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CHEMICAL COMPOSITION AND FIBRE CHARACTERISTICS OF BRANCH WOOD OF SELECTED HARDWOOD SPECIES

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ABSTRACT

The chemical composition and fibre characteristics of branch wood of hardwood species namely European beech (*Fagus sylvatica* L.), common oak (*Quercus Robur* L.), common hornbeam (*Carpinus betulus* L.), sycamore maple (*Acer pseudoplatanus* L.), black locust (*Robinia pseudoacacia* L.), silver birch (*Betula pendula* L.), European ash (*Fraxinus excelsior* L.), black poplar (*Populus nigra* L.), black alder (*Alnus glutinosa* L.), white willow (*Salix alba* L.), small-leaved lime (*Tilia cordata* Mill.) and royal paulownia (*Paulownia tomentosa* (Thunb.) Steud.) were determined. The branch wood of the examined tree species differed in the content of ash (0.44–0.86%), extractives soluble in dichloromethane and hot water (2.9–10.63%), Klason lignin (15.3–23.7%), acid-soluble lignin (1.78–3.53%), polysaccharides glucan (40.6–48.9%), xylan (16.7–25.3%), mannan (0.8–1.8%), galactan (0.5–1.1%) and arabinan (0.3–1.4%). The concentrations of inorganic elements (Ca, K, Mg, Na, P, Fe, Mn, Si, Zn, Cu) in the ash of the branch wood varied depending on the tree species. Differences in the fibre coarseness (4.15–8.52 mg/100 m), but more differences in the arithmetic average fibre length (0.4–1.20 mm) and the weighted average fibre length (0.51−1.45 mm) were found. Branch wood of common hornbeam, European ash, European beech and silver birch had a high content of polysaccharides and a lower content of Klason lignin, which is advantageous for the production of biofuels and for the pulping process. In addition, branch wood of these species has longer fibres with lower coarseness, which is advantageous in terms of pulp and paper quality.

Key words: branch wood, hardwood species, polysaccharides, lignin, extractives, ash, fibre length, fibre coarseness.

INTRODUCTION

Wood is best defined as a three-dimensional biopolymer composite composed of an interconnected network of cellulose, hemicelluloses and lignin with minor amounts of extractives, and inorganics. It is a highly variable and complex material that has inherent variability among species, within species, and also within a tree (ZOBEL and VAN BUIJTENEN 1989, LINDSTRÖM 2001, MARTIN *et al.* 2010, KRISHNA *et al.* 2017, TARELKIN *et al.* 2019).

Generally, anatomical and chemical properties are the features that are often used to identify the species of woods. Utilization of these biomass resources is critically dependant on the in-depth knowledge of their morphological and chemical characteristics. The study of chemical characteristics of wood is important to exploit the potential utilization of wood such as that for pulp and paper, bioethanol, biocomposites and carbonized wood production, whereas the fibre characteristics are studied in order to discover the utilization of wood fibers, such as in pulp, paper and fibreboard production.

All processes used for the conversion of biomass feedstocks are sensitive to feedstock composition and quality to various extents. Reduction in lignin content improves enzymatic hydrolysis, which along with pretreatment, is the most expensive component in the production of bioethanol. It typically results in a proportional increase in the cellulose content per unit mass (Dinus 2001). Ash content and composition, heating value, elemental ratios and proportion of lignin, cellulose, and hemicelluloses are some of the broad compositional characteristics used to screen biomass feedstocks for biofuels applications (Dinus *et al*. 2001).

Chemical composition of wood and fibre characteristics are two important parameters which determine its suitability as raw material for the production of pulp and paper. The extractive content has a direct effect on the pulp yield~~,~~; its ~~a~~ high content reduces the pulp yield. On the other hand holocellulose, α-cellulose and lignin content are mainly related to pulping behaviour, (Zobel and van Buijtenen 1989). The fibre morphological properties are important quality parameters for pulp and paper properties. In fact, the fibre length and coarseness greatly influence the quality and properties of the final product, e.g., they are frequently correlated with the physical and mechanical properties of paper and paperboard (Seth 1995, El-Hosseiny and Anderson 1999, Anjos *et al.* 2014, Keays *et al.* 2015).

Proportion of stem wood of deciduous trees at harvest is 68%. The share of crown and branches ranges from 10% to 19%, the root part makes up 8–25% of the total weight of biomass. The collection of branch wood can substantially increase the quantity of wood fibre per area of forest harvested. According to Okai and Boateng (2007), approximately 35 to 50% of wood biomass is left in the forest in form of stumps, branches and crowns.

The logging residues (especially branch wood) make up a significant quantity of wood volume, and its utilization can increase the yield by about 60% (Shmulski and Jones 2011). Forest residues (e.g. branch wood, bark, etc.) are currently highly preferred as a cover for soil amendment, industrial fuel and are possible raw materials for the production of several organic products.

Particular emphasis is placed on the use of branch wood due to the decline in stem wood resources (Leich and Miller 2017, Dadzie *et al.* 2018, Zhao *et al.* 2019a,b) or the low availability per unit area, for example in arid and semi-arid regions (Andersen and Krzywiski 2007, Li *et al.* 2018). However, branch wood is still little used industrially, as it is associated with many disadvantages. Branch wood contains ~~a~~ higher amount of bark and is less uniform in comparison with stem wood (Schmulski and Jones 2011). It needs an intricate treatment before its utilization, which can reduce production efficiency (Nurmi 2007). When considering the use of branch wood as a potential raw material, it is time to consider what strategy should be used to manage restrictions on branch wood to be useful for commercial purposes.

Branch wood as a part of a tree has been discussed broadly in recent publications (Shmulski and Jones 2011, Dadzie *et al.* 2018, Zhao *et al.* 2019a, b). Investigation on chemical composition and fibre characteristics of the branch wood of the hardwood species is still rare. The results of an extensive research of branch wood of eleven species growing in India have shown that branches are not identical to stem in all the technical properties but the difference between the two is not so large as to treat the branch material separately in the manufacture of pulp, paper and boards. Furthermore, the branch diameter is an important parameter of the quality of raw material, as it affects many properties, such as the proportion of bark, the fibre length and the density of wood and bark of some species (Bhat *et al.* 1985).

Branch wood can be used for pulp papermaking or wood-based panels (ZHAO *et al.* 2018), low-grade paper (ZHAO *et al.* 2019a), or glued plates (ZHAO *et al.* 2019b).

Branch wood of *Acacia gerrardii*, *Tamarix aphylla*, and *Eucalyptus camaldulensis* has several drawbacks that markedly limit its potential for commercial uses (SUANSA *et al.* 2020). It might not be favorable for particle board, flake board, or fibre board because of its high shrinkage. Even though all of the fibres show suitability as a raw material for pulp and paper, the quality is low due to the high density of vessels or parenchyma proportions. However, branch wood of all examined species might be used as a blending material (papermaking and glued plates) or for light construction purposes. While considering the chemical composition of branch wood, classes of green products, such as biofuel, bioenergy, and biochar might maximize the value of branch wood.

