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ORIGINAL ARTICLE

Effects of growth rate of eastern poplar trees on the chemical and morphological characteristics of wood fibers

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Abstract

Attempts are underway to speed up timber production using genetic improvement and enhanced management practices. However, the impacts of possible morphological and chemical changes on the properties of secondary wood products are less studied. This research thus studied the relationship of tree-ring widths of eastern poplar trees (*Populus deltoides* Bartr.) and the morphological and chemical characteristics of the wood fibers. Cellulose, lignin, ash, and extractives contents were determined according to the Technical Association of Pulp and Paper Industry standards. Accordingly, the mean values of the various parameters measured, such as the fiber length and diameter, the diameter of the cell cavity, and the cell wall thickness along with functionality parameters such as Runkel, slenderness, and flexibility ratio, and the amounts of cellulose, lignin, extractives, and ash contents were determined. As a result, statistical analysis indicated significant correlations between tree-ring width and length and diameter of the fiber, cell cavity, Runkel ratio, cell wall thickness, cellulose content and wood density. On the contrary, there were no significant correlations between tree-ring width and slenderness and flexibility ratios, lignin, ash, and extractives contents. The investigation on the radial variation of wood properties showed from the pith to the bark, fiber length and diameter, cell wall thickness, cellulose, and density increased, and cell cavity, Runkel ratio, ash, extractives, and lignin contents decreased. Overall, increases in tree-ring width of eastern poplar improved wood quality, as raw material, for manufacturing of the most common secondary products in the wood industry, including paper and fiberboard with wide-ranging wood applications.

1 Introduction

Fast-growing timber tree species are suitable alternative wood sources for reducing the gap between wood demand and supply (Adi et al. 2014). Trees of the Salicaceae family have been planted in more than 70 countries due to their high growth rates, adaptability to various climates, and easy propagation (Ball et al. 2005). The poplar species in this family enjoys excellent economic value because of its high capability in producing industrial wood (Verani and Sperandio 2008). Eastern poplar, a species belonging to the genus Populus in the Salicaceae family, is a sun-loving, deciduous and dioecious tree with shallow roots, and individual flowers that are mostly pubescent in clustered inflorescences and pubescent seeds. It reaches a height of 25 m in less than 15 years. Due to its straight stem, easy debarking, homogeneous wood texture, and light color, poplar wood is suitable for making paper pulp. Its highly efficient lignin separation is also possible (Rohde et al. 2018). Various poplar species are used in paper, matchmaking, particleboard, MDF, boxmaking, veneer, plywood, and furniture industries, and they

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are also utilized as a source of energy (Searle and Malins 2014; Ivanisevic et al. 2012). Eastern poplar wood is also a raw material suitable for ethanol production due to its high cellulose content (Kaushal et al. 2016). New applications can also be defined for poplar wood with physical and chemical treatments that increase its mechanical strengths (Ding et al. 2013). Knowledge of fiber physical and chemical properties is an appropriate solution for the optimal use of this valuable raw material (Yu et al. 2001).

Genotype and phenotype traits are generally related to the fiber dimensions (Hong et al. 2014). For example, negative genetic correlations are observed between annual ring width (as a measure of stem diameter growth) and wood density or modulus of elasticity (MOE) in Norway spruce (Chen et al. 2016). These trees with higher growth rates have larger fiber dimensions and thinner wall thicknesses, so their wood density is lower (Chen et al. 2016). Generally, fiber-dimension traits show relatively higher heritability than growth traits in conifer species (Hong et al. 2014). In Norway spruce, heritability is moderate for wood density and modulus of elasticity but is low for microfibril angle (Chen et al. 2016), and density increases from the pith to the bark (Chen et al. 2014). However, other characteristics such as the number of cell divisions, and ring width are dependent on tree age (Lundqvist et al. 2018). Environmental cues such as drought, rainfall, air pollution, habitat slope, cold weather, frost, flood, and avalanche also affect the chemical and morphological characteristics of wood (Speer 2010). Tree-ring widths are influenced by non-environmental factors, including age and management, as well as environmental factors such as temperature, rainfall, and sunshine (García-González and Eckstein 2003). Tree age (Zhang et al. 2003), planting distance (Riahifar et al. 2008), soil quality (Calderon et al. 2012), weather, and geographical location play essential roles in tree growth. Some studies have reported relationships between fiber morphological properties and weather variables such as temperature and rainfall (Watt et al. 2008; Huda et al. 2011; Dufour and Morin 2013; Pritzkow et al. 2014; Matisons et al. 2015). Environmental variations influence tree-ring widths and change properties such as cell wall thickness and cell cavity diameter (Seo et al. 2011). Tree-ring widths increase at higher temperatures (Tumajer and Treml 2016) and affect some wood properties (Giroud et al. 2016). In various species of coniferous trees, increases in growth rate significantly change wood density, fiber length, and microfibril angles (Blanchette et al. 2015). There is a negative correlation between tree-ring widths and fiber length in fir trees (Dutilleul et al. 1998). The quality of manufactured products depends mainly on wood morphological properties (Blanchette et al. 2015). Since fiber morphological properties and wood chemical compounds are critical factors in the cellulose industry (Horn 1974; Ververis et al. 2004), it is possible to predict the suitability of tree species for the various industries by studying the mentioned properties. For example, bursting strength and tensile strength of paper are two properties considerably influenced by both fiber length and fiber wall thickness (Oluwadare and Ashimiyu 2007). Fiber morphological properties also influence the mechanical properties of particleboard (Baharoğlu et al. 2013). Wood with more cellulose and less lignin is more suitable for papermaking, and less chemical compounds, thermal heat, and time will be required for these processes (Gominho et al. 2001). Moreover, an increased percentage of extractive matter reduces paper pulp efficiency. Consequently, lower percentages of extractive matter will allow savings in pulping chemicals and pulping time (Casey 1980); in contrast, the tensile strength of wood-plastic composites decreases with increases in lignin content (Alexy et al. 2000). Genetic improvement and optimal management of poplar cultivation are potential factors for improving wood production efficiency (Anderson and Luckert 2007). Under optimal environmental and management conditions, tree growth and tree-ring width increase (Sabatti et al. 2014; Pearson et al. 2010), influencing various wood chemical and morphological properties. Increases in tree-ring width may cause significant changes in fiber chemical and morphological properties. These changes can influence the characteristics and quality of secondary products manufactured from these fibers. Therefore, this research intended to determine the relationship between the tree-ring width of eastern poplar and the morphological and chemical properties of its fibers. It is assumed that increases in tree-ring width significantly affect wood morphological properties, including fiber length, fiber diameter, the diameter of cell cavity, wall thickness, slenderness ratio, flexibility ratio, and Runkel ratio, and its chemical properties such as cellulose, lignin, extractives, and ash contents.

