Potential of Pulp Production from Whole-tree Wood of *Betula platyphylla* Roth. Based on Wood Characteristics

Xiping Zhao,[a] Pingping Guo,[a,]* Haixin Peng,[b] Penghui Zhao,[a] Yongqiang Yang,[a] and Zhaolin Zhang [a]

To ascertain the possibility of using branchwood, trunkwood, and rootwood of *Betula platyphylla* Roth. in papermaking, this study investigated tissue proportion, fiber features, and major chemical components in whole-tree wood of the tree species. Analysis of variance (ANOVA) indicated that the rootwood had a significantly lower density and vessel proportion, higher ray proportion, wider lumen, and thicker wall of fiber than the trunkwood and branchwood ($p < 0.05$). The branchwood had a significantly shorter fiber and smaller length/width than the trunkwood and rootwood ($p < 0.05$). The trunkwood had significantly longer and narrower fibers with thinner wall and higher cellulose, but lower hemicelluloses than the branchwood and rootwood ($p < 0.05$). The study concluded that the trunkwood of *B. platyphylla* was suitable for producing good paper, while the branchwood and rootwood met the basic requirements of papermaking and could be used to produce low-grade paper.

Keywords: Betula platyphylla (L) Roth; Chemical component; Fiber feature; Tissue proportion; Whole-tree format

*Contact information: a: College of Forestry, Henan University of Science and Technology, 263 Kaiyuan Avenue, Luoyang 471023, P.R. China; b: Department of Biosystems Engineering, College of Engineering, Auburn University, Auburn, AL, 36849, USA; *Corresponding author: guopingping_1982@126.com*

INTRODUCTION

Birch, a tree species with wide adaptability, fast growth, and strong germination ability, is widely distributed in the cold temperate zone and Northern Hemisphere temperature zone (Zhang *et al*. 2002; Osumi 2005). It is a pioneer component of secondary vegetation and forms a secondary distribution center in northeastern China (Guan 1998). Birch is widely used in construction, veneer, and other industries because of its straight trunk and excellent wood quality, such as suitably long fibers, large ratio of fiber length to width (Tang *et al*. 2018), low lignin content (Yao 1991), good mechanical properties (Wang *et al*. 2001), *etc*. Also, birch wood has been widely used in papermaking in many countries (Tilli *et al*. 2001; Sippola *et al.* 2016). It is reported that birch pulp can be produced through the sulfate process, which can produce many kinds of paper, such as advanced cultural paper, cardboard, and special paper (Borrega *et al*. 2018). In China, the application of birch in the pulp and paper industry has gained mature technology (Yao 1991; Peng *et al*. 1994; Song *et al*. 2014; Hou *et al*. 2016). A small amount (about 10%) of birch pulp is often used for industrial packaging paper production, and more than 50% of bleached birch pulp is used to produce offset paper (Wang 2003).

With the increasing shortage of long-fiber coniferous materials, the utilization of suitably long-fiber, broad-leaved wood such as birch has attracted extensive attention from the paper industry all over the world. Based on the sources of raw materials, wood fiber morphology, and chemical component, forestry experts believe that birch is a raw material with broad prospects in the paper industry (Tilli *et al*. 2001). For China, where timber resources are scarce, birch pulpwood is in high demand. Meanwhile, most branches and roots of birch are abandoned when pulpwood harvesting operations concentrate on trunks. One reason is that branches and roots play important role in the process of soil maturation and the maintenance of soil fertility (Zhang *et al*. 1991; Palviainen and Finér 2012). Another reason is the fact that the cost of cleaning and transportation is high. According to statistics, the rootwood and branchwood account for about 35% of the whole tree (Nilsson and Wernius 1976). The development of science and technology provides powerful tools for collecting branches and roots. However, the utilization of them is still very limited due to the lack of full understanding of their wood characteristics (Leitch and Miller 2017).

A previous study has shown that the branch and root of birch tree have smaller and more numerous vessels than its trunk (Zhao 2015). Spatial variation of grouping type and pore shape of vessels are varied among root, trunk, and branch (Zhao 2016). Though these studies are helpful for processing and production of pulp, they may not be enough for highly efficient utilization of rootwood and branchwood. Therefore, the objectives of this study were to determine the wood tissue proportion, density, fiber features, and major chemical component (lignin, cellulose, and hemicellulose), and to compare the wood characteristics of the root, branch, and trunk.