The aim of this work was to determine the chemical composition and fibre characteristics of branch wood from hardwood species in order to assess the possibility of their utilization in the production of biofuels, pulp and paper.

MATERIAL AND METHODS

Materials

Branch woods were selected from tree species with a higher occurrence in forests of the Slovak Republic such as European beech (*Fagus sylvatica* L.), common oak (*Quercus Robur* L.*)*, common hornbeam (*Carpinus betulus* L.) and sycamore maple (*Acer pseudoplatanus* L.) and less represented tree species black locust (*Robinia pseudoacacia* L.), European ash (*Fraxinus excelsior* L.), silver birch (*Betula pendula* L.), black poplar (*Populus nigra* L.), black alder (*Alnus glutinosa* L.), white willow (*Salix alba* L.) and small-leaved lime (*Tilia cordata* Mill.). Royal paulownia (*Paulownia tomentosa* (Thunb.) Steud.) was chosen for its high potential as a fast growing species.

All samples of branch wood were collected in the region of Bratislava, Slovak Republic, from different areas and trees. The diameter of the branches ranged from 2.0 to 4.5 cm. Average samples were prepared for every tree species.

Methods

Preparation of samples

The branch wood samples were debarked and chips were prepared on a single-knife laboratory disc chipper. Sawdust was prepared from chips in the device Brabender for determination of the chemical composition. For determining the fibre length and coarseness samples were prepared from debarked branches, from which 2 cm high discs were prepared by hand and then samples with dimensions of half-matchstick. Samples prepared in this way were macerated under reflux with a mixture of 30% hydrogen peroxide and glacial acetic acid in a ratio of 1: 1 for 1 to 2 hours until the wood samples turned white (BEREŠOVÁ and ČUNDERLÍK 1999). After cooling, the samples were filtered and washed with water, the fibres were separated after stirring the sample in distilled water.

Analyses

The *ash content* was determined according to ISO 1762. The *extractives* content in dichloromethane was determined according to Tappi T 204 cm-94, and the extractives content in hot water according to Tappi T 207 cm-08. The *Klason lignin* content was determined according to Tappi T 222 om-98 and *acid-soluble lignin* content according to Tappi UM 250. Standard deviations were calculated from duplicate measurements for all tree species.

Polysaccharides glucan, xylan, mannan, galactan and arabinan content was calculated based on the concentrations of glucose, xylose, mannose, galactose and arabinose in the hydrolysate after determination of lignin. The hydrolysate before determination of monosaccharides was treated with 4% H_2SO_4 at 121°C for 2 hours, to hydrolyse the oligosaccharides. Subsequently, the hydrolysate was neutralized with $BaCO_3$. The concentration of monosaccharides was determined ~~by~~ using HPLC with Rezex ROA H^+ column. The mobile phase was 0.005 N H_2SO_4 at a flow rate of 0.5 ml.min^{-1} at 30°C. The samples were passed through a 22 µm filter before testing.

Inorganic elements in ash

The concentration of K, Ca, Mg, Na, Fe, Mn, Zn, Cu elements in the branch wood was determined by atomic absorption spectrometry (AAS) using flame atomization according to the method Tappi T 266. The soluble portion of the ash in hydrochloric acid was used in their determination. The concentration of P element was determined by a spectrometric method with ammonium molybdate according to standard STN EN ISO 6878. The concentration of Si in the branch wood was calculated from the gravimetrically determined SiO_2 content in the insoluble ash residue after a treatment with hydrofluoric acid. Standard deviations were calculated from duplicate measurements for all tree species.

Fibre length and coarseness

Fibre length was determined using ADV-3 analyser (PPRI Bratislava, Slovak Republic). The basis of the analyser is a conductivity sensor, through which a very dilute suspension of fibres passes, the surface of which is covered with an electric charge double layer and the outer part of the charges participates on conducting current in the area of the sensor electrodes. Electrical impulse arises by passing the fibre through the sensor interface at the output of the amplifier. Its length depends on the speed of the fibre passing through the capillary and on the fibre length. The fibre lengths were measured in the range of 0-5 mm with the number of 10,000 fibres in the sample. Arithmetic and weighted fibre length distributions were obtained by measuring the fibre suspension and the arithmetic average fibre lengths and weighted average fibre lengths were calculated. The arithmetic average fibre length was calculated as the sum of all individual fibre lengths divided by the total number of fibres measured. The weighted average fibre length was calculated as the sum of individual fibre lengths squared divided by the sum of the individual fibre lengths.

Fibre coarseness was determined using ADV-3 analyser by a special measurement of the arithmetic average fibre length of a suspension containing 1 mg of fibres.

Standard deviations were calculated from duplicate measurements of fibre length and coarseness for all tree species.

RESULTS AND DISCUSSION

Chemical composition

The results of the chemical composition of branched woods of different tree species are shown in Tab. 1. The values of each of the chemical components varied between the examined species. The differences in the content of ash and extractives were the highest of all chemical components. The content of ash of the branch woods were found in the range from 0.44 to 0.86%. Branch wood of black locust had the highest ash content, while the smallest one was found in the branch wood of royal paulownia. In our previous work (FIŠEROVÁ *et al.* 1986), the ash content in branch wood of black poplar varied from 0.5 to 0.8 % depending on the diameter of the branches. According to CÁRDENAS-GUTIÉRREZ *et al.* (2018), the ash content in branch wood of various hardwood species ranged from 0.74 to 1.13%. The differences in ash content are caused to the fact that the content of inorganic components varies greatly depending on the environmental conditions in which the tree has grown, also on the tree species and the diameter of branch.

The content of extractives soluble in dichloromethane and hot water in the branch wood of the examined tree species ranged from 2.90 to 10.63% (Tab. 1). Small-lived lime branch wood had the highest content of extractives, while the lowest was determined in branch wood of European ash. The content of extractives soluble in dichloromethane ranged from 0.26 to 5.18%. The branch wood of the small-leaved lime contained the most extractives soluble in dichloromethane, while the smallest one was found in the branch wood of common hornbeam. The content of extractives soluble in hot water ranged from 2.49 to 5.50%. The branch wood of royal paulownia contained the most extractives soluble in hot water and the least one had the branch wood of European ash. The content of extractives in wood varies greatly depending on tree species, as it is controlled by genetics (ZOBEL and JACKSON 1995). The combined effect of genetics and methods and the solvents used on extraction leads to a wide range of results in the literature. The total content of extractives in black poplar branch wood ranged from 3.95 to 4.90% (FIŠEROVÁ *et al.* 1986) and for various hardwood species ranged from 6.9 to 15.3% (CÁRDENAS-GUTIÉRREZ *et al.* 2018).