2 Material and methods

2.1 Sampling

The studied trees were the acclimatized exotic *Populus deltoides* trees selected from clones imported from the United States of America to Iran in 1976 (Ghasemi and Modirrahmati 2004). This clone (*P. deltoides*, clone 69.55) with a volumetric growth of 30 m^3 of wood per hectare per year and 2.67 m longitudinal growth and 1.8 cm diameter growth per year is known as one of the fastest-growing non-native clones in the study area (Fao 2016). Two studied stands of the same age (19 years) were selected from an eastern poplar research plantation area with an altitude of about 100 m. This eastern poplar research plantation area with an area of 34.99 hectares has a longitude 48°6′0″E and latitude 37°34′30″N. The stands were planted with trees 4 m

Table 1 Diameter of the randomly selected samples in each diameter class

Diameter class (cm)				
A	B	C	D	E
27 ≤ D ˂ 29	29 ≤ D < 31	31 ≤ D < 33	33 ≤ D < 35	35 ≤ D < 37
27.2	29.2	32.4	33.7	35.5
28.3	30.6	31.4	33.3	36.7
27.4	29.4	32.3	34.6	36.8
28.7	30.8	31.8	33.2	35.3
27.9	29.7	32.7	34.7	36.6
28.4	30.3	31.2	34.4	35.1

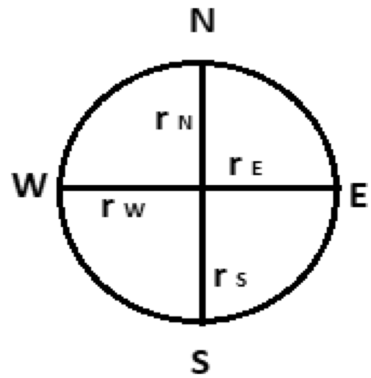

Fig. 1 Measuring the average annual ring width in the four main cardinal directions

by 3 m apart. Full-callipering method was employed for all the trees. First, a code was assigned to each tree, and then a caliper was used to measure the diameter of the trees, and a Suunto clinometer was used to measure their height. After the diameter of all the trees was set, based on the 5-class diameter classification table, for each diameter class, six healthy trees were randomly selected from two stands (three from one stand and three from another stand). In total, 30 trees were cut down. The smallest diameter of the cut trees was 27.2 cm, and the largest 36.8 cm (Table 1).

Considering the high soil moisture in the region, the suitable amount of rainfall, and the high groundwater level, the trees were irrigated twice per month using flood irrigation from May 15 to the end of September. Except for the first six years when plowing, manuring, and NPK [nitrogen (N), phosphorus (P) and potassium (K)] fertilizer treatments were applied, and weeds were controlled using the same weed control method, no treatments were applied besides irrigation.

2.2 Measuring the average annual ring width

According to Table 1, 30 trees were cut down, and a 10 cm-thick disk was prepared at the breast height of each one. The radii of the disks were measured in the four cardinal directions (N, S, W and E) to obtain the tree-ring widths (Fig. 1). The mean radius for each tree was divided by age (19 years) to determine its mean tree-ring width.

$$\text{The average width of annual rings} = \frac{r_N + r_S + r_W + r_E}{(\text{Age})19 * (\text{Geographical Directions})^4}. \quad (1)$$

After determining the average tree-ring widths of the samples, the required samples were cut according to Fig. 2 to measure the chemical and morphological properties. Previous research has shown that some chemical and morphological properties of fibers change from the pith to the bark (Panish and de Zeeuw 1980; Zabel 1998; Cobas et al. 2013; Ištok et al. 2017; Jahan et al. 2019). Therefore, three 10×2×2 cm blocks were prepared from three areas in the radial direction to study the changes of morphological and chemical properties from the pith to the bark and to moderate the effect of these changes to study the effect of annual ring width on the studied properties. These three samples were prepared from three parts [the first six rings (I), the second six rings (II), and the third six rings (III)] in the radial direction. Each block with a length of 10 cm was cut into three 2 ×2 × 2 cm cubes and coded.

2.3 Measurement of morphological characteristics

The Franklin method (Franklin 1945) (equal volumes of hydrogen peroxide and acetic acid) was used to separate the fibers to investigate their morphological properties (Fig. 3a, b). The samples were put inside test tubes, and the acetic acid and hydrogen peroxide mixture was poured into the test tubes (Fig. 3c). After capping the test tubes, they were put in an oven at 60 °C for 24 h. They were then removed, and the content of each one was poured on a filter paper, neutralized by washing with water, and the odor was removed (Fig. 3d). Each washed sample was then poured together with distilled water in a beaker and put on an electric mixer to separate the fibers. The separated fibers were stained by methylene blue, and some samples were poured on separate slides with a dropper, and the dimensions of the fibers were determined (Fig. 3e). One microscope slide of the fibers was prepared from each of the samples (I, II and III) cut from each tree (in all, 3×30 = 90 slides). Fiber length (L), wall thickness (P), fiber diameter (D), and cell cavity diameter (C) were measured using a Nikon YS 100 microscope equipped with

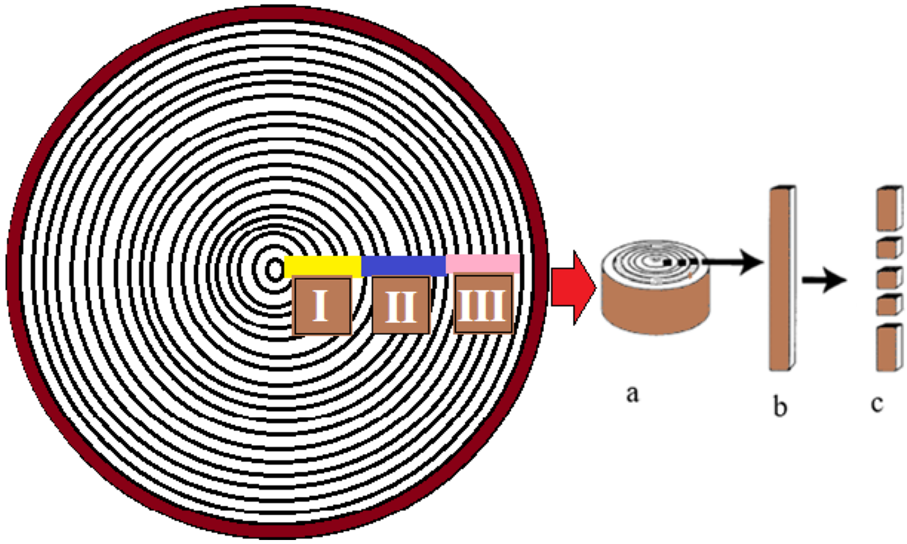

Fig. 2 Cross-section segmentation method for preparing samples from disks

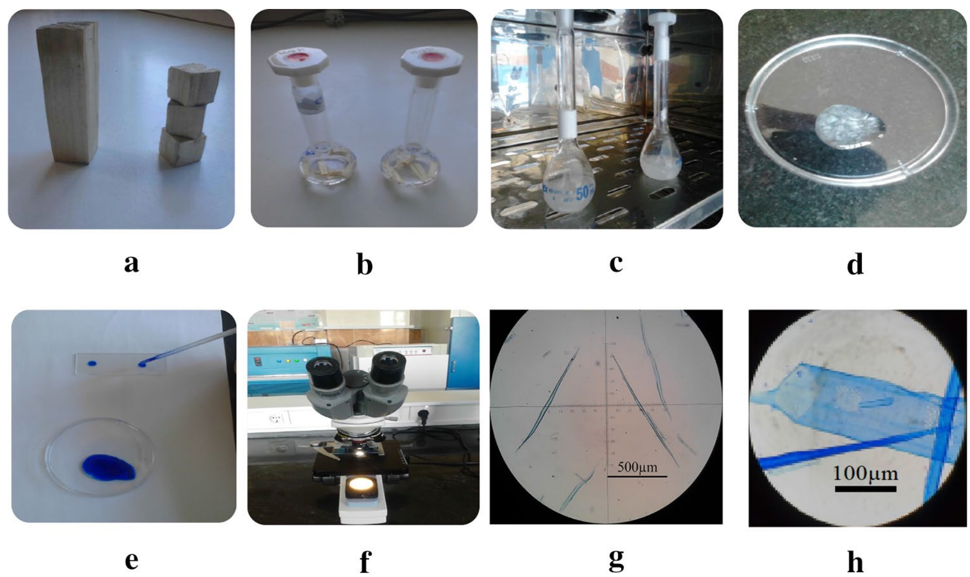

Fig. 3 Separation (**a**–**d**), coloring (**e**) and measuring the dimensions of the fibers (**f**–**h**)

