Wood Density, Anatomical Characteristics, and Chemical Components of *Alnus sibirica* Used for Industrial Applications

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Abstract

In this study, wood density, anatomical characteristics, and major chemical components were investigated on branchwood, trunkwood, and rootwood of three *Alnus sibirica* trees grown in Maoershan Mountain, Northeast China. The anatomical structure and composition of xylem within a tree were spatially heterogeneous. At the alpha = 0.05 level, the differences among branchwood, rootwood, and trunkwood were significant in wood density, cell dimensions, extractives, and ash content. The trunkwood was desired as papermaking raw material and structural timber because of its high-quality fibers, cellulose content, and medium density value. Because of its similar density to trunkwood, large-sized branchwood could be used as a substitute for structural materials. The rootwood with low densities and large vessel dimensions was suitable for producing short fiber biocomposite.

Forest coverage in China is low. When the People's Republic of China was founded in 1949, the available area of timber forests was only 13 percent, and external dependence of timber in China is close to 50 percent (Qian 2014). Under the national guidance on forestry development and ecological construction, a remarkable increase in forest coverage was achieved. According to the State Forestry and Grassland Administration, forest coverage in China was 22.96 percent in 2018 (Wang 2019), which is still below the world average of 30.7 percent (Food and Agriculture Organization of the United Nations 2018). With the development of the economy and the improvement of living standards, the structural contradiction between timber supply and demand is very prominent. Therefore, efficient use of existing natural secondary forest and artificial forest timber resources could be one of the most effective measures to solve this contradiction.

Alnus sibirica is a deciduous tree of *Betulaceae*, which is produced in Heilongjiang, Jilin, and Shandong provinces of China. They are also distributed throughout Siberia and the Far East, Korea, and Japan (Cheng 1992, Kim et al. 2016). *A. sibirica* is one of the pioneer tree species in natural forest regeneration and generally exists in pure stands. The roots of *A. sibirica* have abundant rhizobiums that enable them to fix nitrogen (Trappe et al. 1968). Therefore, *A. sibirica* is suitable for afforestation in barren hills where soil fertility is insufficient (Yang et al. 1986, Ye et al. 2005). In addition, the bark of this plant could be a raw material for medicine (Yin et al. 2017). The wood is commonly used for farm tools, matchsticks, and boxes. A small amount of *A. sibirica* wood is used for building, musical instruments, and furniture (Chen et al. 2002). One of the main problems hindering the efficient use of *A. sibirica* wood is that research into its wood properties, various processing methods, and utilization technologies is not complete and systematic. Most of the information regarding the wood species properties was published more than 20 years ago. Wang and Li (1989) compared the wood structure between normal and dwarf *A. sibirica*; Cheng (1992) investigated some anatomical, physical, mechanical, and chemical properties of *A. sibirica* trunkwood; and Hu et al. (1997) studied the anatomical structure of *A. sibirica* rootwood. In addition, Zhu et al. (2006) found that some anatomical

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characteristics varied in trunkwood and rootwood of *A. sibirica*. However, studies on wood density, chemical components, and anatomical characteristics such as fiber dimensions, vessel characteristics, and tissue proportions of branchwood and rootwood, both alone or in comparison with the trunkwood, have not been found and therefore appear limited or unavailable.

Knowledge and understanding of the wood properties and how they vary within *A. sibirica* trees are critical for producers and consumers. In this article, the anatomical structure, cell dimensions, wood density, and main chemical components of *A. sibirica*, a natural secondary forest in northeast China, were studied. Additionally, the differences of wood properties among different positions (root, trunk, and branch) were compared in order to provide basic data for the development and use of whole-tree wood resources of *A. sibirica*.