EXPERIMENTAL

Materials

Three birch trees (*Betula platyphylla* (L) Roth) were chosen from the Maoershan Forest Ecosystem Research Station in Heilongjiang Province, northeastern China (127°30'–34'E, 45°20'–25'N, 300 m elevation). One branch was chosen from the upper, middle, and lower canopy of each tree. Three roots were excavated from each tree. The characteristics of sample trees are summarized in Table 1. Two disc samples (5 cm thick) were cut from each trunk (at abreast height1.3m), and each branch and root just above the basal swelling to avoid abnormality. Further descriptions of sites, sampling, and processing procedures were described in the literature (Zhao 2015).

Table 1. Characteristics of the Sampled Trees

Tree Height(m)	Tree diameter at breast height (cm)	Tree Age (years)	Branch Length(m)	Branch Diameter (cm)	Root Diameter (cm)
20.2 ± 1.6	25.8 ± 3.1	55.1 ± 1.6	5.9±2.1	8.7±4.6	6.3±2.7

Methods

Because the boundary between heartwood and sapwood of birch cannot be assessed visually on cross-sections through the observation of color changes, wood characteristics were measured without discriminating heartwood and sapwood in this study.

Wood density

The wood density was determined according to the Chinese national standard GB/T1933-2009(2009). For each disc sample, three 2 cm×2 cm×2cm wood blocks were cut, polished, and soaked in distilled water until the specimen had sunk completely. The saturated water volume of wood block was measured using the drainage method. The material was then air-dried, oven-dried, and weighed. The volume of air-dried wood and absolute-dried wood were measured by wax sealing method. Then air-dry density, absolute dry density, and basic density were calculated based on the measured quality and volume values.

Fiber morphological and anatomic properties

A matchstick-sized wood strip was cut from the disc samples for the maceration process. The wood strip was macerated in a 1:1 10% chromic acid:10% nitric acid solution at 60 °C for several h (Jeffrey 1917). The macerated material was rinsed and placed on microscopic slides for taking photographs using a digital microscope (Mshot-MD50, Micro-shot Technology Limited, Guangzhou, China). The fiber size was measured with an image computer analysis system (TDY-5.2, Beijing Tian Di Yu Technology Co. Ltd., Beijing, China). Tissue proportion was performed on the digital images of wood transverse section, which were reexamined from the previous work (Zhao 2015). Using vessel proportion as an example, "threshold and binary segmentation" was executed to separate cell lumens from their walls. Then, all fiber and ray lumens were filtered. The reserved vessel lumens were dilated a cell wall width. Finally, vessel proportion was calculated from the ratio of sum of vessel grain areas to the whole image area. Certainly, the similar approach can be used in the same image to measuring the fiber proportion and ray proportion (Yu *et al*. 2009). At least 60 measurements were performed for each sample per parameter.

Chemical component

The chemical component of the wood was determined using wet chemistry analysis according to the Chinese national standard GB/T 5889-86 (1986). Little wood strips were cut from the disc samples, milled down to chips that were 3 mm in size, and then ground to 40-mesh sizes. The moisture content of 40 to 60 mesh samples was calculated according to the weight lost when it was dried to constant weight at 102 ± 3 °C.

The 40 to 60 mesh samples with known weight (G_0) were extracted first by acetone, and then hydrolyzed by 72% (w/w) sulfuric acid. The solution was distilled and filtered. The residue was dried and weighed (G_1) to calculate the lignin content (W_1) based on Eq. 1.

$$W_1 = \frac{G_1}{G_0} \times 100 \tag{1}$$

The 40-60 mesh samples with known weight (G_2) were extracted first by acetone, and then hydrolyzed by NaOH solution (20 g/L). The solution was then distilled and filtered. The residue was dried and weighed (G_3). Lost weight (G_4) was the difference in the values between $G_2$and G_4. The residue was extracted by 72% (w/w) sulfuric acid, then distilled and filtered. The final residue was dried and weighed (G_5) to calculate the cellulose (W_2) and hemicellulose (W_3) based on Eqs. 2 and 3.

$$W_2 = \frac{G_3 - G_5}{G_2} \times 100 \quad (2)$$

$$W_3 = \frac{G_4 - \left(W_1 \times G_2 - G_5\right)}{G_2} \times 100 \quad (3)$$

The chemical analysis was repeated three times.