a calibrated eyepiece reticle (Fig. 3f–h). Photographs were taken with a digital camera (Canon IXY DIGITAL 510 IS) and analyzed using Image J 1.46r software. Biometric coefficients were also determined using below equations. For this purpose, 50 intact fibers were put on each slide to measure fiber length and fiber diameter and 25 intact fibers on each slide for measuring the diameter of the cell cavity and fiber wall thickness. The means of each tree were used for the statistical analyses. Finally, fiber morphological properties were determined based on Eqs. (2–4).

$$\text{Slenderness ratio} = L/D \tag{2}$$

$$\text{Flexibility ratio} = C/D \times 100 \tag{3}$$

$$\text{Runkel ratio} = 2P/C \tag{4}$$

Figure 3 presents the images related to the different stages of measuring the morphological properties of eastern poplar wood.

2.4 Measurement of chemical properties

Cell wall contents, including lignin and ash, were measured based on the Technical Information Papers (TIPs) of the Technical Association of Pulp and Paper Industry (TAPPI). Cellulose, lignin, and ash contents were determined according to TAPPI T264 om-88, TAPPI T 222 om-98, and TAPPI T211 om-85 standards, and the American Society for Testing and Materials (ASTM) D1107-84 standard for the extractive matter. The following equations were used to determine the ash, extractives, cellulose, and lignin contents.

$$\text{Ash \%} = \frac{\text{Dry ash weight}}{\text{Dry weight of the sample}} \times 100 \tag{5}$$

$$\text{Extractives \%} = \frac{\text{Weight of extracted materials (completely dry)}}{\text{Primary dry weight of wood powder}} \times 100 \tag{6}$$

$$\text{Cellulose \%} = \frac{\text{Cellulose weight (completely dry)}}{\text{Primary dry weight of wood powder}} \times 100 \tag{7}$$

$$\text{Lignin \%} = \frac{\text{Lignin weight (dehydrated)}}{\text{Primary dry weight of wood powder}} \times 100 \tag{8}$$

2.5 Measurement of density

The density of the samples was determined according to ASTM D2395-02-Standard Test Methods for Density and Specific Gravity (relative density) of wood and wood-based materials. From each of the samples (I, II, and III), three cubes with dimensions of 2 × 2 × 2 (cm) were prepared. In total, the density of 270 cube samples (30 trees × 3 samples (I, II, and III) × 3 cubes) was measured. The cube samples were placed in an oven at 103 ± 2 °C for 24 h, and then placed in a desiccator containing desiccant. After drying, the weight was measured with a digital scale with an accuracy of 0.01 g. The exact dimensions of the dried cubes were measured by micrometer in three directions: longitudinal, tangential, and radial. Then, the density of the samples was calculated according to the standard instruction.

2.6 Data analysis

Pearson correlation coefficients were used to determine the correlations between the independent and dependent variables. In this study, the independent variable was growth ring width and the dependent variable included fiber length, fiber diameter, cell cavity diameter, cell wall thickness, slenderness, flexibility, and Runkel ratios, and amount of cellulose, lignin, ash, extractives, and also density. The relationship between the width of the annual ring and each of these variables was investigated using simple linear regression and the corresponding R-squared was obtained. In the next step, according to the sampling method, radial variation of morphological and chemical characteristics was examined and a graph of each was drawn. SPSS and Excel software were used to analyze the data and draw the graphs.

Table 2 Tree stands characteristics

Properties	Stand 1	Stand 2
Diameter at breast height (cm) (mean ± SD)	28.81 ± 2.82	28.84 ± 2.89
Height (m) (mean ± SD)	31.28 ± 2.71	31.25 ± 2.65
Number per hectare	833	833
Planting distance	3 × 4	3 × 4
Age (years)	19	19

Table 3 Average annual ring width in the study area

Properties	Trees × rings	Mean ± SD
Average annual ring width (cm)	30 × 19	0.76 ± 0.01

3 Results and discussion

3.1 Specifications of the studied stands

Table 2 lists the characteristics of the studied stands. The results indicated the mean diameter and height of the trees.

3.2 Specifications of tree stands

The average tree-ring width of the eastern poplar trees in the four cardinal directions for the 30 studied stands in the study region was 0.76 cm (Table 3).

3.3 Morphological characteristics

Table 4 presents the mean fiber morphological properties and the number of measured samples in the study region.

Measurements of 4500 intact fibers revealed that the mean fiber length and diameter of the eastern poplar trees in the study area were 1230.56 and 26.458 µm, respectively. Cell cavity diameter and cell wall thickness were 17.476 and 4.576 µm, respectively. The slenderness ratio measured by using Eq. 2 was 46.596. The flexibility and Runkel ratios, measured using Eqs. 3 and 4, were 65.590% and 0.5323, respectively.

Since fiber morphological properties and wood chemical compounds are considered factors that influence the wood processing industries (Ververis et al. 2004; Horn 1974; Oluwadare and Ashimiyu 2007), this research studied the relationships between tree-ring widths and wood

Table 4 Morphological characteristics of wood fibers in the study area

Properties	Number of samples: trees × slides per tree × measured fibers in each slide	Mean ± SD
Fiber length (μm)	30 × 3 × 50	1230.56 ± 139.87
Fiber diameter (μm)	30 × 3 × 50	26.458 ± 2.05
Cell cavity diameter (μm)	30 × 3 × 25	17.476 ± 1.38
Cell wall thickness (μm)	30 × 3 × 25	4.576 ± 0.391
Slenderness ratio	30 × 3 × 50	46.596 ± 4.81
Flexibility ratio %	30 × 3 × 25	65.590 ± 5.75
Runkel ratio	30 × 3 × 25	0.5323 ± 0.047

chemical and morphological properties in the eastern poplar trees. The results indicated that some of the chemical and morphological properties were not affected by tree-ring widths, but others were.