Materials and Methods

Sample collection and preparation

Rootwood, trunkwood, and branchwood were sampled from three mature and healthy *A. sibirica* trees at the Maoershan Forest Ecosystem Research Station in Heilongjiang Province, northeastern China (127°30′ to 127°34′E, 45°20′ to 45°25′N, 300 m elevation). The characteristics of the sample trees are summarized in Table 1. Three roots and three branches were chosen from each tree. Nine branches with diameters ranging from 6.1 to 11.8 mm and lengths from 2.9 to 3.7 m were used for the study. Branches often bend at the branch collar, where reaction wood is prone to occur (Groover 2016, Kidombo and Dean 2018). Thus, the diameter of the branch was measured about 20 cm above the basal collar. Nine horizontally oriented proximal root logs with diameters ranging from 5.7 to 12.0 cm were excavated from root collars near the soil surface. The sampled trees were somewhat smaller, but a considerable amount of mature wood was included in them. Two disc samples (5 cm thick) were cut from each trunk (at abreast height 1.3 m) and each branch and root above the basal swelling in order to avoid any abnormality. The disc samples were placed directly in the freezer to avoid losing their moisture content.

Three to five small wood blocks with a certain volume (2 by 2 by 2 cm) were obtained from one disc sample for measuring wood density. It was difficult to determine whether these small wood blocks came from heartwood or sapwood because the boundary between them could not be assessed visually directly on disc samples through the observation of color changes.

One 1-cm-wide strip (from pith to bark) was sawed from each disc for wood sectioning. Three matchstick-sized wood strips were cut from each disc sample for the maceration process. The remaining wood fragments from disc samples were used for detecting the chemical component.

Table 1.—The basic characteristics of the sample trees.

No.	Tree age (yr)	Tree diameter at breast height (cm)	Tree height (m)	Under branch height (m)	Crown width (m)
1	46	21.5	12.8	6.9	5.7
2	50	22.2	13.5	7.5	6.8
3	47	20.4	14.2	7.7	6.8

Data collection

Wood density.—Wood density was tested by the Chinese Standard GB/T 1933-2009 (Standardization Administration of the People's Republic of China [SAC] 2009). The green volumes (V_0) of the small wood blocks were measured using the immersion method. The blocks were air-dried in a laboratory to equilibrium moisture content (mean 12%), weighed (G_1), and dipped in a solution of paraffin wax in carbon tetrachloride. Then, the air-dried volume (V_1) was also measured by the immersion method. Second, the air-dried blocks were oven-dried at 103°C ± 2°C until they reached a constant weight (G_2). The ovendried blocks were dipped in the solution of paraffin wax in carbon tetrachloride and then used to determine the ovendried volume (V_2) by the immersion method. The air-dried density (ρ_1), ovendried density (ρ_2), and basic density (ρ_3) were calculated based on Equations 1, 2, and 3.

$$\rho_1 = \frac{G_1}{V_1} \tag{1}$$

$$\rho_2 = \frac{G_2}{V_2} \tag{2}$$

$$\rho_3 = \frac{G_2}{V_0} \tag{3}$$

Anatomical determination.—The 1-cm-wide wood strips were softened by soaking in a solution of 5 percent ethylenediamine. A 15-μm-thick transverse section was made from each strip using a Leica slicing machine, stained with 1 percent safranin in water, and then placed on microscopic slides (Lin 1993). The matchstick-sized wood strips were macerated in a 1:1 10 percent chromic acid:10 percent nitric acid solution at 60°C for maceration (Jeffrey 1917). The macerated material was rinsed and placed on microscopic slides. The microscopic slides were photographed using a digital microscope (Mshot-MD50; Microshot Technology Limited, Guangzhou, China). The tissue proportion, fiber dimensions, vessel dimension, and density were done with an image computer analysis system (TDY-5.2; Beijing Tian Di Yu Technology Co. Ltd.; Yu et al. 2009). At least 60 measurements were done per parameter.

Two derived values were also calculated using fiber dimensions: aspect ratio as fiber length/fiber diameter and Runkel ratio (as 2 times fiber cell wall thickness)/lumen diameter (Ohshima et al. 2005).

Chemical components.—The wood fragments were milled down and then ground to 40 to 60 mesh dimensions wood powder. The moisture content of the wood powder was tested by the Chinese Standard GB/T 2677.2-2011 (SAC 2011) and was calculated according to weight lost when it was dried to constant weight at 105°C ± 2°C.

