemicellulose and lignin contents were estimated by the hydrochloric acid hydrolysis-DNS method and the ulfuric acid titration method (Xiong et al. 2005), respectively.

Statistical analysis

The weighted means of WD, FL, FW and FL/FW in the four directions at 1.3 m and only in the south direction for the discs were calculated according to Eq. 1, while the weighted means of cellulose, hemicellulose and lignin were calculated by Eq. 2.

$$W_x = \sum x_i TRW_i / \sum TRW_i \tag{1}$$

$$W_x = \sum x_i TRW_i WD_i / \sum TRW_i WD_i \tag{2}$$

where, x represents WD (g cm^{-3}), FL (μm), FW (μm), FL/FW and the contents of cellulose, hemicellulose and lignin (%), respectively; W_x is the weighted mean of these indicators.

In addition, the yield of cellulose, hemicellulose and lignin per hectare were estimated by Eq. (3):

$$Y_x = v \times W_{WD} \times x \times n \times 1000 \tag{3}$$

where, Y_x (kg ha^{-1}) is the yield of cellulose, hemicellulose and lignin per hectare; W_{WD} is the weighted mean of the discs at 1.3 m, v the tree volume (m^3 stem^{-1}) and n is the planting density (stem ha^{-1}).

One-way analysis of variance (ANOVA) was performed to examine differences in TRW, WD and fiber traits among directions, tree heights and planting spacings. Comparisons of the means were conducted using Tukey's Honestly Significant Difference (HSD) test. Pearson correlation analysis was applied to examine the relationship among the weighted means of TRW, WD and fiber traits. Data are reported as the mean ± standard deviation. All statistical analyses were carried out using Matlab2014a (Math Works Inc., Natick, MA, USA) and SPSS20.0 (SPSS Inc., Chicago, IL, USA) at $\alpha = 0.05$.

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) was used to comprehensively assess the fiber potential and quality prioritization of the four planting spacings and was implemented with the DPS v 7.05 statistical software package (Hangzhou Information Ruifeng Technology, Co., Ltd., Hangzhou, China) (Meshram et al. 2020; Fang et al. 2021).

Results

Radial growth

Stemwood diameters (without bark) at breast height were significantly affected by plant spacing after 13 growing seasons ($p < 0.05$, Fig. 1a), and the highest diameter was observed in the 6 m × 6 m (24.5 cm) plantation and the smallest in the 5 m × 5 m spacing (19.8 cm). The arithmetic mean over 13 years of TRW in the four spacings showed a similar order with stemwood diameters, whereas significant differences in TRW were only observed among the four planting spacings after six growing seasons ($p < 0.05$, Fig. 1b). For all spacings, the dynamics of TRW displayed similar patterns, with the pith-to-bark trend leveling off around ring 11 (Fig. 1b) and TRW reaching a maximum in the fourth year.

ANOVA showed that there were no significant differences in TRW among the four directions at 1.3 m for each spacing ($p > 0.05$, Table S1), although slight variations were observed among the directions.

Wood basic density

Similar to tree-ring widths, there were no significant differences in wood basic density (WD) among the four directions at 1.3 m for each plant spacing ($p > 0.05$, Table S2).

However, WD in the east and west directions were slightly larger than in the south and north directions in 4.5 m × 8 m and 3 m × 8 m spacings (Fig. 2a–d). Significant differences were observed among the four spacings, with the highest WD in the 3 × 8 m spacing (0.3543 g cm^{-3}) and the smallest in the 5 × 5 m spacing (0.3374 g cm^{-3}) ($p < 0.05$, Fig. 2e). In addition, WD showed an increasing trend with growth rings from the pith but with little variability after 10 growth rings or 10 years (Fig. 2f). As shown in Fig. 2g, the mean WD significantly increased with tree height, and the highest value was at the 17.6 m height, reaching 0.4089 g cm^{-3} ($p < 0.05$), which is 12.4% higher than that at the 1.3 m height.