3.4 Correlation between morphological properties with annual ring

3.4.1 The relationship between fiber length and diameter, cell cavity diameter, and cell wall thickness with the width of the annual ring

As shown in Fig. 4a, fiber length increases with increasing average annual ring width. The highest fiber length was related to the class E with a value of 1374.8 μm, and the lowest was related to the class A with a value of 1100.3 μm. Fiber diameter was also directly related to the average width of annual ring. The lowest fiber diameter was related to the class A with a value of 24.69 μm, and the highest was related to the class E with a value of 28.21 (Fig. 4b). As shown in Fig. 4c, the average cell cavity increases with the average annual ring width. The highest cell cavity diameter was related to the class E with a value of 18.85 μm, and the lowest was related to the class A with a value of 16.08 μm. The cell wall thickness was also inversely related to the average annual ring width. The highest cell wall thickness was related to the class A with a value of 4.91 μm and the lowest was related to the class E with a value of 4.19 (Fig. 4b).

Fiber length is among the properties regarded as criteria for determining fiber quality and defining the factor of paper pulp quality, and strength and durability of paper are related to fiber length (Ek et al. 2009). The results showed that the average fiber length of eastern poplar wood in the Shafaroud basin was 1207.05 μm. Fibers longer than 1 mm are acceptable raw materials for paper production (Smook 2002; Saxena and Gupta 2011). Moreover, the results of this study indicated that increases in tree-ring widths simultaneously improved fiber length and diameter. Previous research also showed that increases in tree-ring widths in poplar species (Fujiwara and Yang 2000) and red alder (Lei

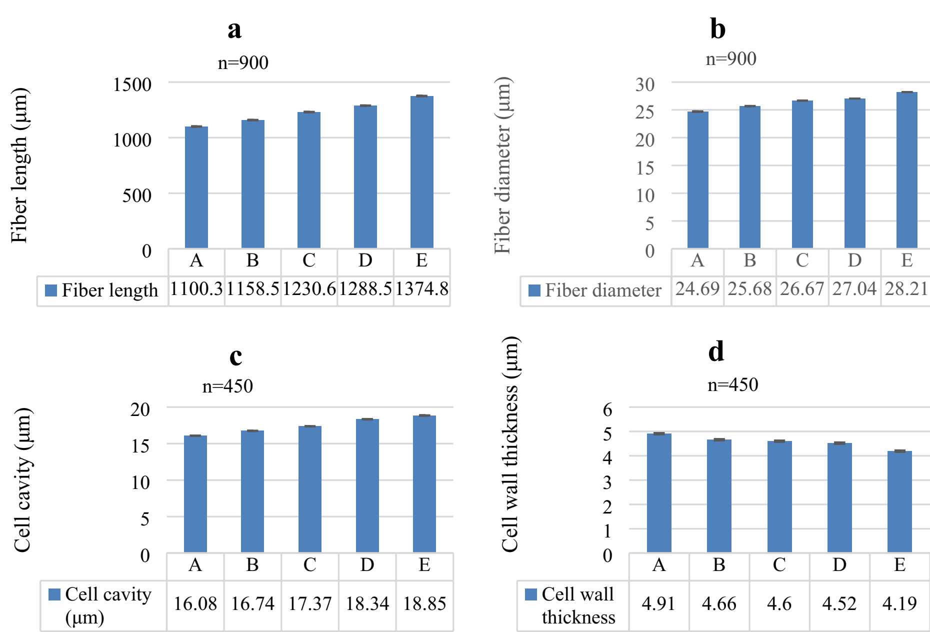

Fig. 4 Effect of annual ring width on the fiber length (**a**), the fiber diameter (**b**), the cell cavity (**c**), and the cell wall thickness (**d**)

et al. 1997) improved fiber length significantly. The longer the fiber length and the more significant its diameter are, the smaller their slenderness and flexibility ratios will be. Hence the more desirable they will be for the paper industry. The ratio of fiber length to its diameter influences many paper properties such as tensile, tearing, bursting strengths, flexibility ratio, and mechanical properties (Fujiwara and Yang 2000). Tensile properties depend on fiber width and gradually decrease with fiber width increases (Prasad and Sain 2003). The results of this research indicated that there was a significant correlation (at the 99% confidence interval) between tree-ring widths and fiber length and diameter, and increases in tree-ring widths increased fiber length and diameter. Therefore, considering the simultaneous increases in fiber length and diameter, we cannot expect substantial changes in the characteristics of the manufactured products. Moreover, elastic fibers with fiber flexibility between 50 and 70% as well as the fibers with a Runkel ratio less than 1 (Sadiku and Abdukareem 2019) are acceptable raw materials for the paper production. These changes can improve tear and impact strengths, interconnections and paper opaquer (Oluwadare and Ashimiyu 2008) and can qualify the wood to be used in the paper manufacturing industry.

There was also a significant relationship between tree-ring widths and the diameter of the fiber cell cavity at the 0.01 significance level, and increases in tree-ring widths increased the diameter of the cell cavity. A significantly negative relationship at the 0.05 significance level was observed between tree-ring widths and fiber wall thickness; i.e., fiber wall thickness decreased with tree-ring width increases. Reme and Helle (2001) also noticed that refining fibers with thinner cell walls required less energy, and the refined fibers had higher compressibility and flexibility. Previous research suggested that fiber wall thickness and the diameter of the cell cavity also had significant effects on the quality of the manufactured secondary products leading to changes in the characteristics of the final products (Blanchette et al. 2015; Baharoglu et al. 2013). Consequently, it is essential to know the factors that influence wall thickness and the diameter of the cell cavity in manufacturing products. The larger the diameter of the cell cavity is, the lower the density of the produced wood will be, and this is important for insulation board production. Moreover, the increased diameter of the cell cavity improves the fiber flexibility ratio, which plays an essential role in the various strengths of the paper. As for wall thickness, the thicker it is, the higher the Runkel ratio will be. This ratio influences the manufacture of essential products, including wood-plastic composite, particleboard, and fiberboard (Rowell et al. 1997). In broad-leaved trees with high density, fibers with thicker walls, which constitute a large part of wood tissue, allow the production of more compact and printable paper. In general, fibers with larger wall thickness increase the durability and stiffness of the final product (Downes et al. 1997; Muneri and Raymond 2001).

3.4.2 The relationship between slenderness, flexibility, and Runkel ratios with the width of the annual ring

The slenderness ratio decreased as the average annual ring width increased (Fig. 5a). The lowest slenderness ratio was related to the class E with a value of 44.58, and the highest