Ash content was tested by the Chinese Standard GB/T 2677.3-1993 (SAC 1993a), which is equivalent to the American standard TAPPI T211 om-85 (Technical Association of the Pulp and Paper Industry [TAPPI] 1991). Water solubility was tested by the Chinese Standard GB/T 2677.4-1993 (SAC 1993c), which is equivalent to the American standard TAPPI T207 om-88 (TAPPI 1988a). One percent sodium hydroxide solubility was tested by the Chinese Standard GB/T 2677.5-1993 (SAC 1993b), which is equivalent to the American standard TAPPI T212 om-88

(TAPPI 1988b). Benzene-alcohol extractive was tested by the Chinese Standard GB 2677.6-1994 (SAC 1994b), which is equivalent to the American standard TAPPI T204 om-97 (TAPPI 1997). Lignin was tested by the Chinese Standard GB/T 2677.8-1994 (SAC 1994a), which is equivalent to the American standard TAPPI T222 om-11 (TAPPI 2011).

Holocellulose was tested by the Chinese Standard GB/T 2677.10-1995 (SAC 1995). Wood powder with 2 g weight (G_3) was extracted by benzene–alcohol solution. The residue was dried and extracted by glacial acetic acid and sodium chlorite mixture until the residue turned white. The residue was washed with distilled water and then with acetone. The final residue was dried and weighed (G_4) to calculate the holocellulose content (W_1) based on Equation 4.

$$W_1 = \frac{G_4}{G_3} \times 100 \tag{4}$$

Cellulose was tested by the nitric acid–ethanol method (Wang et al. 2015). Wood powder with known weight (G_5) was extracted by 68 percent nitric acid and absolute alcohol mixture (1:4). The residue was washed with the 68 percent nitric acid and absolute alcohol mixture, followed by the hot water and absolute alcohol. The residue was dried at 105°C ± 2°C and weighed (G_6). The final residue was dried at 500°C and weighed (G_7). The cellulose content (W_2) was calculated based on Equation 5.

$$W_2 = \frac{G_7 - G_6}{G_5} \times 100 \tag{5}$$

Data analysis

Differences among the branchwood, trunkwood, and rootwood were evaluated by analyses of variance. Multiple comparisons were performed using the IBM SPSS Statistics software (Version 24.0; International Business Machines Corporation, Armonk, New York) with the significance assessed at the alpha less than 0.05.

Results and Discussion

Wood density

Wood density was one of the most important wood quality indicators for industrial processes; it was directly related to the physical–mechanical behavior of wood for timber, pulp, and paper production (Ferreira 2006, Ortega Rodriguez and Tomazello-Filho 2019, Van Duong et al. 2019). Branchwood density was lower than the trunkwood, but the difference was not significant at the alpha = 0.05 level. Rootwood exhibited significantly lower density than the trunkwood and branchwood. The differences in wood density between sampling positions were partially explained by their different anatomical structures, such as vessel features, fiber dimensions, tissue proportion, and chemical composition (Zanne et al. 2010, Nakagawa et al. 2016, Van Duong et al. 2019), which affect the quality of pulp and paper produced (Santos et al. 2012, Carrillo et al. 2018). The basic density of *A. sibirica* wood met the density requirement (0.3 to 0.5 g/cm) of papermaking raw material (Fang et al. 2000). Rootwood could also be used for pulping and papermaking, but chemical pulping production is preferable because chemical pulping requires lower wood density than mechanical pulping production (Fang et al. 2000). As expected, the trunkwood with the highest basic density had the highest air-dried density and absolute dried density, whereas the rootwood with the lowest basic density had the lowest air-dried density and absolute dried density. The air-dried densities of trunkwood and branchwood were on average 0.58 and 0.554 g/cm^3, respectively (Table 2), which were classified as medium density (Yin 1991). Based on the requirements of structural timber, air-dried density of deciduous wood should be at least 450 kg/m^3 (British Standards Institution 2007), which suggests that trunks and large-sized branches of *A. sibirica* could be used as structural timber for construction and furniture.