Fiber anatomical characteristics

Planting spacing showed no significant effects on average fiber length and width, and the FL/FW ratios at breast height ($p > 0.05$, Table 2). In most cases, there were no significant variations in these fiber traits in the four sampling directions for each spacing (Table S3). A consistently increasing pattern was observed in the FL, FW and FL/FW ratios from the pith outwards ($p < 0.05$, Fig. 3a, c). For FL and FL/FW, there was a rapid increase as is typical for juvenile wood, followed by a transition zone with slow increasing, and then the trend was relatively constant after the 10 th year (Fig. 3a, c). However, FW increased first and then stabilized after seven years (Fig. 3a). Moreover, there were significant differences in the FL, FW and FL/FW at different heights (Fig. 3b, c), showing a decreasing trend with increasing height but only a slight variation after 11.6 m (Fig. 3b, c).

Based on a data set of tree rings at breast height (12 trees and 624 rings), a normal distribution in percentage of FL and FL/FW by different length classes was observed for all spacings (Fig. 4). The maximum distribution in FL ranged from 1000 to 1200 µm in the four planting spacings, while about 50% of the FL/FW ranged from 35 to 50. According to the wood classification standard of the International Association of Wood Anatomists, the medium-length fiber percentage (900–1600 µm) of clone Nanlin-895 in the 6 m × 6 m, 5 m × 5 m, 4.5 m × 8 m, and 3 m × 8 m spacings were 74.7%, 80.4%, 73.7%, and 75.0%, respectively. The ratio of FL/FW $^{>}$ 35 by spacing was 4.5 m × 8 m (81.4%) > 5 m × 5 m (80.2%) > 6 m × 6 m (77.7%) > 3 m × 8 m (76.3%) (Fig. 4).

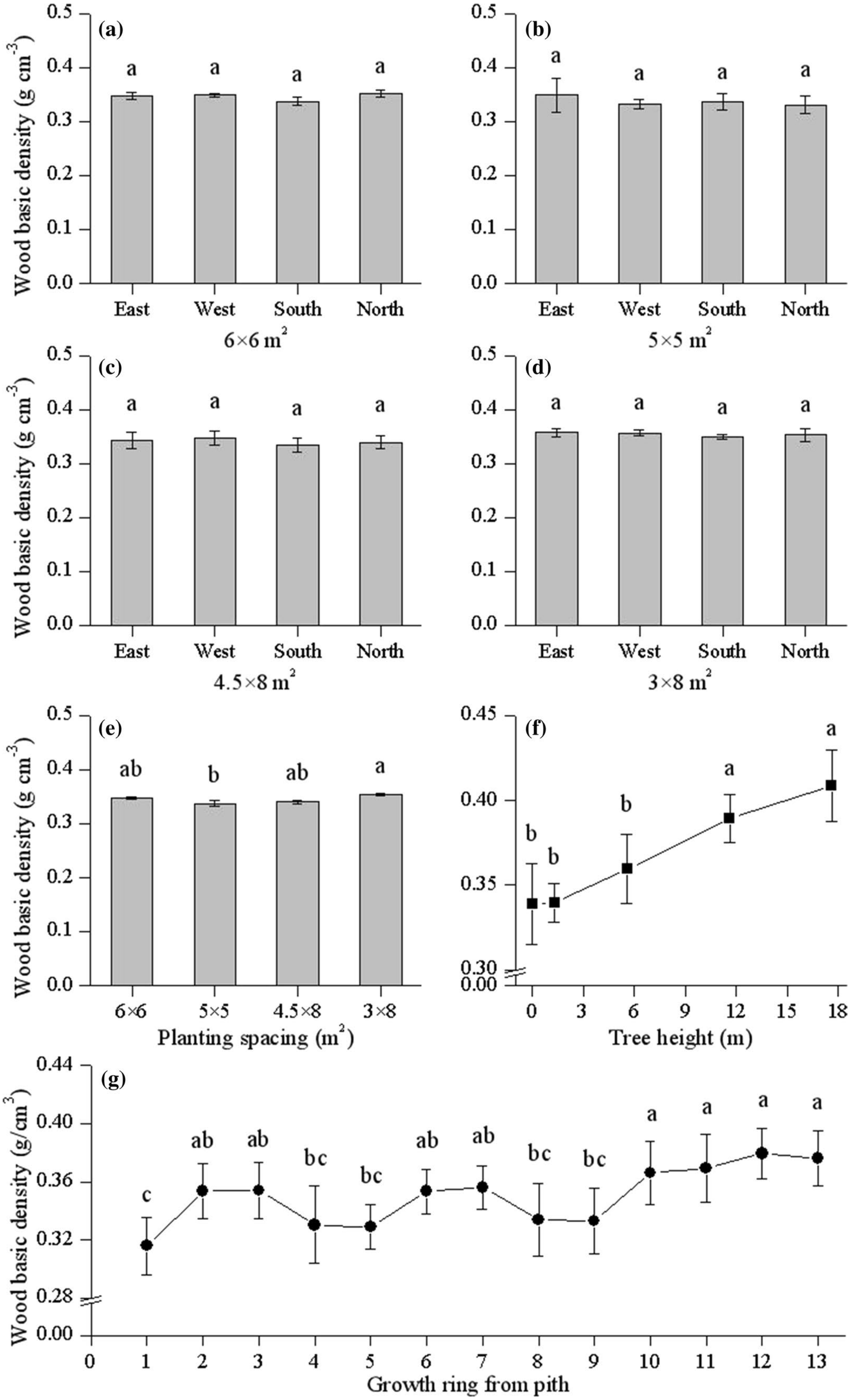
Cellulose, hemicellulose and lignin contents