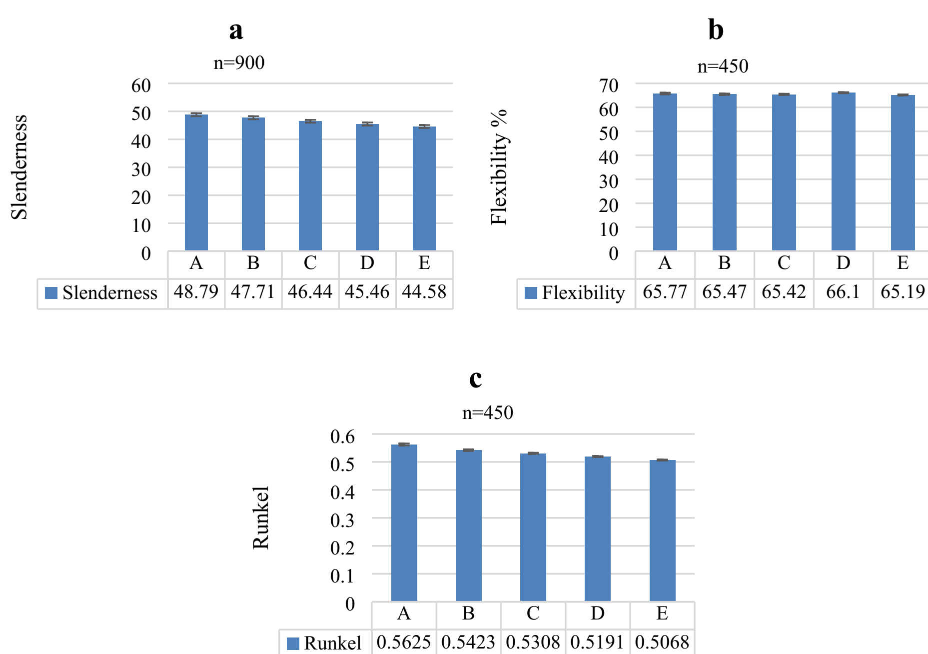

Fig. 5 Effect of annual ring width on slenderness (**a**), flexibility (**b**), and Runkel (**c**) ratios

was related to the class A with a value of 48.79. As shown in Fig. 5b, the average annual ring width has no direct or inverse relationship with the flexibility ratio. The highest flexibility ratio was related to the class D with a value of 66.1, and the lowest was related to the class E with a value of 65.19. As shown in Fig. 5c, Runkel ratio and the width of the annual ring were inversely related. Runkel ratio was 0.5625 in the class A and 0.5068 in the class E.

Increases in fiber length and decreases in fiber diameter lead to increased fiber slenderness ratio. Fiber diameter indicates its flexibility in the pulp refining process. The thicker the fibers are, the higher their impact strength will be, and the greater strength they will exhibit. Slenderness ratio (the ratio of fiber length to fiber diameter) and the other derived ratios have essential effects on the paper's strength (Kellogg and Thykeson 1975). Slenderness ratios vary from 20 to 150. The higher this ratio is, the longer and slenderer the fibers will be. This research showed that fiber length and diameter simultaneously increased with increases in tree-ring width. Consequently, we can conclude that the positive effect of increased fiber length canceled out the negative effect of increased fiber diameter so that the tree-ring widths had no significant effect on the slenderness ratio. The ratio of fiber length to fiber width also is one of the essential properties of fibers as it indicates the strength of fibers and hence their capabilities for various applications (Rowell et al. 1997). The fiber length ratio to its diameter significantly influences the tensile and flexural properties of agro-based fiberboard (Lee et al. 2006). Studies have shown that fiber length (Kellogg and Thykeson 1975; Matolcsy 1975) and fiber slenderness ratio (Horn 1974; Watson and Dadswell 1961; Seth and Page 1988; Oluwadare and Ashimiyu 2007) influence the mechanical properties of paper, especially tearing strength.

Increases in tree-ring width did not significantly change flexibility ratios. The diameter of the cell cavity and also fiber length simultaneously increase with increases in tree-ring width. Therefore, the non-significant relationship between increased tree-ring width and flexibility ratios is not unexpected. The increases in diameter of the cell cavity offset the decreases in fiber diameter. The higher the flexibility ratio is, the higher the bursting and tearing strengths and folding endurance of the paper will be (Oluwadare and Ashimiyu 2007).

Increases in tree-ring width significantly changed Runkel ratio at the 0.01 level: Runkel ratio declined with increases in tree-ring width. Runkel ratio increases with increases in fiber wall thickness. Since Runkel ratio in this research was 0.5323, we can conclude that the fibers of the eastern poplar trees enjoyed a high specific surface area due to the large diameter of the cell cavity and the suitable Runkel ratio. Such fibers with suitable Runkel ratio and high specific surface areas have desirable bonding capability. Hence it is expected that the paper produced from them will be compact and have a smooth surface and good folding endurance and tensile, and bursting strength (Tutus et al. 2010). The higher Runkel ratio is, the higher the tearing strength of the paper will be (Oluwadare and Ashimiyu 2007).

3.5 Correlation between morphological properties with annual ring width using the Pearson test

The results of Pearson correlation coefficients in determining the relationships between tree-ring widths and fiber morphological properties showed that there were significantly positive correlations between tree-ring widths and fiber length and diameter and diameter of cell cavity at the 0.01 significance level (Table 5). In contrast, there was a significantly negative correlation between tree-ring widths and cell wall thickness at the 0.05 significance level. There was also a significantly negative correlation between the tree-ring widths and Runkel ratio. Increases in tree-ring width significantly decreased Runkel ratio. However, there was no significant relationship between tree-ring widths and slenderness ratio

Table 5 Investigation of the correlation between morphological and chemical properties with annual ring width using the Pearson test

Model	Sig	Adjusted R Square	Std/ error of the Estimate	Durbin–Watson	Regression equation
Fiber length**	0.008	0.212	82.56	2.426	y = 1289.3x + 145.31
Fiber diameter**	0.0011	0.416	2.241	1.763	y = 15.945x + 13.036
Cell cavity diameter**	0.001	0.268	2.134	2.223	y = 13.55x + 6.0661
Cell wall thickness*	0.038	0.131	0.3561	1.622	y = -3.002x + 7.103
Slenderness ratio^{ns}	0.136	0.039	5.441	2.112	y = -20.251x + 63.642
Flexibility ratio^{ns}	0.950	-0.036	9.393	2.209	y = 0.2419x + 69.33
Runkel ratio**	0.0012	0.457	0.0541	2.259	y = -0.2555x + 0.747

ns non-significant

*Significant at the 95% level of probability

**Significant at the 99% level of probability or between tree-ring widths and flexibility ratio according to Pearson correlation coefficients.

Since most poplar hybrids are fast-growing, it is essential to know the effect of growth rate on the fiber length. As shown in Table 5, there is a significantly positive correlation between fiber length and width of annual ring. Van Buijtenen (1969) also showed a significantly positive correlation between fiber length and annual ring width in *Populus tremuloides*. Similar results were obtained by Cech et al. (1960) and Koubaa et al. (1998). Pliura et al. (2007) showed that poplars that grew in suitable sites and had a wider annual ring had longer fiber length.

3.6 Radial variation of morphological properties

3.6.1 Radial variation of fiber length and diameter, cell cavity diameter, and cell wall thickness from the pith to the bark

According to the sampling method, it was possible to study the morphological properties changes of wood fibers in the trees' cross-section from the pith to the bark. The average fiber length in samples I, II, and III was 1207.87, 1227.67, and 1256.16 µm, respectively. The cell cavity diameter decreased from the pith to the bark. The average diameter of the cell cavity near the pith, in the middle, and near the bark was 17.66, 17.49, and 17.28 µm, respectively. The average thickness of cell wall near the pith was lower than near the bark. The average cell wall thickness in samples I, II, and III was 4.49, 4.57, and 4.67 µm, respectively.