The content of Klason and acid-soluble lignin in the branch wood of the examined tree species ranged from 17.97 to 26.53% (Tab. 1). The highest lignin content was found in the branch wood of black poplar, while the smallest in the branch wood of small-leaved lime. The Klason lignin content ranged from 15.3 to 23.7%. The highest Klason lignin content was found in the branch wood of royal paulownia, while the lowest one in the branch wood of small-leaved lime. The content of acid-soluble lignin ranged from 1.78 to 3.53%. Branch wood of common hornbeam contained the most of acid-soluble lignin while the black alder contained the least. The total content of lignin in branch wood of various hardwood species ranged from 17.64 to 28.87% (CÁRDENAS-GUTIÉRREZ *et al.* 2018), while for black poplar varied from 25.35 to 28.67%, depending on the diameter of the branches (FIŠEROVÁ *et al.* 1986). Results obtained for the lignin content differ, which may be related to a different tree morphology. This is supported by the fact that, so far as it is known, the content of lignin and its structure differ depending on the region of the woody xylem (SJÖSTRÖM 1993).

The content of polysaccharides glucan, xylan, mannan, galactan and arabinan in the branch wood of the investigated tree species ranged from 63.0 to 69.6% (Tab. 1). The highest content of polysaccharides was found in the branch wood of common hornbeam, while the lowest in the branch wood of royal paulownia. Glucan and xylan formed the highest proportion of polysaccharides. The glucan content ranged from 40.6 to 48.9%. The highest content of glucan was determined in the branch wood of black poplar, while the lowest in the branch wood of silver birch, black alder and royal paulownia. The xylan content ranged from 16.7 to 25.3%. The highest xylan content was found in the branch wood of silver birch, while the lowest in the branch wood of black poplar. The content of other polysaccharides mannan, galactan and arabinan ranged from 1.9 to 3.5%, while the highest content was determined in the branch wood of small-leaved lime and royal paulownia, the lowest in the branch wood of common hornbeam. The mannan content ranged from 0.8 to 1.8%, galactan from 0.5 to 1.1% and arabinan from 0.3 to 1.4. The polysaccharides content in the black poplar branch wood ranged from 63.43 to 67.80% depending on the diameter of the branches (FIŠEROVÁ *et al.* 1986).

According to the results from the literature (FIŠEROVÁ *et al.* 1986, CÁRDENAS-GUTIÉRREZ *et al.* 2018), branch wood of various hardwood species contains less polysaccharides but more lignin, extractives and ash than stem wood.

Based on the obtained results, it may be concluded that the contents of individual wood chemical components vary significantly as a function of the wood species. Therefore, it is almost impossible to find any relations between the variation in the content of one component and the contents of other examined wood chemical components. The main restrictive factor that influences these relationships lies in the fact that the contents of individual components (except ash) are more or less determined by the pre-treatments that preceded their isolation (FENGEL and WEGENER 1984).

Among the examined tree species the branch wood of common hornbeam, European beech, European ash and silver birch had the highest content of polysaccharides (68.5–69.6%), as well as glucan and xylan content (65.9–67.7%), from which bioethanol or biobutanol is produced by hydrolysis. A great advantage of the branch wood of these tree species is also the low content of Klason lignin (16.2–18.7%), as lignin plays a negative role in the production of biofuels and pulp. Lignin can reduce the strength of paper because it could be a barrier for hydrogen bonding and could be an inhibitor in the hydrolysis process in the production of bioethanol and biobutanol. The high proportion of glucan, low content of lignin and extractives should contain wood for the production of biocomposite (ŠPANIČ *et al.* 2018). Branch wood of black poplar meets the most of these requirements from the examined species.

Tab. 1 Chemical composition of branch woods of hardwood species.

Species	Ash [%]	Extractives [%]			Lignin [%]			Polysaccharides [%]					
		Dichloro-methane	Hot water	Total	Klason*	Acid-soluble	Total	Glucan	Xylan	Mannan	Galactan	Arabinan	Total
European beech *Fagus sylvatica* L.	0.54 ±0.00	0.31 ±0.01	3.40 ±0.01	3.71 ±0.02	17.5 ±0.18	4.40 ±0.08	21.90 ±0.19	44.3 ±0.35	22.1 ±0.35	1.20 ±0.12	0.80 ±0.03	0.4 ±0.02	68.8 ±0.89
Common oak *Quercus robur* L.	0.50 ±0.01	0.33 ±0.03	3.88 ±0.14	4.21 ±0.14	21.0 ±0.20	2.40 ±0.07	23.40 ±0.16	41.1 ±0.07	23.0 ±0.14	1.10 ±0.14	0.50 ±0.03	1.40 ±0.05	67.1 ±0.42
Common hornbeam *Carpinus betulus* L.	0.51 ±0.01	0.26 ±0.03	3.39 ±0.06	3,65 ±0.10	16.2 ±0.00	3.53 ±0.02	19.73 ±0.04	45.3 ±0.49	22.4 ±0.49	0.80 ±0.05	0.50 ±0.05	0.60 ±0.03	69.6 ±0.64
Sycamore maple *Acer pseudoplatanus* L.	0.81 ±0.02	0.47 ±0.01	3.76 ±0.01	4.23 ±0.02	23.0 ±0.03	1.93 ±0.05	24.93 ±0.02	45.7 ±0.35	18.9 ±0.14	1.20 ±0.12	0.50 ±0.02	1.30 ±0.02	67.6 ±0.85
Black locust *Robinia pseudoacacia* L.	0.86 ±0.01	0.76 ±0.03	3.89 ±0.03	4.65 ±0.01	22.6 ±0.07	2.91 ±0.03	25.51 ±0.03	42.1 ±0.28	21.6 ±0.28	1.40 ±0.08	0.80 ±0.06	0.50 ±0.02	66.4 ±0.64
Silver birch *Betula pendula* L.	0.49 ±0.01	1.48 ±0.01	3.43 ±0.04	4.91 ±0.02	18.5 ±0.07	3.11 ±0.06	21.61 ±0.13	40.6 ±0.21	25.3 ±0.00	1.50 ±0.10	0.50 ±0.01	0.60 ±0.03	68.5 ±0.35
European ash *Fraxinus excelsior* L.	0.53 ±0.00	0.41 ±0.01	2.49 ±0.02	2.90 ±0.03	18.7 ±0.05	2.65 ±0.08	21.32 ±0.03	48.0 ±0.28	18.2 ±0.28	0.90 ±0.05	0.50 ±0.02	1.40 ±0.04	69.0 ±0.67
Black poplar *Populus nigra* L.	0.64 ±0.02	0.78 ±0.02	2.65 ±0.01	3.43 ±0.02	23.5 ±0.18	3.03 ±0.06	26.53 ±0.12	48.9 ±0.42	16.7 ±0.35	1.40 ±0.08	0.60 ±0.06	0.30 ±0.02	67.9 ±0.89
Black alder *Alnus glutinosa* L.	0.65 ±0.03	0.84 ±0.06	4.35 ±0.11	5.19 ±0.11	23.6 ±0.04	1.78 ±0.01	25.38 ±0.03	40.6 ±0.42	20.4 ±0.35	1.50 ±0.11	0.80 ±0.07	0.60 ±0.02	63.9 ±0.87
White willow *Salix alba* L.	0.62 ±0.01	0.66 ±0.05	2.97 ±0.02	3.63 ±0.03	20.8 ±0.18	2.79 ±0.08	23.59 ±0.08	45.8 ±0.49	18.3 ±0.49	1.70 ±0.08	0.90 ±0.04	0.60 ±0.03	67.3 ±0.98
Small-leaved lime *Tilia cordata* Mill.	0.80 ±0.00	5.18 ±0.05	5.45 ±0.09	10.63 ±0.15	15.3 ±0.08	2.67 ±0.01	17.97 ±0.07	41.2 ±0.21	20.3 ±0.35	1.80 ±0.14	1.00 ±0.13	0.70 ±0.02	65.0 ±0.71
Royal paulownia *Paulownia tomentosa* (Thunb.) Steud.	0.44 ±0.01	1.04 ±0.03	5.50 ±0.01	6.54 ±0.02	23.7 ±0.06	2.42 ±0.05	26.12 ±0.04	40.6 ±0.14	18.9 ±0.21	1.70 ±0.06	1.10 ±0.14	0.70 ±0.03	63.0 ±0.31