One-way ANOVA results indicated that spacings and sampling directions did not affect the levels of cellulose, hemicellulose and lignin ($p > 0.05$, Tables 3 and S4). However, hemicellulose significantly decreased with growth rings from the pith but cellulose and lignin changed slightly (Fig. 5a). Hemicellulose levels slightly decreased with increasing tree height, whereas height did not influence cellulose, hemicellulose and lignin contents ($p > 0.05$, Fig. 5b).

Discussion

Effects of planting spacing on tree ring widths, wood basic density and fiber traits

With regards to the effects of sampling directions on TRW and wood properties, the results show no significant differences among the four sampling directions at 1.3 m for each spacing, except for a few growth rings of fiber anatomical characteristics (Tables S1–S4 and Fig. 2a–d). The TRW growth found in various directions are similar to the results from Tun et al. (2018) who reported no significant differences in *DBH* between the narrow and wide spacings in rectangular configurations (such as 3 m × 8 m and 4.5 m × 8 m), but mean *DBH* in 8 m spacing was slightly higher than in the 4.5 m and 3 m spacings. However, relatively low planting density significantly improved radial growth, especially for the square 6 m × 6 m configuration (Fig. 1a), which is supported by several studies (Lasserre et al. 2009; Tun et al. 2018; Zhang et al. 2020). In addition, TRW growth


(a)
(b)
(c)
(d)
(e)
(f)
(g)
Wood basic density (g cm^{-3})
Wood basic density (g/cm^3)
East
West
South
North
6×6 m^2
5×5 m^2
4.5×8 m^2
3×8 m^2
6×6
5×5
4.5×8
3×8
Planting spacing (m^2)
Tree height (m)
Growth ring from pith
ab
b
ab
a
c
bc

◂**Fig. 2** **a**-**d** Variation in weighted mean of wood basic density (WD) at breast height after 13 growing seasons among different directions for each spacing **a**-**d**, and **e** among the different spacings; **f** variation in mean WD at 1.3 m (four planting spacing averaged), and **g** the weighted means of WD at different heights; Means with the same letters were not significantly different in Tukey test at $\alpha = 0.05$