Anatomical characteristics

Based on micrographs of transverse sections (Figs. 1A, 1B, and 1C) and element segregation (Fig. 1D), arrangements and morphology of *A. sibirica* wood cells were observed. The wood was diffuse-porous with vessels surrounded by other cells, such as fibers and rays. The vessels were abundant (40 to 95 vessels per mm^2) and generally isolated or grouped with the diameter ranging between 15 and 190 μm and had a length from 90 to 1130 μm (Table 3). The average fiber diameter and length were about 27 and 830 μm. Some fibers reached a length of up to 1,560 μm. The rays were abundant (10 to 20 rays per mm^2) with cell length between 20 and 110 μm and width from 18 to 40 μm. The longitudinal parenchyma cells were scarce and could not be found in our samples. The observations and measurements of anatomical features were in accordance with previous studies by other authors (Wang and Li 1989, Cheng 1992), but there were large ranges in size. The variation in the measurements of anatomical characteristics resulted largely from the sampling position of the tree.

Tissue proportions.—Table 4 shows that the average values of fiber proportion range from 52.13 to 58.61 percent, which suggests *A. sibirica* is inside the high fiber proportion of hardwoods (Ona et al. 1999). The fiber proportion is directly linked to the wood-based panel and pulp production because wood fiber is the primary component in paper, paperboard, and structural fiberboard (Groom et al. 2002). The tissue proportion in wood is different between sampling positions. The trunkwood with the highest fiber proportion also has the lowest parenchymal tissue proportion (vessels and rays), whereas the rootwood with the lowest fiber proportion also has the highest parenchymal tissue proportion (Table 4). The abundant parenchyma, especially the rays in wood, can give wood a more appealing texture, thus improving the appearance of furniture and other wood products (Desch and Dinwoodie 1996). However, wood with a high parenchyma proportion has possibly low resistance to biological degradation. The parenchyma tissues store nutrients (such as unstructured carbohydrates)

Table 2.—Multiple comparisons of the wood density of the branch, root and trunk from Alnus sibirica.[a]

Position	Basic density (g/cm^3)	Air-dried density (g/cm^3)	Ovendried density (g/cm^3)
Trunkwood	0.46 ± 0.04 A	0.58 ± 0.06 A	0.55 ± 0.03 A
Branchwood	0.456 ± 0.009 A	0.554 ± 0.013 A	0.528 ± 0.014 A
Rootwood	0.322 ± 0.029 B	0.400 ± 0.039 B	0.364 ± 0.034 B

[a] Means ± standard deviation with different letters within a column were significant at the alpha = 0.05 level.