* Klason lignin was corrected for ash content in Klason lignin.

Inorganic elements in ash

The inorganic elements present in the biomass form its ash content and represent the waste stream during its conversion to biofuels and are a source of biochar and slagging during thermochemical conversion. Knowledge of the ash content and composition is essential regardless of the conversion pathway or end product. Ash is composed of many major and minor elements that trees need for their growth. The major elements include Ca, K, Fe, Mg, P, Na and Mn (VESTERINEN 2003). The amount of the major elements in wood ash varies with the type of plant tissues that are part of the wood (PITMAN 2006).

In Tab. 2, there are concentrations of inorganic elements (Ca, K, Mg, Na, P, Fe, Mn, Si, Zn, Cu) in the ash of the branch wood of the examined tree species. Of the major components, the elements Ca and K were the most abundant. The concentration of Ca ranged from 287 to 1776 $mg \cdot kg^{-1}$, while the concentration of K was in a very wide range from 558 to 3412 $mg \cdot kg^{-1}$. Most of Ca was in the branch wood of black locust, while the least was in the branch wood of royal paulownia. Therefore in the case of K, the concentration was the highest in the branch wood of small-leaved lime and the lowest in the branch wood of common hornbeam. The inorganic elements Ca and K are essential for tree metabolism and various physiological processes associated with growth. In recent years, special interest has been attributed therefore to the effect of both cations on cambial activity and xylem development (FROMM 2010).

The third most common abundant chemical element in the branch wood of the examined tree species was Mg, the concentration of which ranged from 141 to 521 $mg \cdot kg^{-1}$, the highest concentration was determined in the branch wood of sycamore maple and the lowest in the branch wood of common hornbeam. The concentration of P in the branch wood ranged from 170 to 408 $mg \cdot kg^{-1}$, the highest concentration was determined in the branch wood of black poplar and the lowest in the branch wood of sycamore maple.

The concentration of Na in the branch wood of the examined tree species ranged from 9.20 to 97.7 $mg \cdot kg^{-1}$, while it was mostly found in the branch wood of black poplar and the least in the branch wood of common oak. The concentration of Mn ranged from <0.5 to 122 $mg \cdot kg^{-1}$, while the highest concentration was determined in the branch wood of European beech and the lowest in the branch wood of black locust, European ash, white willow and royal paulownia. Of the major inorganic elements, Fe was the least represented in the branch wood of the examined species. The concentration of Fe ranged from 5.82 to 19.2 $mg \cdot kg^{-1}$, the highest concentration was determined in the branch wood of small-leaved lime and the smallest in the branch wood of common hornbeam.

The concentration of minor elements Si, Zn and Cu in ash is important from the point of view of industrial use of branch wood, as their concentration can affect some technological processes. The concentration of Si in the branch wood of the examined species ranged from 28.5 to 116 $mg \cdot kg^{-1}$, while the highest concentration was determined in the wood of small-leaved lime and the lowest in the branch wood of European beech. The concentration of Zn in the branch wood ranged from 2.59 to 24.3 $mg \cdot kg^{-1}$, the highest concentration was in the wood of black poplar and the lowest in the branch wood of black locust. The amount of Cu was the smallest of the above-mentioned minor elements in the branch wood, its concentration ranged from 1.47 to 4.48 $mg \cdot kg^{-1}$.

The branches and twigs contain more ash-forming components than stem wood. The K and Na content in the branches and twigs is significantly higher than that in stem wood (WANG and DIBDIAKOVA 2014). When wood was used as a fuel, it was found that ash slagging tendency correlated well to content of Si and K in the fuel (ÖHMAN *et al*. 2004).

Tab. 2 Inorganic elements concentration in branch wood of hardwood species.

Species	Inorganic elements [mg·kg^{-1}]									
	Ca	K	Mg	P	Si	Na	Mn	Fe	Zn	Cu
European beech *Fagus sylvatica* L.	1007 ±27.0	790 ±14.1	191 ±2.12	178 ±2.83	28.5 ±0.71	77.9 ±0.13	122 ±3.54	8,62 ±0.69	4.70 ±0.78	1.71 ±0.04
Common oak *Quercus robur* L.	691 ±16.4	1385 ±21.9	196 ±2.12	277 ±4.95	60.2 ±0.92	9.20 ±0.14	115 ±0.71	14.5 ±0.28	3,50 ±0.57	2.47 ±0.15
Common hornbeam *Carpinus betulus* L.	1483 ±14.1	558 ±3.10	141 ±3.54	206 ±2.83	78.6 ±0.92	11.7 ±1.00	3.11 ±0.03	5.82 ±0.08	15.3 ±0.42	2.33 ±0.14
Sycamore maple *Acer pseudoplatanus* L.	1478 ±20.5	1863 ±19.6	521 ±12.1	170 ±5.36	57.6 ±0.78	18.9 ±0.78	1.71 ±0.04	9.23 ±0.29	3.94 ±0.57	1.47 ±0.04
Black locust *Robinia pseudoacacia* L.	1776 ±8.50	1205 ±7.07	275 ±5.66	220 ±1.41	103 ±0.85	60.3 ±0.88	< 0.5 ±0.02	13,6 ±0.35	2.59 ±0.12	1.68 ±0.29
Silver birch *Betula pendula* L.	482 ±12.1	1240 ±27.0	252 ±6.36	327 ±8.48	82.5 ±2.54	88.2 ±0.61	64.7 ±0.78	12,1 ±0.53	23.5 ±0.57	2.58 ±0.03
European ash *Fraxinus excelsior* L.	834 ±24.0	1551 ±14.8	244 ±1.91	233 ±3.54	107 ±0.64	34.4 ±1.10	< 0.5 ±0.02	13.0 ±0.28	10.3 ±0.46	2.35 ±0.11
Black poplar *Populus nigra* L.	932 ±15.5	1517 ±17.5	271 ±4.95	408 ±2.12	51.4 ±1.69	97.7 ±0.60	1.27 ±0.11	9,96 ±1.72	24.3 ±0.42	4.21 ±0.15
Black alder *Alnus glutinosa* L.	1354 ±21.0	1832 ±19.0	385 ±4.24	368 ±2.83	74.2 ±0.14	41.0 ±0.42	26.9 ±0.42	29.6 ±0.57	12.8 ±0.42	2.47 ±0.13
White willow *Salix alba* L.	901 ±18.4	1733 ±24.0	241 ±1.32	358 ±8.19	91.1 ±2.26	93.7 ±0.65	< 0.5 ±0.02	6,98 ±0.66	21.7 ±0.71	2.86 ±0.09
Small-leaved lime *Tilia cordata* Mill.	1088 ±17.0	3412 ±20.5	440 ±12.0	359 ±3.43	116 ±1.41	18.0 ±0.21	73.7 ±0.49	19.2 ±0.28	21.8 ±0.42	3.91 ±0.11
Royal paulownia *Paulownia tomentosa* (Thunb.) Steud.)	287 ±12.0	1325 ±10.6	177 ±4.24	213 ±4.24	97.7 ±1.98	11.0 ±0.57	< 0.5 ±0.02	19,0 ±0.78	19.1 ±0.74	4.48 ±0.12