responded significantly to spacing after six growing seasons (Fig. 1b). A plausible reason is that canopy competition occurred in the narrow spacing treatment and inhibited radial growth (Tun et al. 2018; Ahmed et al. 2020; Zhang et al. 2020). Furthermore, compared to the results at a lowland site reported by Fang et al. (2021), poplar growth rate in this study is much lower owing to differences in clones and water table levels between the two sites. Our results are in agreement with previous reports that both groundwater levels and soil moisture impact radial growth of different tree species (Orwig and Abrams 1997; He et al. 2020; Heilig et al. 2021). Likewise, the significant effect of plant spacing on WD was found in the present study at the stand age of 13, which is inconsistent with some reports of wood air-dry density and oven-dried density for conifer species (Lasserre et al. 2009; Watson et al. 2011) where WD was not significantly influenced by plant spacings, confirming that, except for spacing, wood air-dry density (density when wood is equilibriated to 40% RH and 20 °C; equivalent to 7–8% moisture content) is affected by other factors such as species, genotype and site conditions (Pliura et al. 2007). In the fiber traits, Watson et al. (2011) noted that the outer fiber length of coastal western hemlock was significantly shorter at the widest spacing, while Lasserre et al. (2009) found that fiber width of *Pinus radiata* D. Don was not significantly different among spacing treatments. Fiber length and FL/FW ratios were higher (up to 33%) in the clone Nanlin-895 compared to clones of *Populus tomentosa* Carr. in northern China (Wu et al. 2013), and average precipitation was about half of this study site. Previous studies also reported a significant site effect (including annual precipitation) in fiber morphology, holocellulose and lignin content of *Dendrocalamus giganteus* Munro (Wang et al. 2016a, b). However, our study indicated that plant spacing did not influence fiber anatomical characteristics and cellulose, hemicellulose and lignin contents (Tables 2 and 3), suggesting that the poplar clone had less phenotypic plasticity in fiber traits.

Temporal-spatial variations in wood basic density and fiber traits

In this study, fiber anatomical characteristics had a gradually increasing tendency from pith to bark (Fig. 3a, c), showing a strong influence of cambial age on these properties in agreement with previous research (Yanchuk et al. 1984; Fang and Yang 2003; Fang et al. 2004). This is possibly due to the increase in size of cambial initials with age that is related to the development of the stem (Ilona 1994). Nevertheless, cellulose and lignin contents did not change significantly from the pith to the bark, remaining relatively constant, whereas hemicellulose decreased from the pith (Fig. 5a).

In addition, our results found that the average fiber length decreased with increasing tree height (Fig. 3b), which is in accordance with Fang and Yang (2003), and further shows that cambium age is an important factor regulating fiber length. However, average WD showed a general increase with increasing tree height (Fig. 2g), in line with previous studies (Fang and Yang 2003; Fang et al. 2021). This spatial variation pattern in WD is possibly related to the proportions of juvenile and mature wood. Juvenile wood generally accounts for a large proportion in the lower trunk (Elspeth and Jason 2002), while there were higher contents of lignin and NaOH extractives in juvenile wood compared to mature wood (Pitre et al. 2007; Wu et al. 2011). Larson (1964) indicated that wood density was related to plant nutritional status, and the top of the stem was easier receive nutrients produced by canopy photosynthesis.

Our study highlights that growth rings from the pith outwards and tree height have significant effects on WD and some fiber traits (Figs. 2f, g, 3 and 5), while plant spacing did not significantly affect average WD and fiber traits except for WD in the 5 m × 5 m spacing (Fig. 2e, Tables 2 and 3), indicating that the main factors driving wood formation were the developmental stage and genetic qualities (Pitre et al. 2007; Watt et al. 2008; Lasserre et al. 2009; Silva et al. 2009). Our results, however, did not find a significant

Table 2 Effects of planting space on weighted means of fiber anatomical characteristics at breast height

Planting spacing (m^2)	Fiber length (FL) (μm)	Fiber width (FW) (μm)	FL/FW
6×6	1051.34 ± 7.05^{a}	25.60 ± 0.28^{a}	41.82 ± 0.45^{a}
5×5	1049.40 ± 20.00^{a}	26.00 ± 1.00^{a}	41.10 ± 1.50^{a}
4.5×8	1059.77 ± 34.30^{a}	24.66 ± 0.62^{a}	44.24 ± 2.55^{a}
3×8	1060.90 ± 19.56^{a}	26.16 ± 2.08^{a}	41.35 ± 2.70^{a}

The same letters for the same index indicate no significant difference among the planting spacings according to Tukey test at $\alpha = 0.05$

spatial variation in cellulose, hemicellulose and lignin levels at different tree heights (Fig. 5b).