As shown in Fig. 6, the length of the fibers increases from the pith to the bark. DeBell et al. (2002) also showed that in the case of young poplar trees, the fiber length increases from the pith to the bark. In addition, Koubaa et al. (1998) examined the changes in fiber length in poplar clones and showed that fiber length increases significantly from the pith to the bark. Significant changes in fiber length from the pith to the bark have been reported repeatedly (Huda et al. 2011; Ištok et al. 2017). Chen et al. (2016) also reported that fiber width, and fiber wall thickness of Norway spruce increase from the pith to the bark. Koubaa et al. (1998) reported that the average fiber length for poplar hybrids increases significantly from the pith to the bark. Chauhan et al. 2001 also showed that the same is true for *P. deltoides*. Wen (2003) examined the radial variation of morphological characteristics for seven poplar clones and showed that fiber length and fiber diameter increase from the pith to the bark. Salvo et al. (2016) reported that the diameter of the cell cavity in *Eucalyptus nitens* increases and the thickness of the cell wall first increases and then decreases from the pith to the bark.

3.6.2 Radial variation of slenderness, flexibility, and Runkel ratios from the pith to the bark

The slenderness ratio decreased from the pith to the bark. The highest slenderness ratio was related to the area close to the pith (I) with a value of 47.31, and the lowest was related to the area close to the bark (III) with a value of 46.11 (Fig. 7a). There was no direct or inverse relationship between flexibility ratio and annual ring width, and the changes were negligible. The highest flexibility ratio was related to the area close to the pith (I) with a value of 65.68%, and the lowest was related to the middle area (II) with a value of 65.54% (Fig. 7b). Runkel ratio decreased

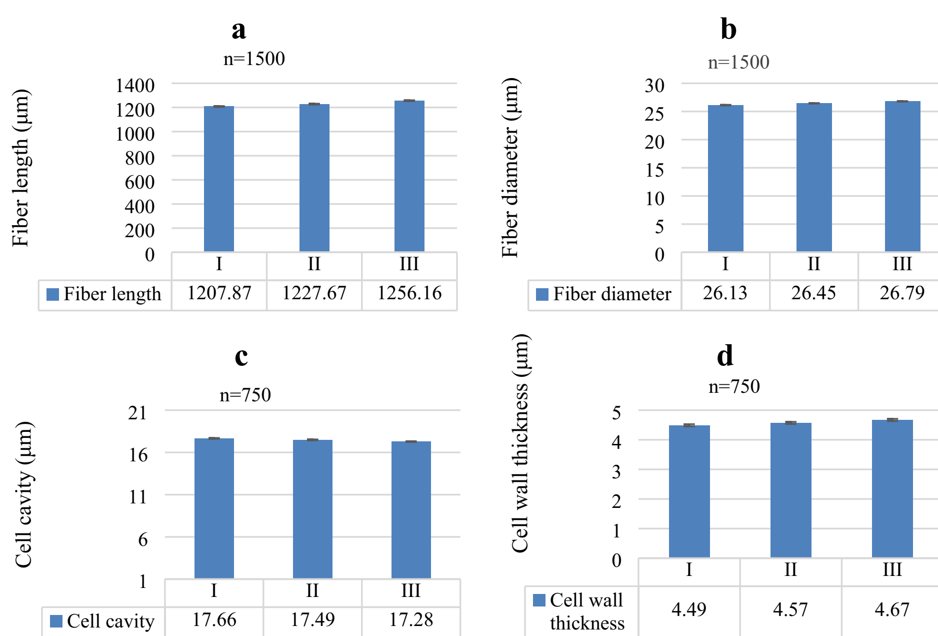

Fig. 6 Fiber length (**a**) and diameter (**b**), cell cavity diameter (**c**), and cell wall thickness (**d**) changes from the pith to the bark

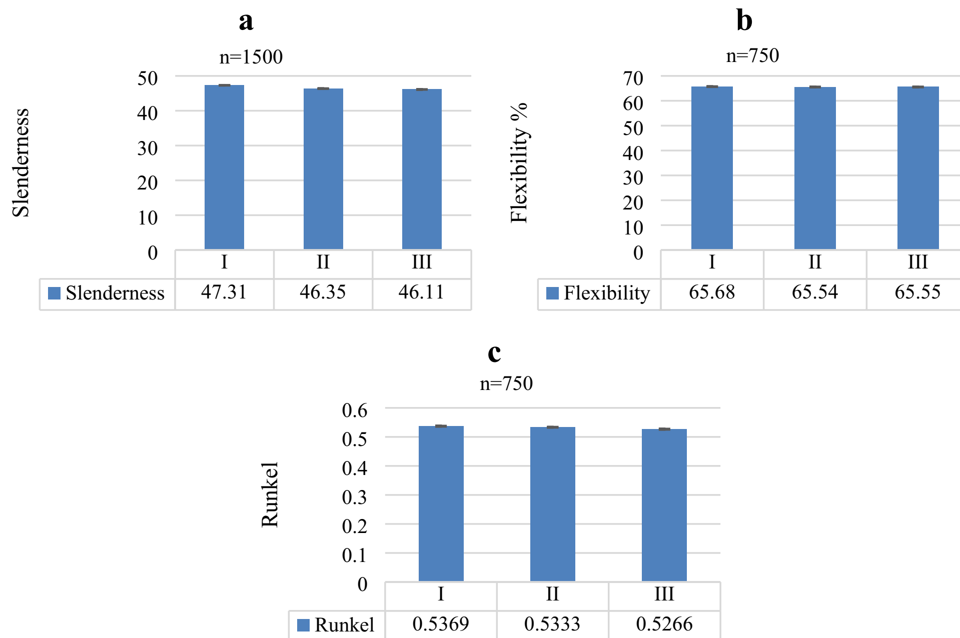

Fig. 7 Slenderness (**a**), flexibility (**b**), and Runkel ratios (**c**) changes from the pith to the bark

from the pith to the bark. The highest Runkel ratio was related to the area close to the pith (I) with a value of 0.5369, and the lowest was related to the area close to the bark (III) with a value of 0.5266 (Fig. 7c).

Ištok et al. (2017) showed that in *Pupolus alba*, fiber length, cell wall thickness, and cell cavity change significantly from the pith to the bark, which can cause changes in slenderness, flexibility, and Runkel ratios. Hizal and Erdin (2016) studied *Alnus glutinosa L. Gaertner* trees. They reported that fiber length, fiber diameter, and cell wall thickness increase from the pith to the bark, and cell cavity diameter decreases, leading to changes in slenderness, flexibility, and Runkel ratios. In other species, such as *Acacia mangium*, it has been reported that fiber length, fiber diameter, and cell wall thickness increase from the pith to the bark, and cell cavity diameter decreases. Zha et al. (2005) showed that in poplar clones from the pith to the bark, the fibers' dimensions change significantly, which affects the fiber ratios. Similar results were reported by Pande and Dhiman (2012) and Pande (2012). Anoop et al. (2014) showed wall thickness, diameter, slenderness, and Runkel ratios of tracheid of tropical pines increase, and the flexibility ratio of them decreases, from the pith to the bark.

3.7 Chemical properties

The mean cellulose, lignin, extractive matter, and ash contents of the studied eastern poplar trees are reported in Table 6.

Ninety samples were studied to determine the chemical properties of the wood fibers. The results obtained using Eq. (5) demonstrated that the eastern poplar trees in the study region contained 0.910% ash. The obtained extractive matter content of the studied trees employing Eq. 6 was 1.203%. The TAPPI T 222 om-88 and TAPPI T 264 om-88 standards were used for lignin and cellulose purification. Using Eqs. 8 and 7, the determined lignin and cellulose contents were 50.473 and 27.813%, respectively.