Wood ash has been commonly used in the past as a fertilizer applied to agriculture soil. Ca is a valuable element in ash, gives ash the properties of agricultural lime. Ash is also a good source of K, P, and Mg (SAHOTA 2007). The application of ash to the soil fulfills the idea not only sustainable soil use, but also the secondary use of waste (FAZEKAŠOVÁ 2003).

Fibre characteristics

Fibre length

Fibre length is an important property with respect to paper and paperboard performance. Length and shape of fibres depends on the tree species (OLUWADARE and ASHIMIYU 2007). Deciduous trees produce short fibres, whereas coniferous trees produce long fibres. Typical fibres used in papermaking are short hardwood fibres (1–1.5 mm in length) and long softwood fibres (3–4 mm in length). Short fibres provide smoothness for printing papers, while long fibres provide paper strength. Long fibres create a stronger network compared to shorter fibres (DINWOODIE 1965).

The arithmetic and weighted fibre length distributions of the branch wood which differed significantly for examined species are showed in Fig. 1–6. European beech (Fig. 1A) and common hornbeam (Fig. 2A) were characterized by a wide fibre length distribution. Silver birch (3B), white willow (5B), European ash (4A), black poplar (4B), royal paulownia (6B), black alder (5A), small-leaved lime (6A), black locust (3A) and common oak (1B) ranged in a narrower range of fibre lengths. The fibre length distributions of branch wood of sycamore maple (2B) were in a very narrow range of fibre lengths.

The arithmetic average fibre length and weighted average fibre length of the branch wood of the examined tree species are given in Tab. 3. The arithmetic average fibre length and the weighted average fibre length were determined from the fibre length analysis. The arithmetic average fibre length of the branch woods ranged from 0.40 to 1.20 mm, while the weighted average fibre length ranged from 0.51 to 1.45 mm. The arithmetic average and weighted average fibre length of the branch woods increased in the following order: sycamore maple < common oak < black locust < small-lived lime < royal paulownia < black alder < European ash < black poplar < white willow < silver birch < common hornbeam < European beech.

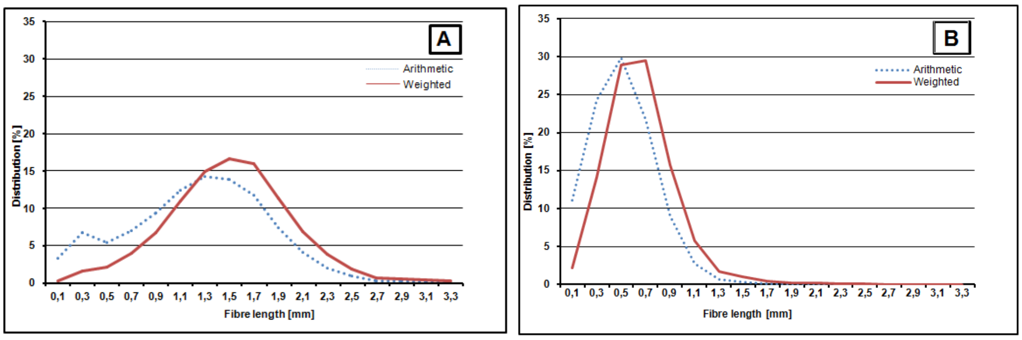

Fig. 1 Arithmetic and weighted fibre length distributions of branch wood of European beech (*Fagus sylvatica* L.) (A) and common oak (*Quercus robur* L.) (B).

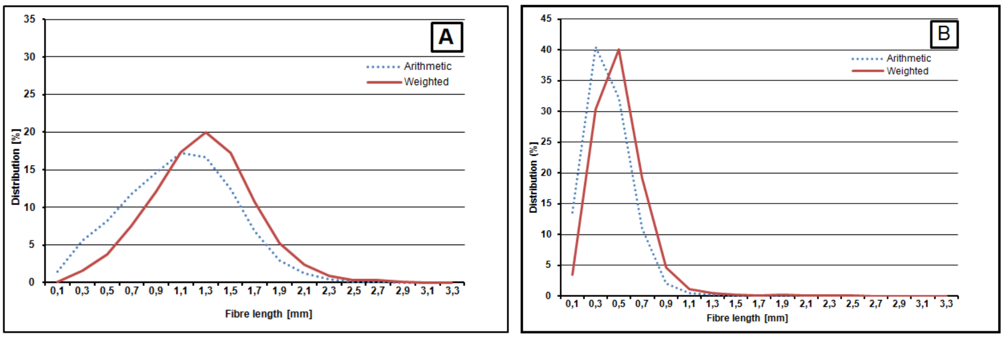

Fig. 2 Arithmetic and weighted fibre length distributions of branch wood of common hornbeam (*Carpinus betulus* L.) (A) and sycamore maple (*Acer pseudoplatanus* L.) (B).

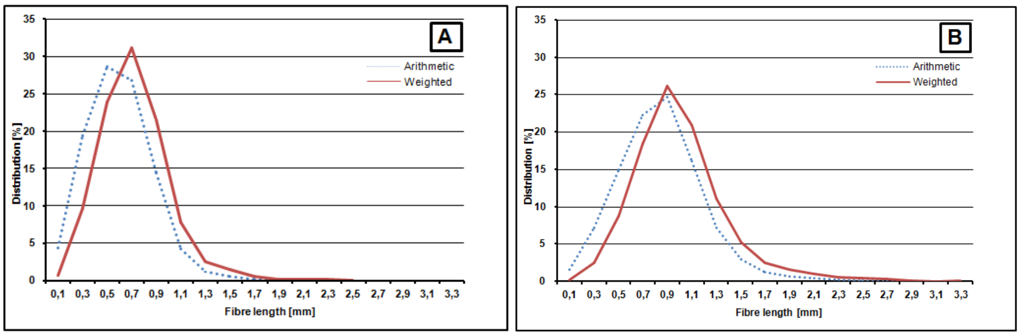

Fig. 3 Arithmetic and weighted fibre length distributions of branch wood of black locust (*Robinia pseudoacacia* L.) (A) and silver birch (*Betula pendula* L.) (B).

