

The Impact of Bark Content of Wood Biomass on Biofuel Properties

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Woody biomass is an abundant, renewable energy source. Forest residue is the fraction remaining after harvest and the outtake of wood timber, including tree tops and bark. Compared with the wood portion, bark has a wide variation of ash content. Wood usually has a relatively low ash content, while bark has considerably higher ash content, which may generate clinker in the furnace and thereby tends to create more demand for maintenance. High ash content also generates more particulate emissions. Different types of bark were studied in the present work in terms of their effect on energy content, moisture, and ash content. The ash content of three different samples (Norway spruce, birch, and European beech) were measured at 550 and 815 °C. The results showed the impact of bark content on all parameters, in particular the calorific value and ash content. The ash content increased with increasing bark content. The addition of 1% bark content resulted in increases of ash content in the range 0.033 to 0.044%.

Keywords: Woody biomass; Bark content; Ash; Energy content; Moisture

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INTRODUCTION

The use of firewood for combustion processes in households has a substantial and, from a long-term view, contribution to environmental impacts and sustainability. The bark, which is often present at wood burning, causes a demand for more frequent maintenance of heat sources. Increased ash content in the bark also generates more solid polluting particles.

Tree matter (dendromass) consists of bark, wood, and green material such as branches and needles (or leaves, in the case of deciduous trees). Softwoods have the following portions of various parts: 5% to 15% bark, 70% to 80% wood, and 10% to 15% green mass. Hardwoods have the following portions: 5% to 20% bark, 60% to 75% wood, and 15% to 20% green matter (Blažej 1975). The thickness of the cross-sectional specimen cut from a tree affects the proportion of bark in wood (Dzurenda and Jandačka 2010). It has to be taken in consideration that bark content depends very much on the investigated parts of the tree.

The diverse composition of tree bark reflects its protective, conductive, and dividing functions. Bark, in comparison with wood, contains more ash, less cellulose, and more lignin (Dzurenda *et al.* 2014). Bark is richer in minerals, of which the dominant component is calcium (82% to 95%). It also contains small amounts of potassium, magnesium, and other elements, which represent less than 1% of its composition. The ash content of bark is 5% to 10%, but under realistic conditions during combustion it could be 1.5% to 10.5% (Kurschner 1952; Blažej 1975).

In terms of energy, wood and bark are characterized by a high content of volatile substances: 74% coniferous wood, 76% deciduous wood, and 75% bark. The chemical composition of the bark and wood of deciduous trees varies considerably. Bark has a higher content of lignin (40% to 50% *versus* 18% to 25%) and extractive substances (5% to 10% *versus* 2% to 5%) compared with wood, and a smaller proportion of carbohydrates (cellulose and hemicelluloses) (32% to 45% *versus* 74% to 80%) (Jandačka *et al.* 2007).

This article discusses the impact of bark content on the moisture, heat of combustion, calorific value, and ash content of woody biomass. The subjects of the experiment are the parameters of coniferous and deciduous trees. The goal of this research was to investigate the negative impacts of bark content on firewood properties.

EXPERIMENTAL

Within the experimental work, the features of three types of woody biomass were tested: Norway spruce (*Picea abies* Karst), birch (*Betula pendula* Roth), and beech (*Fagus sylvatica* L.).

Norway spruce (*Picea abies*) is the most widespread tree in northern Slovakia. Because of its characteristics, it is among the most economically important tree species (Čarnogurská *et al.* 2011). Tested spruce wood came from the region of Zilina in the Slovak republic. After felling, it was stored in the exterior, and protected from external weather conditions. During the storage period, natural drying and partial degradation of the quality occurred. The individual samples of spruce wood were derived from one piece of wood that was approximately 1.5 m long and had an average diameter of about 15 cm. A given sample spruce was cut out from the middle part of the piece of wood.

Weeping birch (*Betula pendula*), a tree species from the birch family (Betulaceae), is a type of hard, deciduous tree. In Slovakia, birch grows from the lowest altitudes up to 1.670 meters above sea level. Birch wood is medium-weight, slightly hard, tough, elastic, and relatively easy to work with. Tested birch wood comes from the region of Zilina, directly from the area of the University of Zilina, in the Slovak republic. After felling, it was stored for approximately 24 months in the exterior and protected from external weather conditions.