Correlations among the measured variables

Numerous studies indicate some relationships between tree growth and wood properties (Farmer and Wilcox 1966; Zhang et al. 2003; Lasserre et al. 2009; Ahmed et al. 2020). However, the results from these previous studies on the relationship of tree growth, wood density and fiber traits were often controversial. For instance, Zhang et al. (2003) and Lasserre et al. (2009) reported that there was no significant correlation between growth traits and wood air-dry density. Farmer and Wilcox (1966) and Watt et al. (2005) found that radial growth rate was negatively correlated with wood oven-dried density and air-dry density in poplars and *P. radiata*, consistent with our study (Table 4), but DeBell et al. (2004) indicated the negative correlation between growth rate and wood oven-dry density diminished with increasing tree age. Additionally, our results clearly show that tree-ring width (TRW) was significantly and negatively correlated with fiber anatomical characteristics, whereas a significantly positive correlation existed between WD and fiber anatomical traits (Table 4), in agreement with other studies (Fang et al. 2004; Lasserre et al. 2009). This was inconsistent with the results of Ahmed et al. (2020) where a positive relationship between growth traits and fiber length was found. Moreover, there were significantly positive correlations between TRW and hemicellulose content and a negative relationship between WD and lignin content (Table 4). This is inconsistent with the results of Ona et al. (1997) and Ahmed et al. (2020). Furthermore, only a significantly negative correlation between cellulose and lignin contents was found among three wood chemical compositions (Table 4). Overall, our results suggest that tree growth and wood properties such as density, fiber characteristics and chemical compositions are not genetically independent. Therefore, both genetic and management measures (such as spacing) should be considered to improve wood quality and yield in future afforestation with poplar.

Assessments of potential pulp and paper making

Wood quality is the result of physical and chemical characteristics of a tree or parts of a tree that provide the property requirements for different end products (Briggs and Smith 1986). The potential of poplar as a feedstock for pulp and paper making depends on the quantitative and qualitative characteristics of fiber morphology, holocellulose biomass and total biomass production (Young 1994; Ai and Tschirner 2010; Santos et al. 2012; Pirralho et al. 2014; Neiva et al.

Fig. 3 Variation in mean fiber length (FL), fiber width (FW) and FL/FW at 1.3 m (**a** and **c**, four planting spacing averaged), and the weighted means of fiber anatomical characteristics at different tree heights (**b** and **c**); Means with the same letters were not significantly different in the Tukey test at $\alpha = 0.05$