Table 6 Chemical properties of wood fibers in the study area

Properties	Number of measured samples trees × samples (I, II and III)	Mean ± SD
Ash %	30×3	0.969 ± 0.08
Extractives %	30×3	1.236 ± 0.19
Cellulose %	30×3	50.428 ± 1.41
Lignin %	30×3	27.312 ± 1.87

3.8 The relationship between chemical properties with the width of the annual ring

Except for cellulose, there was no definite trend for other chemical properties with increasing width of the annual ring. The highest amount of the ash was related to the class D with a value of 1.039%, and the lowest was related to the class E with a value of 0.884% (Fig. 8a). The highest extractives content was related to the class C with a value of 1.303%, and the lowest was related to the class B with a value of 1.119% (Fig. 8b). It was observed that the wider ring had higher cellulose content. The lowest amount of cellulose was related to the class A with a value of 48.758%, and the highest was related to the class E with a value of 52.613 (Fig. 8c). The lowest amount of lignin was related to the

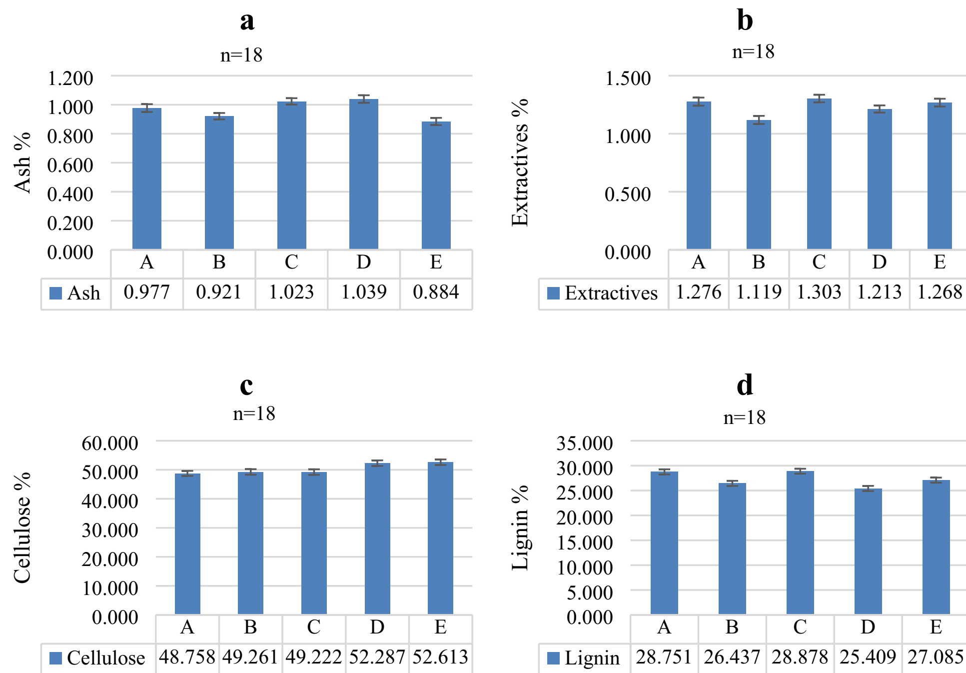

Fig. 8 Effect of annual ring width on the ash, extractives, cellulose, and lignin content

class D with a value of 25.409%, and the highest was related to the class C with a value of 28.878 (Fig. 8d).

3.9 The effect of chemical properties of wood on its utilization

In this research, increases in tree-ring width improved wood cellulose content at the 0.05 level. However, the lignin, ash, and extractive matter contents did not change significantly with increases in tree-ring width. The high cellulose content and the low ash and extractives contents in the studied eastern poplar trees attract greater interest from industries, especially the paper industry. The extractive matter content also influences the mechanical properties of wood and its natural endurance. It can be substantially important in the paper pulp industry, in the manufacture of wood-plastic products and the manufacturing processes of cellulose products (Ververis et al. 2004). Further, the lignin, ash, and extractive matter contents have technical, economic, and environmental effects during paper production. The efficiency of paper pulp, transparency of the paper, and the efficiency of biofuel production are influenced by wood cellulose content. Transparency of the paper produced varies depending on the chemicals used, and paper's whiteness level depends on wood cellulose and lignin contents (Ebrahimipour et al. 2011). Apart from morphological properties, the chemical compounds in the raw material (the lignin and cellulose contents) influence the strength of paper and the direct relationship between the tensile strength of paper, and the cellulose content of the raw material, and the undesirability of lignin in the paper manufacturing process can be considered the most prominent result of the research on this subject (Madakadze et al. 1999). High cellulose contents increase paper pulp efficiency and the strengths of the manufactured paper. Conversely, reduced cellulose contents negatively influence both paper efficiency and the strengths of the paper. Lignin is considered an undesirable substance in paper pulp industries, and hence delignification, a costly operation, is carried out during paper production. Consequently, the higher the cellulose content is, and the lower the lignin, ash, and extractive matter contents are, the more desirable the wood will be for paper production (Ebrahimipour et al. 2011). The lower the lignin content of the raw material is, the easier the pulp processing and bleaching of fiber will be, and the less chemicals, thermal energy, and time will be required (Gominho et al. 2001). Moreover, lignin connects fiber fibrils, reduces fiber elasticity, and increases the brittleness of fiber. Various chemical treatments are applied to lignin to reduce moisture absorption and increase fiber strength. Lignin removal increases fiber cellulose content and increases its tensile strength (Alwar et al. 2009).

3.10 The correlation between chemical properties and annual ring width

Pearson correlation coefficients demonstrated that there were no significant correlations between tree-ring widths and percentage lignin content, between tree-ring widths and percentage ash content, and between tree-ring widths and extractive matter content. In other words, changes in tree-ring width did not influence lignin, ash, or extractive matter

Table 7 Investigation of the correlation between morphological and chemical properties with annual ring width using the Pearson test

Model	Sig	Adjusted R Square	Std/error of the estimate	Durbin–Watson	Regression equation
Ash^{ns}	0.306	0.003	0.3021	2.252	y = − 0.1296x + 1.7289
Extractives^{ns}	0.864	− 0.035	0.1156	2.379	y = − 0.0081x + 1.2602
Cellulose*	0.015	0.163	0.6006	1.962	y = 1.0736x + 47.208
Lignin^{ns}	0.088	0.068	1.102	1.672	y = − 0.4361x + 28.621

ns non-significant

*Significant at the 95% level of probability

**Significant at the 99% level of probability

percentages. However, there was a significantly positive correlation between tree-ring widths and percentage cellulose at the 95% confidence interval (Table 7).

3.11 Radial variation of the chemical compounds from the pith to the bark

The highest amount of ash with a value of 1.148% was related to the area close to the pith (I), and the lowest with a value of 0.831%, was related to the area close to the bark (III) (Fig. 9a). Extractives from the pith (I) to the bark (III) decreased. The highest extractives content was related to the area near the pith (I) with a value of 1,630%, and the lowest was related to the area close to the bark with a value of 0.872% (Fig. 9b). The highest amount of cellulose was observed close to the bark (III) with a value of 52.036%, and the lowest was observed close to the pith (I) with a value of 49.200% (Fig. 9c). The amount of lignin from the pith to the bark decreased with a low slope. The highest amount of lignin was near the pith with a value of 28.827%, and the lowest was near the bark with a value of 26.714% (Fig. 9d).