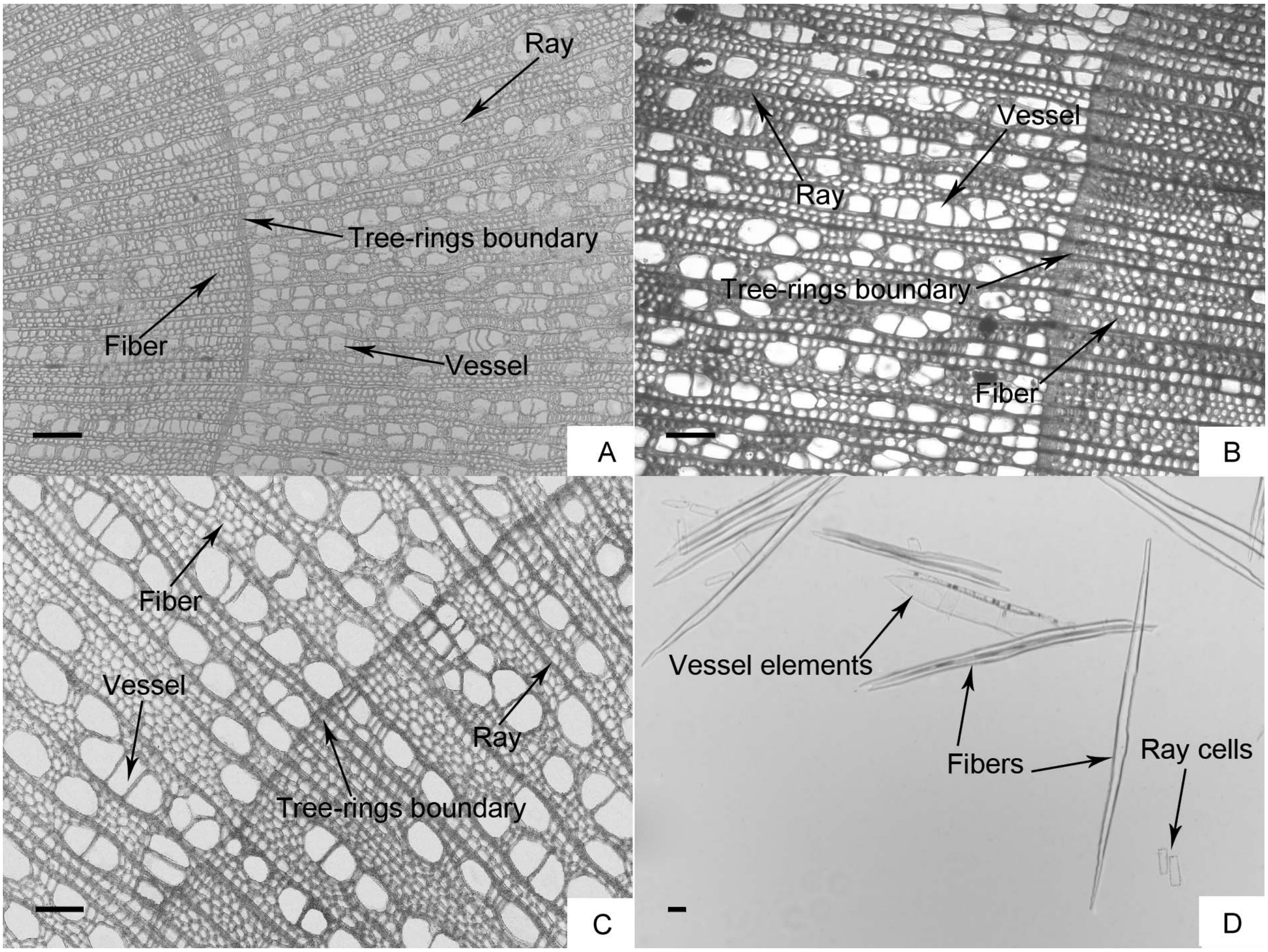

Figure 1.—Xylem anatomical cross-sections of branchwood (A), trunkwood (B), and rootwood (C), and separated wood elements (D) of Alnus sibirica*. Scale bar represents 100 m.*

during growth (Longui et al. 2012), and these nutrients are the main food source for some insects and microorganisms (Shmulsky and Jones 2011). However, low resistance to biological degradation could be compensated by using chemical treatments to increase durability. When wood is modified with chemicals, these parenchyma tissues become an important way to affect wood permeability. A high parenchyma proportion is conducive to improving wood permeability (Ahmed and Kyoung Chun 2014, Emaminasab et al. 2017). There are significant differences in vessel proportions between the branchwood and rootwood at the alpha = 0.05 level. However, parenchyma (vessel and ray) proportions in trunkwood show no significant differences with those in branchwood or rootwood, which suggests branchwood and rootwood have possibly the same permeability and decay resistance as trunkwood (Chen et al. 1998). However, the permeability and decay resistance of wood also involves other factors, such as wood extractives.

Table 3.—Measurements of anatomical features from Alnus sibirica *wood.*

Anatomical features	Mean	SD	Minimum	Maximum
Vessel density (mm^{-2})	80.61	14.22	40	95
Vessel diameter (μm)	77.43	9.54	15.0	190.0
Vessel length (μm)	667.32	24.15	90.0	1130.0
Fiber width (μm)	27.01	1.07	19.22	35.98
Fiber length (μm)	830	27.57	507.13	1560
Ray density (mm^{-2})	13.5	0.31	10	20
Ray cell width (μm)	24.7	0.82	18.0	40.0
Ray cell length (μm)	57.44	1.98	20.0	110