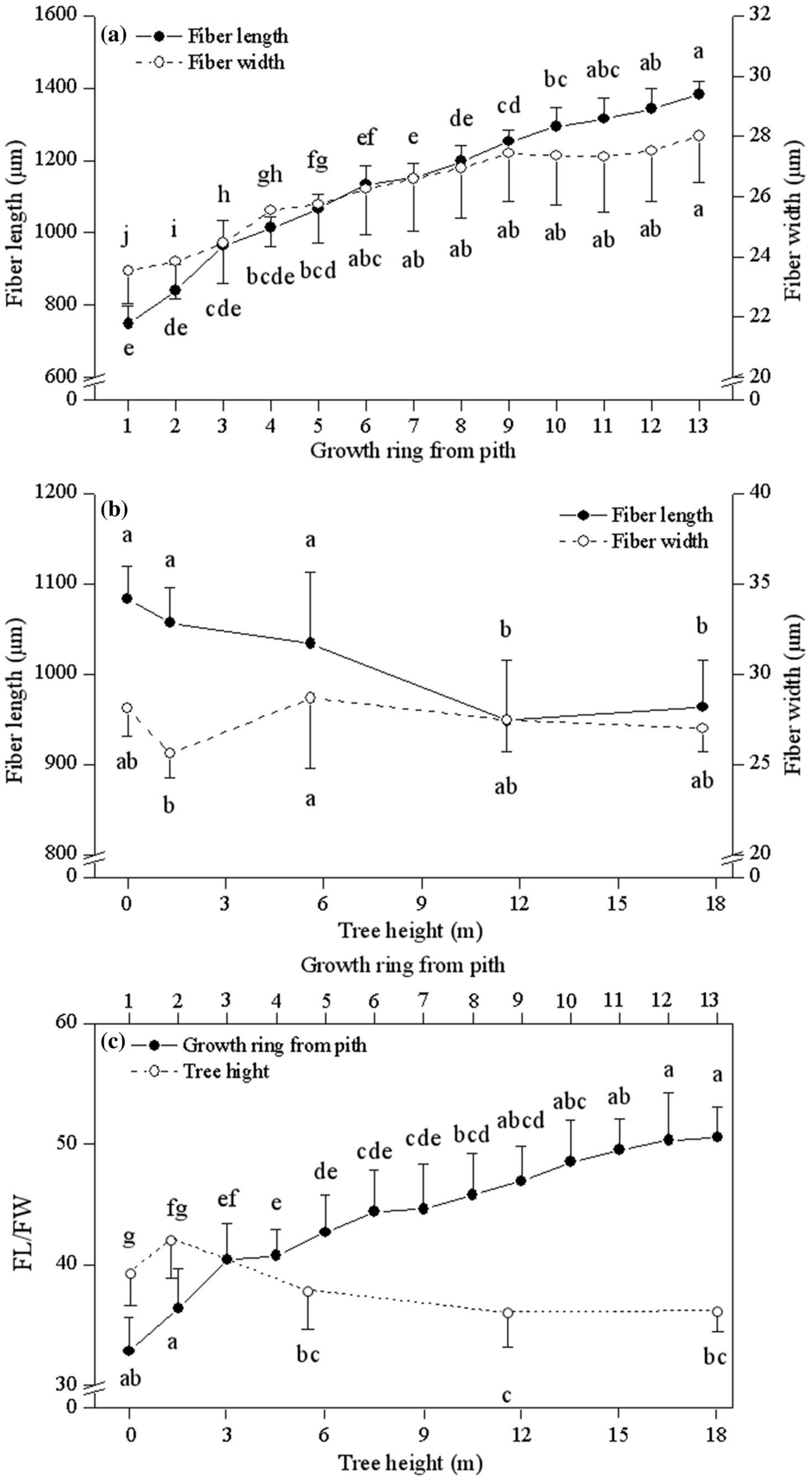


Fig. 4 **a** fiber length and **b** FL/FW (fiber length/ fiber width) distribution of all tree-rings at breast height in four spacings

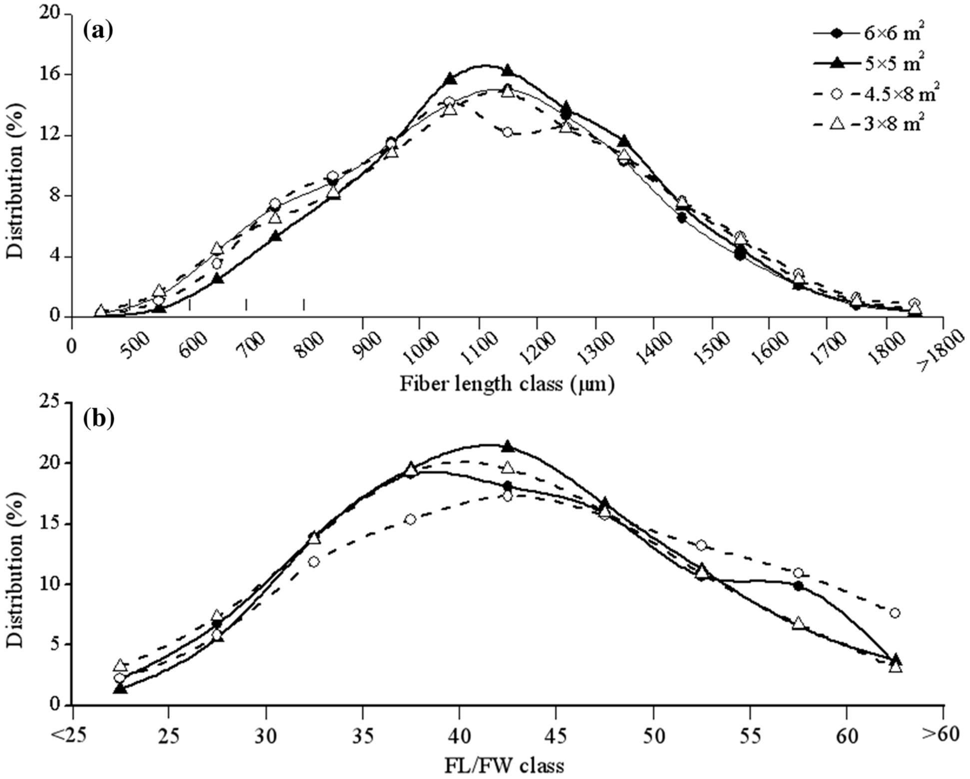


Table 3 Effects of planting spacing on the means of cellulose, hemicellulose and lignin contents at breast height