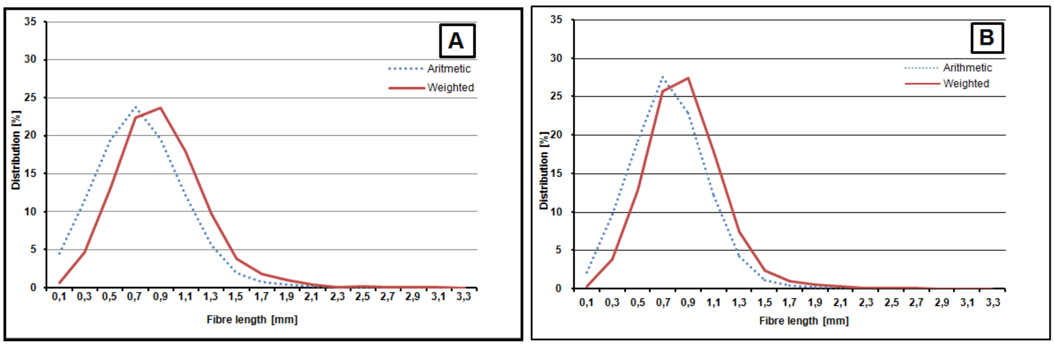

Fig. 4 Arithmetic and weighted fibre length distributions of branch wood of European ash (*Fraxinus* excelsior L.) (A) and black poplar (*Populus nigra* L.) (B).

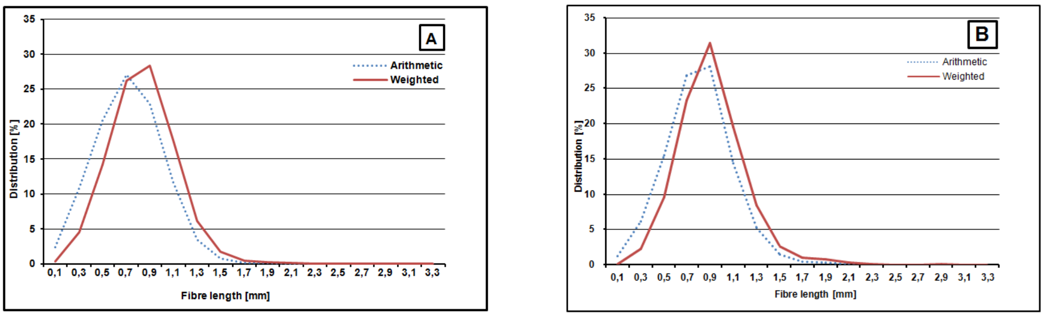

Fig. 5 Arithmetic and weighted fibre length distributions of branch wood of black alder (*Alnus glutinosa* L.) (A) and white willow (*Salix alba* L.) (B).

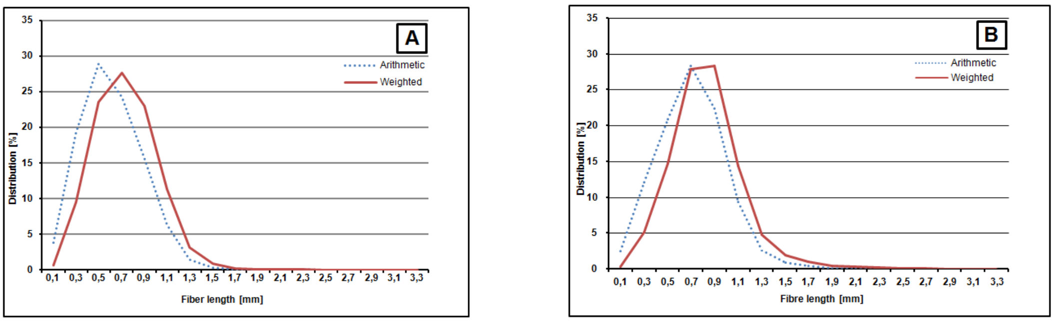

Fig. 6 Arithmetic and weighted fibre length distributions of branch wood of small-leaved lime (*Tilia cordata* Mill.) (A) and royal paulownia (*Paulownia tomentosa* (Thunb.) Steud.) (B).

The branch wood of *Betula platyphyla* Roth contained significantly shorter fibre length than stem wood (ZHAO *et al*. 2019a). The fibre length of the branch wood of the European black alder (*Alnus glutinos*a Gaertn.) was approximately about 0.2 mm shorter than the stem wood (VURDU 1977). According to the results published in the literature (WANG 1998), fibres with an average length greater than 0.4 mm are suitable for papermaking. Branch wood could be suitable for the production of low-grade paper and glued plates due to its medium fibre length (ZHAO *et al.* 2019a). Based on the above, it can be stated that the branch wood of the examined tree species can be used for the production of paper of different quality alone or in a mixture, with the exception of branch wood of sycamore maple (Fig. 2B) and common oak (Fig. 1B), which contained which a high proportion of short fibres.

Fibre coarseness

Fibre coarseness is defined as the weight per unit length of fibre expressed as milligrams per 100 m. The number of fibres per unit weight is related to the weight of each individual fibre, to the fibre coarseness and to the percentage of fibre wall in the fibre volume. There is a strong correlation between the number of fibres per unit weight and the coarseness of the fibres (WATSON and BRADLEY 2009). In short, lower fibre coarseness means higher sheet tensile strength, greater bonding area, and more fibres per tonne of pulp, all of which are attributes that are highly prized by technically sophisticated papermakers. Measuring the fibre coarseness has several advantages over measuring the widths of fibres since it is not only much easier and quicker but also includes the effects of fibre thickness, the size of the central canal (or lumen), and the density of the cellulosic material composing of fibres. The coarseness of fibres has an important effect on many properties of paper. Higher fibre coarseness is associated with thicker walled fibres. These fibres produce a more open and loosened paper structure. The corresponding papers are more porous, bulkier, and more absorbent. A better consolidation of the paper web is expected with a large number of fibres per milligram in the paper structure. The result is better interconnection and better properties dependent on bonding (tensile, folding, surface strength, surface smoothness) are achieved.

The fibres coarseness of the branch wood of European beech, common oak, common hornbeam, sycamore maple, black locust, silver birch, European ash, black poplar, black alder, white willow, small-leaved lime and royal paulownia ranged from 4.15 to 8.52 mg/ 100 m (Tab. 3). The fibre coarseness of the branch wood of examined tree species decreased in the following order: sycamore maple > black locust > common oak > European ash > common hornbeam > small-leaved lime > royal paulownia > European beech > white willow > black alder > black poplar > silver birch.