Fiber dimension.—Fiber dimension data for each sampling position are shown in Table 5. There are significant differences in fiber dimensions among the three positions at the alpha = 0.05 level. According to the classification of broad-leaved wood fiber dimension by the Anatomical Association (Committee on Nomenclature 1937), fiber in the trunkwood of *A. sibirica* is slender. Its length is medium (900 to 1600 μm), the aspect ratio is greater than 40, and the Runkel ratio is smaller than 1, which all suggest the trunkwood is suitable for papermaking (Ona et al. 1999). Compared with fibers of trunkwood, the fibers of rootwood and branchwood are stumpy. Although their length is greater than the basic requirements of papermaking fiber length (about 400 μm), the fibers of rootwood and branchwood are not suitable for papermaking because of the small aspect ratio (Wang 1998). Fiber's strength properties are

Table 4.—Multiple comparisons of the tissue proportions in the branchwood, rootwood, and trunkwood from *Alnus sibirica*.[a]

Position	Trunkwood	Branchwood	Rootwood
Vessel proportion (%)	23.05 ± 1.93 AB	21.91 ± 2.27 B	27.71 ± 1.63 A
Fiber proportion (%)	58.61 ± 3.37 A	57.26 ± 3.84 A	52.13 ± 1.39 A
Ray proportion (%)	18.35 ± 1.99 A	20.78 ± 4.72 A	20.15 ± 1.95 A

[a] Means ± standard deviation with different letters within a column were significant at the alpha = 0.05 level.

closely correlated with fiber dimensions, particularly tearing strength (Groom et al. 2002). The tearing strength of paper sheets decreased with decreasing fiber length. Also, fibers with a low aspect ratio had poor flexibility, which tends to decrease paper strength. Rootwood and branchwood could be considered for the production of short fiber biocomposite (Rios et al. 2015). In a short fiber composite, fiber needs to have a length of greater than a critical length in order to avoid being broken during tensile loading of a composite (Pickering et al. 2016). The fiber critical length varies with fiber dimension, fiber treatment, and fiber content of the biocomposite (Wan et al. 2018). Therefore, different fiber treatments and proportions could be used to produce different mechanical performances of biocomposites from branchwood and rootwood.

Vessel dimension and density.—The vessel dimensions of branchwood were lower than those of trunkwood. Furthermore, this study recorded significant differences in trunkwood and branchwood vessel length at the alpha = 0.05 level (Table 6). The vessel dimension in rootwood was significantly larger than that in trunkwood. The diameter measurement of our vessels accorded with the rule of vessel tapering (McCulloh et al. 2003, Petit et al. 2007). However, it was found that vessel densities of *A. sibirica* varied from bottom to top with no clear trend. Most vessel pores in trunkwood and rootwood were shaped as an oval with the radial diameter larger than the tangential diameter, while vessel pores in branchwood tended to be a similar diameter in radial and tangential direction (Table 6).

A high radial/tangential diameter ratio of vessels in trunkwood and rootwood favors paper strength because vessels with higher radial/tangential ratios fold more easily and make more contacts with the fibers during pressing and drying (Ona et al. 2001). Compared with branchwood, the vessels in trunkwood were slender and abundant. Paper produced from trunkwood tends to have trouble in picking up vessels in the printing process. The refining of the vessel rich fraction in pulps could decrease the vessel picking tendency (Nanko and Ohsawa 2010, Sari et al. 2012).

Moreover, vessels provide one of the main pathways for the fluid flow in hardwoods and thus gained an importance in wood permeating treatments such as drying, coating, bonding with adhesives, and impregnation with preservatives (Kamke and Lee 2007, Cǒté 2010). According to the research of Gibson (1968), permeability in hardwood is a function of the diameter of vessels. The larger the vessels in wood, the more favorable it is for liquid penetration. Compared with trunkwood and branchwood, rootwood had a larger size of vessels, which made it easier for strands, particle, fiber, or flour of rootwood to be modified in wood–plastic composites. Also, it was easier for rootwood to bond with adhesives in particleboard and finger-jointed lumber because wood had larger open cells on the surface, allowing the adhesive to flow into the lumen of the cells and provide greater strength of mechanical interlocking (Gardner et al. 2014).