Statistical analysis

Differences among the branchwood, trunkwood, and rootwood were evaluated by analyses of variance (ANOVA), followed by the LSD (least significant difference) test. Multiple comparisons were performed using the IBM SPSS Statistics software (Version 24.0, International Business Machines Corporation, Armonk, United States) with the significance assessed at $p < 0.05$. Correlations among wood densities and fiber features were calculated by Pearson's correlation analysis program in the SPSS Statistics.

RESULTS AND DISCUSSION

Anatomic Properties

The xylem of birch mainly consists of fibers, vessels, and rays with axial parenchyma underdeveloped (Fig. 1A). The fiber proportion of birch wood was very high (more than 60%), especially branchwood, whose fiber proportion was as high as 62.9% (Table 2). High fiber proportion means high pulp yield (Douglas and Floyd 1994). Obviously, the high content of fiber cells in birch wood means that the content of parenchyma cells (vessels and rays) is lower. The presence of parenchyma cells is not conducive to the refining of pulp (Li and He 2009). Redundant parenchyma cells increase the sticking of rollers in the paper machine, leading to increased frequency of web breaks (Speranza *et al*. 2009). In particular, vessel elements, which have thin cell walls and large cell diameters (Fig. 1B), can lead to poor mechanical pulp quality (Zha *et al*. 2007). Thus, a low proportion of parenchyma cells was judged to be an advantageous factor for birch wood as a high-quality raw material for papermaking.

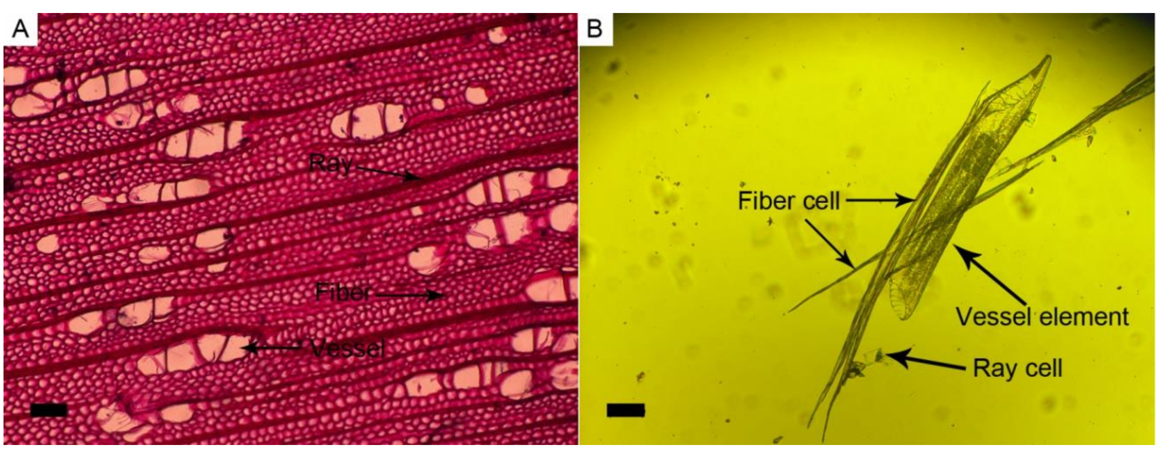

Fig. 1. Anatomical features in the root wood of *B*. *platyphylla*. A: transverse section of xylem; B: separated wood elements; scale bar is 200 μm

Table 2. Multiple Comparison of the Tissue Proportions in the Branch, Root, and Trunk from *B. platyphylla*

Position	Fiber proportion (%)	Vessel Proportion (%)	Ray Proportion (%)
Trunk	61.9±5.1[a]	25.0±1.2[a]	13.1±5.8[b]
Branch	62.9±4.1[a]	24.6±0.7[a]	12.5±4.1[b]
Root	61.5±3.0[a]	20.0±2.3[b]	18.5±1.9[a]

Means ± standard deviation with different letters within a column were significant at p<0.05.