According to the results published in the work ZHAO (2019a), the branch wood of silver birch had significantly shorter fibres and lower coarseness than the stem wood. Branch wood of sycamore maple has the highest fibre coarseness and the shortest fibres from the examined tree species, therefore it is the least suitable for paper production.

Branch wood of European beech, common hornbeam, silver birch have fibres with low coarseness and longer fibre length, so they are the most suitable of the examined tree species for pulp and paper production. In addition, they have a high content of polysaccharides and a low content of Klason lignin, which is advantageous from the point of view of pulp production.

Branch wood can be used for light construction purposes or as a mixed material in paper production (SUANSA and AL-MEFARREJ 2020). The results presented in the work (SETH 2011) show that the fibres with higher coarseness have thicker walls, a smaller specific surface and a smaller bonding area as a result of which the pulp have lower strength.

Tab. 3 Fibre length and coarseness of branch wood of hardwood species.

Species	Arithmetic average fibre length ±SD [mm]	Weighted average fibre length ±SD [mm]	Fibre coarseness ±SD [mg/100 m]
European beech *Fagus sylvatica* L.	1.20 ± 0,01	1.45 ± 0,01	5.36 ± 0,06
Common oak *Quercus robur* L.	0,52 ± 0,00	0.66 ± 0,01	6.96 ± 0,12
Common hornbeam *Carpinus betulus* L.	1.09 ± 0,01	1.27 ± 0,01	5.93 ± 0,06
Sycamore maple *Acer pseudoplatanus* L.	0.40 ± 0,00	0.51 ± 0,01	8.52 ± 0,10
Black locust *Robinia pseudoacacia* L.	0.60 ± 0,00	0.73 ± 0,01	8.06 ± 0,04
Silver birch *Betula pendula* L.	0.86 ± 0,01	1.01 ± 0,01	4.15 ± 0,08
European ash *Fraxinus excelsior* L.	0.74 ± 0,01	0.91 ± 0,01	6.70 ± 0,14
Black poplar *Populus nigra* L.	0.76 ± 0,00	0.87 ± 0,01	4.17 ± 0,11
Black alder *Alnus glutinosa* L.	0.72 ± 0,01	0.84 ± 0,01	5.24 ± 0,10
White willow *Salix alba* L.	0.81 ± 0,01	0.92 ± 0,01	5.29 ± 0,05
Small-leaved lime *Tilia cordata* Mill.	0.61 ± 0,01	0.74 ± 0,01	5.91 ± 0,06
Royal paulownia *Paulownia tomentosa* (Thunb.) Steud.)	0.71 ± 0,01	0.84 ± 0,01	5.71 ± 0,08

CONCLUSIONS

Branch wood can be considered to be an important natural resource of future for production of biofuels, pulp and paper, but it has several disadvantages which limit its potential for commercial use compared to stem wood.

The content of polysaccharides in the branched wood of the examined tree species ranges from 63 to 69.6%, it decreases in the following order: common hornbeam > European ash > European beech > silver birch > black poplar > sycamore maple > white willow > common oak > black locust > small-leaved lime > black alder > royal paulownia. The Klason lignin content in branch wood ranged from 15.3 to 23.7%, it increased in the following order: small-leaved lime < common hornbeam < European beech < silver birch < European ash < white willow < common oak < black locust < sycamore maple < black poplar < black alder < royal paulownia. The arithmetic average and weighted average fibre length of the branch woods increased in the following order: sycamore maple < common oak < black locust < small-lived lime < royal paulownia< black alder < European ash < black poplar < white willow < silver birch < common hornbeam < European beech. The fibre coarseness of the branch wood of examined species decreased in the following order: sycamore maple > black locust > common oak > European ash > common hornbeam > small-leaved lime > royal paulownia > European beech > white willow > black alder > black poplar > silver birch.

In terms of industrial use branch wood is important Si concentration, which ranged from 28.5 to 116 $mg \cdot kg^{-1}$, Zn concentration (2.59–24.3 $mg \cdot kg^{-1}$) and Cu concentration (1.47–4.48 $mg \cdot kg^{-1}$).

REFERENCES

ANDERSEN, G.L., KRZYWINSKI, K. 2007. Mortality, recruitment and change of desert tree population in a hyper-arid environment. PloS ONE, 2(2), e208. DOI:10.1371/journal.pone.0000208.

ANJOS, O., SANTOS, A., SIMÕES, R., PEREIRA, H. 2014. Morphological, mechanical and optical properties of cypress. In Holzforschung, 68:861–995. doi: 10.1515/hf-2013-0125.

BEREŠOVÁ, K., ČUNDERLÍK, I. 1999. Morfológia vláknitých buniek smreka s rôznym stupňom poškodenia. In Drevo, štruktúra a vlastnosti, Zvolen: TU vo Zvolene, 1999, ISBN 80-228-0887-3, pp 17–22.

BHAT, K.M., BHAT, K.V., DHAMODARAN, T.K. 1985. Wood and bark properties of branches of selected tree species growing in Kerala. Research Report, Kerala Forest Research Institute, Peechi, Thrissur, India, December 1985.

CÁRDENAS-GUTIÉRREZ, M.Á., PEDRAZA-BUCIO, F.E., LÓPEZ-ALBARRÁN, P., RUTIAGA-QUIŃONES, J.G.R. 2018. Chemical components of the branches of six hardwood species. In Wood Research, 63(5): 795–808.

DADZIE, P.K., AMOAH, M., EBANYENHE, E, FRIMPONG-MENSAH, K. 2018. Characterization of density and selected anatomical features of stem wood and branch wood of *E-cylindricum*, *E-angolense* and *K-ivorensis* from natural forests in Ghana. In European Journal of Wood and Wood Products, 76(2): 655–667. DOI: 10.1007/s00107-017-1195-6.

DINUS, R.J. 2001. Genetic improvement of poplar feedstock quality for ethanol production. In Appl. Biochem. Biotechnol., 91: 23–34.

DINUS, R.J., PAYNE, P., SEWELL, M.M., CHIANG, V.L., TUSKAN, G.A. 2001. Genetic modifications of short rotation popular wood: Properties for ethanol fuel and fiber productions. In Crit. Rev. Plant Sci., 20: 51–69.

DINWOODIE, J.M. 1965. The relationship between fibre morphology and paper properties of: A Review of Literature. In Tappi J., 48: 440-447.

EL-HOSSEINY, F., ANDERSON D. 1999. Effect of fibre length and coarseness on the burst strength of paper. In Tappi J., 82:202–203.