Chemical components

Greater percentages of extractives recorded for the rootwood than trunkwood and branchwood of *A. sibirica* are consistent with the reports of Goulart et al. (2012) for *Stryphnodendron adstringens* and Li et al. (2013) for *Populus deltoids*. This might be due to the greater need of decay resistance of roots in the process of tree growth, because the roots are the most susceptible to damage by microbes in soil (Kuhlman 1980). However, the presence of extractives could reduce the permeability, surface films, bonding properties of wood, and waste chemicals during pulping and bleaching (Hillis 1971). We observed lower content of extractives in branchwood than in trunkwood of *A. sibirica*; hence the branchwoods are the most likely to be used for wood bonding or pulping. The cellulose content of branchwood, trunkwood, and rootwood was relatively high, all above 50 percent (Table 7). Cellulose plays a load-bearing role in the wood cell wall, giving wood tensile strength (Pickering et al. 2016). This is because higher tensile strength is generally achieved with wood having higher cellulose content and with cellulose microfibrils aligned more in the fiber direction. Genet et al. (2005) reported rootwood tensile strength was positively related to cellulose content in both *Castanea sativa* and *Pinus pinaster*. Sun et al. (2018) found the cellulose content of *Robinia pseudoacacia* wood was positively correlated with its mechanical strength. *A. sibirica* wood with higher

Table 5.—Multiple comparisons of the fiber dimensions in the branchwood, rootwood, and trunkwood from *Alnus sibirica*.[a]

Fiber dimensions	Trunkwood	Branchwood	Rootwood
Fiber length (μm)	1017.74 ± 10.68 A	612.81 ± 13.29 C	871.32 ± 18.22 B
Fiber width (μm)	24.95 ± 0.83 B	23.31 ± 0.61 B	33.02 ± 0.82 A
Lumen diameter (μm)	20.14 ± 1.04 B	18.34 ± 0.49 B	26.07 ± 0.67 A
Double wall thickness	4.93 ± 0.92 B	4.98 ± 0.26 B	6.95 ± 0.37 A
Aspect ratio	40.96 ± 0.93 A	27.36 ± 0.73 B	27.20 ± 0.68 B
Runkel ratio	0.24 ± 0.01 B	0.28 ± 0.02 A	0.28 ± 0.02 A

[a] Means ± standard deviation with different letters within a column were significant at the alpha = 0.05 level.

Table 6.—Multiple comparisons of the vessel characteristics of the branchwood, rootwood, and trunkwood from Alnus sibirica[a]

Vessel characteristics	Trunkwood	Branchwood	Rootwood
Radial diameter (μm)	78.26 ± 4.47 B	60.19 ± 3.12 B	102.96 ± 05.88 A
Tangential diameter (μm)	71.11 ± 3.52 B	60.49 ± 2.07 B	91.61 ± 3.85 A
Vessel density (n/mm^2)	90.58 ± 10.35 A	80.34 ± 10.45 A	70.09 ± 11.98 A
Vessel length (μm)	720.45 ± 21.64 A	521.47 ± 20.95 B	760.55 ± 20.45 A

[a] Means ± standard deviation with different letters within a column were significant at the alpha = 0.05 level.