Planting spacing (m^2)	Cellulose content (%)	Hemicellulose content (%)	Lignin content (%)
6×6	45.24 ± 3.64^a	17.07 ± 0.52^a	31.62 ± 5.59^a
5×5	43.27 ± 2.11^a	16.90 ± 0.61^a	33.98 ± 4.69^a
4.5×8	42.97 ± 1.12^a	16.27 ± 0.78^a	28.23 ± 6.15^a
3×8	44.01 ± 1.10^a	15.85 ± 1.33^a	32.40 ± 4.16^a

The same letters for the same index indicate no significant difference among the planting spacings according to Tukey test at $\alpha = 0.05$

2015). For example, kraft pulp yield is highly correlated with cellulose, holocellulose and wood basic density, but low lignin levels would be preferred for several reasons (Hu et al. 1999; Francis et al. 2006; Bose et al. 2009; Neiva et al. 2015). At the same time, it is universally acknowledged that tear index depends strongly on fiber length and higher FL/FW wood fiber with superior printing properties (Young 1994; Ai and Tschirner 2010). In this study, the yield of cellulose and hemicellulose per hectare and fiber characteristics at breast height were positive variables, and the lignin yield per hectare was negative variable. An assessment for paper

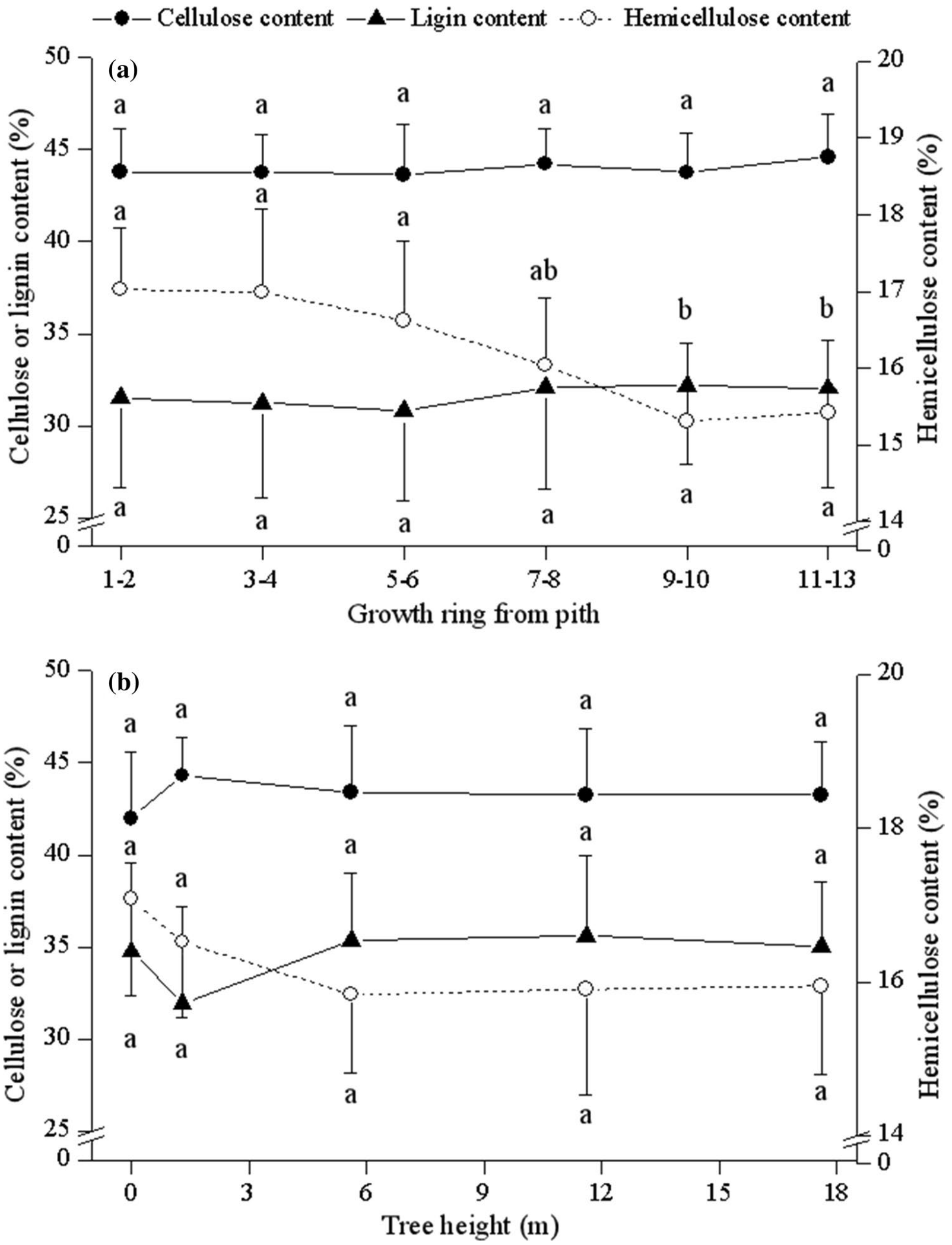


Fig. 5 Variation in mean contents of cellulose, hemicellulose and lignin at 1.3 m (**a**, four planting spacing averaged) and the weighted means of chemical contents at different tree height **b** for 12 sampled poplar trees, means with the same letters were not significantly different in Tukey test at $\alpha = 0.05$

Table 4 Pearson correlations among measured variables based on data at breast height ($n = 288$); weighted averages of TRW, WD and fiber anatomical characteristics were based on the combined sample method for determination of cellulose, hemicellulose and lignin contents

Variables	Tree-ring width	WD	FL	FW	FL/FW	LC	HC
Wood basic density (WD)	– 0.243**						
Fiber length (FL)	– 0.639**	0.362**					
Fiber width (FW)	– 0.435**	0.148*	0.638**				
FL/FW	– 0.526**	0.372**	0.859**	0.161**			