Vessel proportion and ray proportion of rootwood were significantly different from trunkwood and branchwood at the 5% level. Rootwood had the largest ray proportion (18.5%). High proportions of rays were found in rootwood of other tree species (Stokke and Manwiller 1994). Ray parenchyma cells functioned for water conduction, support, and horizontal transport and storage of nutrients (Pfautsch *et al*. 2015). Root need a lot of rays to complete because root played important roles for the acquisition of nutrients and water (Shibata and Sugimoto 2019). Compared with branchwood and trunkwood, the rootwood had less vessel proportion (20%). For papermaking, wood with more vessels had more paper pores, which had some adverse effects on paper properties (Law and Lapointe 1983).

Fiber Morphological Properties

The wood fibers of birch were longer than 400 μm (Table 3). Length is one of the basic characteristics for fiber morphology, and it is closely related to the comprehensive strength of paper (Seth 1995; El-Hosseiny and Anderson 1999; Larsson *et al*. 2018). Longer fibers (more than 400 μm) can provide larger bonding areas, better stress distribution, and produce more bonding between fibers, which makes the fiber network stronger (Wang 2014). Tensile strength, tear strength, and burst resistance were improved with the increase of fiber length (Liu and Dong 2004). But it would not benefit tensile strength once a certain fiber length (about 3 mm) was approached (Broderick *et al*. 1996).

Table 3. Multiple Comparison of the Fiber Features in the Branch, Root and Trunk from *B. platyphylla*

Position	Fiber Length (μm)	Fiber Width (μm)	Lumen Diameter (μm)	Double Wall Thickness	Length/ Width	Wall/ Lumen
Stem	940.7±20.6[a]	24.9±0.3[c]	18.1±0.4[b]	5.9±1.2[b]	39.0±0.6[a]	0.33±0.2[b]
Branch	575.5±17.6[c]	34.1±0.7[b]	17.6±1.0[b]	6.2±1.3[b]	16.9±0.2[c]	0.4±0.0[a]
Root	884.2±18.4[b]	39.7±0.9[a]	27.9±0.7[a]	11.8±0.5[a]	22.8±0.4[b]	0.4±0.0[a]

Means ± standard deviation with different letters within a column were significant at p<0.05

Generally, short fibers with an average length of less than 400 μm are not suitable for papermaking (Wang 1998). The trunkwood had long (940.7 μm) and narrow (24.9 μm) fibers, which met the intermediate standard for fibers (910 mm to 1600 mm) stipulated by the International Society of Wood Anatomy (Smook 1992). However, the wood fibers of roots and branches were all significantly shorter than that of the trunk. The branchwood had the shortest fibers (575.5 μm), and although they were more than 400 μm long, they could only be used for low-grade pulp and paper, or various blends for the production of pulp. Statistically significant differences were found for the fiber lumen diameter and wall thickness, but not for the wall/lumen between the different positions. Furthermore, the smaller wall-to-lumen ratio of fibers not only for trunk, but also for branchwood and rootwood meant that better flatness of fibers could give better bonding strength to paper.

Wood Density

The results showed that the basic density and air-dried density of trunk was 0.46g/cm^3 and 0.38g/cm^3, respectively (Table 4), which was similar to previous studies (Li *et al*. 1995). The wood density of birch branches was almost the same as that of trunks. The density of rootwood was much lower than that of trunkwood, and there was a significant difference between them at the 5% level. Low-density wood was bound to have low hardness, which reduced chipping energy consumption and quality of pulp obtained by uniform pulping soaked in chemicals (Anupam *et al*. 2016). However, specific wood consumption was higher for lower density woods (Colodette *et al*. 2004). The pulp from low-density wood also has smaller fiber coarseness, better interweaving performance, and higher paper strength (McDonough *et al.* 2012). Based on the parameters of wood density, rootwood was more suitable for mechanical pulping than trunkwood and branchwood, regardless of wood consumption.