cellulose content might also have higher tensile strength. This was a favorable factor for expanding the application of *A. sibirica* wood in construction materials. However, additional studies of rootwood, trunkwood, and branchwood mechanical properties were still necessary to determine specific structural application areas. According to the criterion proposed by Nieschlag et al. (1960), cellulose content was satisfactory for all positions of *A. sibirica* as promising for pulp and paper manufacturing. There were no significant differences in the cellulose content between different positions at the alpha = 0.05 level. Hemicellulose was bounded with adjacent cellulose in the wood cell wall. Since a higher hemicellulose content led to an increase in the fiber joint strength (Spiegelberg 1966), the tensile strength was dependent on the hemicellulose content in the pulp (Molin and Teder 2002). Also, pulps with higher hemicellulose content showed an increase in pore volume (Rahman et al. 2017) and a decrease in opacity (Wang et al. 2010). Hemicellulose was similar to cellulose; increasing its content would lead to the higher pulp yield (Liu et al. 2017, Rahman et al. 2017). Holocellulose (i.e., total of hemicellulose and cellulose) content in wood was positively correlated to pulp yield (Neiva et al. 2015). Our results showed that holocellulose content in *A. sibirica* wood was between 72.8 and 77.821 percent, which was desirable to pulp yield. Wood with high cellulose content usually has low lignin content. Table 7 shows that the lignin content of *A. sibirica* wood is low, which suggests *A. sibirica* wood is suitable for pulp, because wood with high lignin content (above 25%) is not recommended in paper production (Joaquim Duarte da Silva et al. 2013). Owing to its hydrophobic nature, lignin on the fiber surface could prevent the formation of hydrogen bonds between cellulose molecules (Shao and Li 2006). Delignification is necessary in the pulping process. Lignin content has a strong influence on delignification rates and chemical consumption during the pulping process (Carrillo et al. 2018). For example, low lignin content in wood leads to less active hydroxide and hydrogen sulfide ions and to lower energy in the kraft cooking process (Luo et al. 2012). Also, the pulp should be separated during oxygen delignification to achieve the desired brightness. However, an increase of oxygen delignification results in the production of pulp with higher fine fibers fragmentation due to the higher cellulose degradation (Jafari et al. 2015, Segura et al. 2016). Lignin content in the rootwood shows a higher value (24.04%) compared with branchwood (19.80%) and trunkwood (23.47%), and higher than the value of trunkwood determined by Cheng (1992). From a chemical composition point of view only, the rootwood, trunkwood, and branchwood of *A. sibirica* are all suitable materials for fiber. However, the delignification efficiency and economic cost should be carefully considered when the rootwood is used for pulping.

Conclusions

The branchwood, rootwood, and trunkwood all showed significant differences in their fiber and vessel dimensions despite showing similar arrangements, morphology, proportions of wood cells, and chemical components. These differences suggested the possibility of replacing trunkwood with branchwood and rootwood, and also different application purposes for the three positions that came from the same tree. This constituted key information for improving the efficient use of *Alnus sibirica* wood.

Rootwood with lower wood densities and larger vessel dimensions showed lighter and softer structures. However, the densities of branchwood and trunkwood were similar and all belonged to medium density, suggesting that branchwood with a large size could be used as structural timber. The mechanical quality testing of timber from the branchwood should be carried out in the future.

The high-quality fibers were observed for trunkwood but not for branchwood and rootwood, suggesting that the trunkwood could contribute to high-quality raw material for papermaking, while the branchwood and rootwood could be used to produce short fiber biocomposite.

Table 7.—Multiple comparisons of the component contents in the branchwood, rootwood, and trunkwood from Alnus sibirica.[a]

Component content (%)	Trunkwood	Branchwood	Rootwood
Cold water extracts	2.70 ± 0.07 B	2.01 ± 0.11 C	3.00 ± 0.06 A
Hot water extracts	3.64 ± 0.08 A	2.62 ± 0.08 B	3.87 ± 0.14 A
1% NaOH extracts	27.34 ± 1.36 A	21.69 ± 1.60 B	29.03 ± 0.01 A
Ethanol–toluene extracts	2.89 ± 0.93 B	2.88 ± 0.04 B	4.62 ± 0.09 A
Cellulose	50.94 ± 2.83 A	58.12 ± 3.60 A	50.85 ± 2.79 A
Holocellulose	73.34 ± 3.53 A	77.21 ± 4.63 A	72.80 ± 3.73 A
Lignin	23.47 ± 3.13 A	19.80 ± 1.26 A	24.04 ± 5.18 A
Ash	0.24 ± 0.11 B	0.41 ± 0.05 A	0.22 ± 0.01 B

[a] Means ± standard deviation with different letters within a column were significant at the alpha = 0.05 level.

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