Lignin content (LC)	– 0.080	– 0.122*	0.005	– 0.067	0.038		
Hemicellulose content (HC)	0.460**	– 0.008	– 0.455**	– 0.117*	– 0.489**	– 0.115	
Cellulose content (CC)	– 0.047	0.103	0.066	– 0.045	0.127*	– 0.169**	– 0.076

*$p < 0.05$

**$p < 0.001$.

Table 5 An assessment of optimal paper pulp and prioritization of four planting spacings by the TOPSIS method

Planting spacing (m^2)	d_f^+	d_i^-	C_i	Ranking order
6×6	0.1996	0.2091	0.5117	1
5×5	0.2118	0.1231	0.3676	4
4.5×8	0.2102	0.202	0.4901	2
3×8	0.2095	0.1572	0.4287	3

pulp and prioritization of different planting spacings was conducted by the TOPSIS method (Table 5). Findings indicate that a 6 m×6 m spacing should be recommended for future poplar silviculture for pulp production at similar sites.

Conclusions

Planting spacing significantly influenced tree-ring width and average wood basic density significantly increased with tree height ($p < 0.05$). Wider spacing increased radial growth but not wood basic density. No significant differences in fiber traits were detected among the four spacings. For each spacing, wood sampling directions at 1.3 m height had no significant effects on tree-ring width, wood basic density and fiber traits. Results from this study show that growth rings and tree heights had significant effects on the wood basic density and fiber anatomy, highlighting obvious temporal-spatial variations in wood basic density and some fiber traits. Pearson correlation analysis showed a significantly negative relationship of tree-ring width to wood basic density, and fiber length and width, a significantly positive relationship between tree-ring width and hemicellulose content, and no effect of tree-ring width on cellulose and lignin contents. Based on a comprehensive assessment by the TOPSIS method, a 6 m×6 m spacing is recommended for future the establishment of poplar plantations for pulp and papermaking on similar sites.

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