FAZEKAŠOVÁ, D. 2003. Trvalo udržateľné využívanie pôdy – vymedzenie a hodnotenie indikátorov a parametrov vývoja pôdy (Sustainable land use - definition and evaluation of indicators and parameters of soil development). Prešov: FHPV PU, 76 pp. ISBN 80-8068-228-3.
FENGEL, D., WEGENER, G. 1984. Wood – Chemistry, Ultrastructure, Reactions, Berlin: De Gruyter, 1984.
FIŠEROVÁ, M., OPÁLENÁ, E., KOČANOVÁ, N. 1986. Chemické zloženie stromovej hmoty topoľa (Chemical composition of poplar tree mass). In Papír a celulóza, 41, V31–V 35.
FROMM, J. 2010. Wood formation of trees in relation to potassium and calcium nutrition. In Tree Physiology, 30(9): 1140–1147. https://doi.org/10.1093/treephys/tpq024.
KRISHNA, K.P., SHAKTI, S.C., ARUN, N.K. 2017. In Wood is good: Current trends and future prospects in wood utilization. Singapore: Springer.
LEICH, M., MILLER, S. 2017. Optimizing wood utilization based on whole tree inherent property maps, in Wood is good: Current trends and future prospects in wood utilization, PANDEY, K.K., RAMAKANTHA, V., CHAUHAN, S.S., KUMAR, A.N.A. (eds.), Springer, Singapore, pp 3–17.
KEAYS J.L., HATTON J.V., BAILEY G.R., NEILSON R.W. 2015. Present and Future Uses of Canadian Poplars in Fibre and Wood Products. Available online: http://digitalcommons.usu.edu/aspen_bib/5234/
LI, Q., JIA, Z, FENG, L., He, L., Yang, K. 2018. Dynamics of biomass and carbon sequestration across a chrono sequence of *Caragana intermedia* plantations on Alpine sandy land. In Scientific Reports, 8(1), 12432. DOI: 10.1038/s41598-018-30595-3.
LINDSTRÖM, H. 2001. Intra-tree models of basic density in Norvay spruce as an input to simulation software. In Silva Fennica, 34(4): 411–421. DOI: 10.14214/sf622.
MARTIN, J.A., ESTEBAN, L.G., DE PALACIOS, P., FERNANDEZ, F.G. 2010. Variation in wood anatomical traits of *Pinus sylvestris* L. between Spanish regions of provenance. In Trees Structure and Function, 24(6): 1017–1028. DOI: 10.1007/s00468-010-0471-4.
NURMI, J. 2007. Recovery of logging residues for energy from spruce (*Picea abies*) dominated stands. In Biomass Bioenergy, 31(6): 375–380. DOI: 10.1016/j.biobioe.2007.01.011.
OKAI, R., BOATENG, O. 2007. Analysis of sawn lumber production from logging residues of branchwood of *Aningeria robusta* and *Termina liaivorensis*. In European Journal of Forest Research, 126(3): 385–390. DOI: 10.1007/s10342-006-0157-z.
OLUWADARE, A.O., ASHIMIYU, O.S. 2007. The Relationship between Fibre characteristics and Pulp-sheet Properties of *Leucaena leucocephala* (Lam.) De Wit. In Middle-East Journal of Scientific Research, 2(2):63–68.
ÖHMAN, M., BOMAN, C., HEDMAN, H., NORDIN, A., BOSTRÖM, D. 2004. Slagging tendencies of wood pellet ash during combustion in residential pellet burners. In Biomass and Bioenergy, 27: 585–596.
PITMAN, R. 2006. Wood ash use in forestry – a review of the environmental impacts. In International Journal of Forest Research, 79(5): 563–588. https://doi.org/10.1093/forestry/cpl041.
SAHOTA, T.S. 2007. Lime or wood ash? Which one should apply? In Northwest Link, pp 6–7.
SETH, R.S. 1995. The effect of fiber length and coarseness on the tensile strength of wet webs: a statistical geometry explanation. In Tappi J., 78(3): 99–102.
SETH, R.S. 2011. Fibre quality factor in papermaking – II The importance of fibre coarseness, In Symposium U-Materials Interactions Relevant to the Pulp, Paper and Wood Industries, pp 143–197. DOI: https//doi.org./10.1557/PROC-197-143.
SHMULSKY, R., JONES, P.D. 2011. Forest Products and Wood Science an Introduction sixth edition, John Wiley and Sons Ltd. Publisher, UK.
SJÖSTRÖM, E. 1993. Wood Chemistry: Fundamentals and Applications, second edition, Academic Press, San Diego, 1993.
SUANSA, N.I., AL-MEFARREJ, H.A. 2020. Branch wood properties and potential utilization of this variable resource. In BioResources, 15(2): 479–491.
ŠPANIČ, N., JAMBREKOVIČ, V., KLARIČ, M., 2018. Basic chemical composition of wood as parameter in raw material selection for biocomposite production. In Cellulose Chem. Technol., 52(3–4): 163–169.

VURDU, H. 1977. Anatomical characteristics of stem, branch and root wood in European black alder (*Alnus glutinosa* L. Gaertn). Iova State University Capstones, Theses and Dissertation.
TARELKIN, Y., HUFKENS, K., HAHN, S., VAN DENBULCKE, J., BASTIN, J.-F., ILONDEA, B.A., DEBEIR, O., VAN ACKER, J., BEECKMAN, H., DE CANNIÉRE, C. 2019. Wood anatomy variability under contrasted environmental conditions of common deciduous and evergreen species from central African forests. In Trees, 33(3): 893–909. DOI:10.1007/s00468-019-01826-5.
WANG, J. 1998. Important achievements in the field of paper fiber morphology in the 20th century. In Pap. Paper Making, 4: 7–9. DOI:10.13472/j.ppm.1998.04.002.
WANG L., DIBDIAKOVA J. 2014. Characterization of ashes from different wood parts of norway spruce tree. In Chemical Engineering Transactions, 37: 37–42. DOI: 10.3303/CET1437007
VESTERINEN, P. 2003. Wood ash recycling state of the art in Finland and Sweden. In VTT Research Report/PRO2/6107/03/31.10.203 www.cti2000it/solidi/wWoodAshReport%20VTTpdf
WATSON, P., BRADLEY, M. 2009. Canadian pulp fibre morphology: Superiority and consideration for end use potential. In The Forestry Chronicle, 85(3): 401–408.
ZHAO, X., GUO, P., ZHANG, Z., WANG, X., PENG, H., WANG, M. 2018. Wood density and fibre dimensions of root, stem and branchwood of *Populus unsuriensis* Kom. Trees. In BioResorces, 13(3): 7026-7036. DOI: 1015376/biores.13.3.7026-7036.
ZHAO, X., GUO, P., PENG, H., ZHAO, P., YANG, Y., ZHANG, Z. 2019a. Potential of pulp production from whole-tree wood *of Betula platyphylla* Roth based on wood characteristics. In BioResources, 14(3): 10. DOI: 10.15376/biores.14.3.7015-7024.
ZHAO, X., GUO, P., ZHANG, Z., PENG, H. 2019b. Anatomical features of branch wood and stem wood of *Betula costata* Trautv. from natural secondary forest in China. In BioResources, 14(1): 1980–1981. DOI: 1015376/biores.14.1.1981-1991.
ZOBEL, B.J., BUIJTENEN, J.P.V. 1989. Wood variation: Its causes and control, Berlin: Springer-Verlag.
ZOBEL, J., JACKSON, B.J. 1995. Genetics of Wood Production. Berlin Heidelberg: Springer- Verlag.

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