Wood density is closely related to the fibers, which are the main cells that make up wood (Lu *et al*. 2018). The correlation analysis on wood density and fiber features for the birch tree showed that wood density was negatively correlated with fiber length and length/width, and positively correlated with other fiber features (Table 5). Among them, the correlation between absolute dry density and all measured fiber features reached significant levels (p<0.01), which suggested the possibility of fast and simple sift for pulp based on absolute dry density of birch wood.

Table 4. Multiple Comparison of the Wood Density of the Branch, Root, and Trunk from *B*. *platyphylla*

Position	Basic Density(g/cm^3)	Air-driedDensity(g/cm^3)	Absolute DriedDensity(g/cm^3)
Trunk	0.46±0.04^a	0.58±0.06^a	0.55±0.03^a
Branch	0.48±0.03^a	0.57±0.04^a	0.51±0.01^a
Root	0.32±0.01^b	0.38±0.01^b	0.36±0.01^b

Means ± standard deviation with different letters within a column were significant at p<0.05.

Table 5. Correlation Analysis on Wood Density and Fiber Features in Wood of *B. platyphylla*

Wood Density	Fiber Length (μm)	Fiber Width (μm)	Lumen Diameter (μm)	Double Wall Thickness	Length/ Width	Wall/ Lumen
Basic	-0.951**	0.833*	0.954**	0.762	-0.947**	0.723
Air-dried	-0.954**	0.849*	0.962**	0.782	-0.959**	0.742
Absolute Dried	-0.823*	0.985**	0.975**	0.960**	-0.969**	0.933**

*Significant at p<0.05, **Significant at p<0.01

Chemical Components

The results of chemical composition determination of trunkwood were similar to those of Li *et al* (1995). The holocellulose content of trunkwood was slightly higher than that measured by Bian *et al*. (2010). The content of cellulose in the trunkwood was higher (61%) and that of lignin was lower (20.4%) (Table 6), which was beneficial to pulping (Koljonen *et al*. 2004). The cellulose content of branches and roots were both about 50%. There was no significant difference between them, but they were lower than that of trunks.

The variation of hemicellulose content among different positions was just the opposite. The trunkwood had the lowest hemicellulose content (17.3%). Hemicellulose can be defined as a cell wall polysaccharide (structural carbohydrates) but likely acted as additional carbon reserves similar to starch (nonstructural carbohydrates) in living cells during growth (Hoch 2007). Schädel *et al* (2009) had reported hemicelluloses appeared to respond in branch sapwood of *Carpinus* to the enhanced carbon demand during bud break. Branches and roots usually had more sapwood percentage than trunks, which might be the reason for the low hemicellulose content in the trunkwood. Different positions of the *B. platyphylla* tree showed no variations in the cellulose and hemicellulose content. The differences of lignin between different tree positions were also not statistically significant at the 5% level. Judging from the chemical composition alone, birch branches and roots, like trunks, could be used for papermaking. Similar lignin content suggested that it was possible for birch branchwood and rootwood as a substitute for trunkwood to make paper.

Table 6. Multiple Comparison of the Component Content (%) in the Branch, Root, and Trunk from *B. platyphylla*

Position	Cellulose	Hemicellulose	Holocellulose	Lignin
Trunk	61.0±3.8[a]	17.3±4.6[b]	78.3±6.1 [a]	20.4±1.1[a]
Branch	48.7±2.4[b]	30.5±3.9[a]	78.2±3.3 [a]	20.6±1.5[a]
Root	51.0±6.7[b]	29.5±5.5[a]	79.5±6.2 [a]	19.4±1.2[a]

Means ± standard deviation with different letters within a column were significant at $p<0.05$

CONCLUSIONS

1. The wood from branch and root of *B. platyphylla* was much less attractive despite its low density, higher fiber proportions, smaller wall/lumen of fibers, and lower lignin content, which was similar to trunk wood.
2. According to the results, the trunkwood of *B. platyphylla* was suitable for producing paper because of its intermediate fiber size. The wood fibers of branch and root were significantly shorter and narrower than that of trunk, which met the basic requirements of papermaking and could be utilized in various blends for the production of pulp.
3. Whole-tree wood characteristics of *B. platyphylla* were investigated in this study and believed to be potentially attractive for papermaking. The quality testing of pulp and paper from the branchwood, trunkwood, and rootwood of *B. platyphylla* should be carried out in the future.

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