Cobas et al. (2013) studied the radial variation of chemical properties of poplar and willow. They showed in the poplar trees, cellulose and hemicellulose increased and extractives decreased from the pith to the bark, and lignin did not change significantly. In the willow case, the extractives from the pith to the bark decreased, and hemicellulose increased, but the changes of cellulose and lignin were not significant. Further, Jahan et al. (2019) studied the radial variation in the chemical properties of *Acacia auriculiformis*. Their results showed that lignin and extractives reduced from the pith to the bark, and hemicellulose and cellulose increased. These results are in line with the results described in the present study.

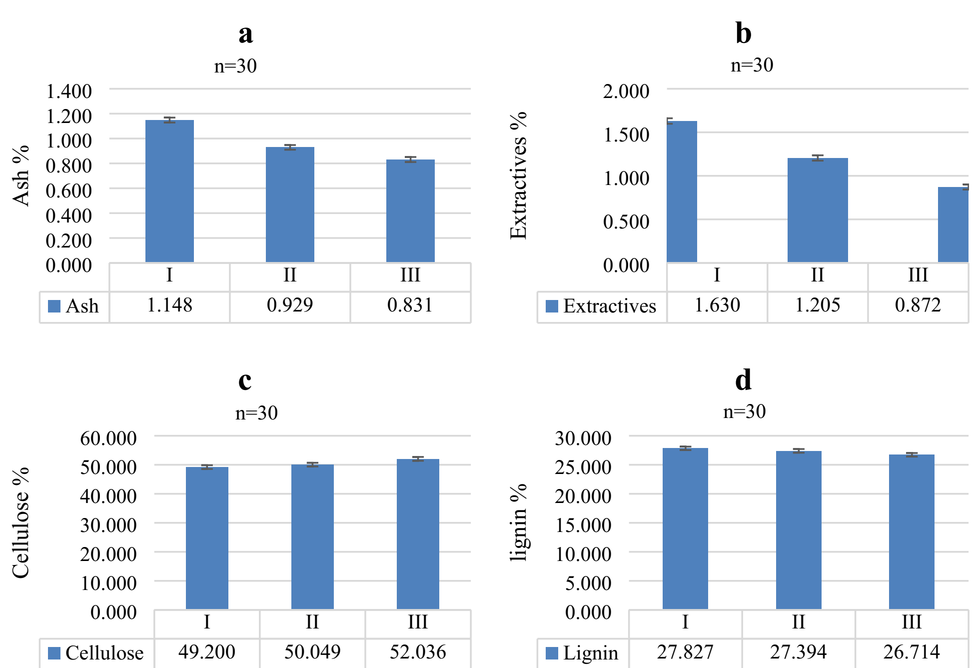

Fig. 9 Radial variation of ash (**a**), extractives (**b**), cellulose (**c**), and lignin (**d**) content from the pith to the bark

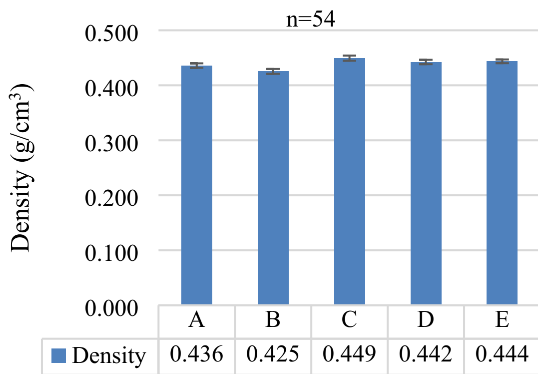

Fig. 10 Effect of annual ring width on the wood density

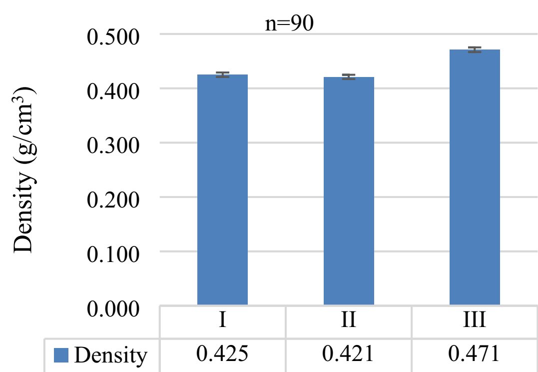

Fig. 11 Density changes from the pith to the bark

3.12 The relationship of wood density with the annual ring width

As shown in Fig. 10, the density increased with increasing width of the annual ring, but the changes were not always linear. Linear regression model was $y = 0.0033x + 0.4295$ and R-squared was 0.31337. The highest density was related to the class C with a value of 0.449 g/cm^3. The lowest density was related to the class B with a value of 0.425 g/cm^3.

The study of density changes is critical because it affects many physical and mechanical properties of wood and its economic efficiency (Miranda et al. 2001). DeBell et al. (2002) studied the effect of poplar annual ring width on the wood density and their results showed no significant effect between annual ring width and wood density.

3.13 Radial variation of wood density from the pith to the bark

As shown in Fig. 11, from the pith to the middle, the density decreased and then increased to the bark radially with a low slope. The average density in the region I was 0.425 g/cm^3, and in the region II it was 0.421 g/cm^3. However, the highest density was in the region III with a value of 0.471 g/cm^3.

DeBell et al. (2002) showed that the wood density increases from the pith to the bark in the studied poplar trees. Further, Pande and Dhiman (2011) and Pande (2011) reported that the density increases from the pith to the bark in *P. deltoides* clones. Cobas et al. (2013) showed that the wood density increases from the pith to the bark in poplar and willow. Chen et al. (2014) demonstrated that in the case of Norway spruce, the density from the pith to the bark first decreases slightly and then increases, which is in line with the results of the present study.

4 Conclusion

This study of the morphological properties of eastern poplar wood fibers showed that this wood can be used in pulp and paper industries. Increases in tree-ring width of the eastern poplar trees caused a relative increase in fiber length and diameter of cell cavity.

Results on the effects of tree-ring widths on chemical properties of eastern poplar wood indicated that increases in tree-ring width improve cellulose content. It can be concluded that fibers from trees with wider growth rings are more suitable for paper manufacturing industry and will increase the efficiency of paper production. Furthermore, the results showed that increasing the width of annual ring increases wood density. In fact, it can be interpreted that increasing annual ring width, increases the yield in the paper industry. Further, the study of radial variation in morphological and chemical characteristics showed that the cellulose content increases from the pith to the bark and the morphological properties of the fibers relatively improve along this direction. For this reason, wood harvesting is recommended at older ages to achieve better raw material quality.

Finally, it can be concluded that the optimization of growing conditions and increased growth rate of eastern poplar trees, which increases tree-ring widths, cause a relative improvement in wood morphological and chemical properties and improve the wood quality for manufacturing of secondary products such as pulp, paper, and fiberboard, and increase the application scope of the wood.

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