During the storage period, natural drying occurred. The birch wood samples were taken from one piece of wood with a length of approximately 0.5 m and an average diameter of approximately 22 cm. A given sample of birch wood was cut from the middle part of the piece of wood.

European beech (*Fagus sylvatica*) is a deciduous tree of the beech family (Fagaceae). It is the most widespread mechanical pulp in the Slovak forests, with the highest representation of all deciduous woody plant species (Račko and Čunderlík 2005). Its wood is medium-weight. It is hard, heavy, inflexible, and has a pinkish color. The tested beech wood originated in areas around the city Kysucke Nove Mesto in the Slovak republic. After felling, it was stored for approximately 36 months in the exterior and protected from external weather conditions.

During the storage period, natural drying occurred. The individual samples were taken from one piece of wood with a length of approximately 0.7 m and an average diameter of about 18 cm. A given sample was cut from the center of the piece of wood. From individual mechanical pulps, the following samples were created:

1. N1 - Norway spruce without bark
2. N2 - Norway spruce with 5% bark content
3. N3 - Norway spruce with 10% bark content
4. N4 - Bark of Norway spruce (100%)
5. B1 - Weeping Birch without bark
6. B2 - Weeping Birch with 5% bark content
7. B3 - Weeping Birch with 10% bark content
8. B4 - Bark of Weeping Birch (100%)
9. E1 - European beech without bark
10. E2 - European beech with 5% bark content
11. E3 - European beech with 10% bark content
12. E4 - Bark of European beech (100%)

Samples N1, N4, B1, B4, E1, and E4 were produced directly from pieces of wood, and represent samples of wood without bark to samples of 100% bark. The samples with 5% and 10% bark contents were created by mixing samples without bark with samples of corresponding bark contents. Ratios of 5% and 10% were selected due to the high number of trees with bark contents in the range of 5 to 10%, based on the results of various works (Kurschner 1952; Blažej 1975; Dzurenda and Jandačka 2010; Filbakk *et al.* 2010).

Individual samples of wood biofuel were prepared in accordance with standard EN 14780 (2012). The main goal of sample preparation was to reduce the sample to match the size corresponding to one or more testing specification, which are usually smaller than the original sample. The guiding principle in reducing the sample is that its composition during all steps of preparation may not change. Each of the created parts must represent the original sample. To achieve this goal, each particle in the sample before division must have the same probability of entering the part obtained by the dividing.

The samples of wood biofuel were reduced to fractions with sizes of 10 to 30 mm with cutting tools. To avoid the change of moisture of the material during cutting, the evolution of heat and air flow through the material was prevented. Subsequently, a cutting mill was used to reduce the size of the sample fractions to less than 1 mm. From each sample of wood biofuel, 150-g fractions were created, which were used to test various properties (Fig. 1). The tested parameters of the prepared samples of dendromass included moisture content, higher and lower heating values, and ash content.

The moisture content was determined in accordance with EN 14774-2 (2010) (Pňakovič and Dzurenda 2015). Empty, clean aluminum plates were weighed to an accuracy of 0.001 g, and the sample of dendromass was evenly distributed over the surface of the plate so that 1 cm² of the surface was occupied by 1 g of the sample. The filled plate was weighed with an accuracy of 1 mg. Subsequently, the sample with the plate was dried at 105 °C ± 2 °C to a constant weight (the weight change did not exceed 0.2% of the total weight loss for a further period of 60 min). The samples were dried in the drying scale RADWAG WPS 50 SX (RADWAG, Poland). The final moisture content of the sample as a percentage by mass was determined by Eq. 1,

$$M_{ar} = \frac{(m_2 - m_3) + m_4}{(m_2 - m_1) + m_4} \cdot 100 \text{ [%]} \quad (1)$$

where m_1 is the weight of the empty drying plate in grams, m_2 is the weight of the drying plate and sample before drying in grams, m_3 is the weight of the drying plate and sample after drying in grams, and m_4 is the weight of the moisture of wrapping in grams.

For each sample, the experiment was performed three times, and the resulting value was the average of the three measurements.

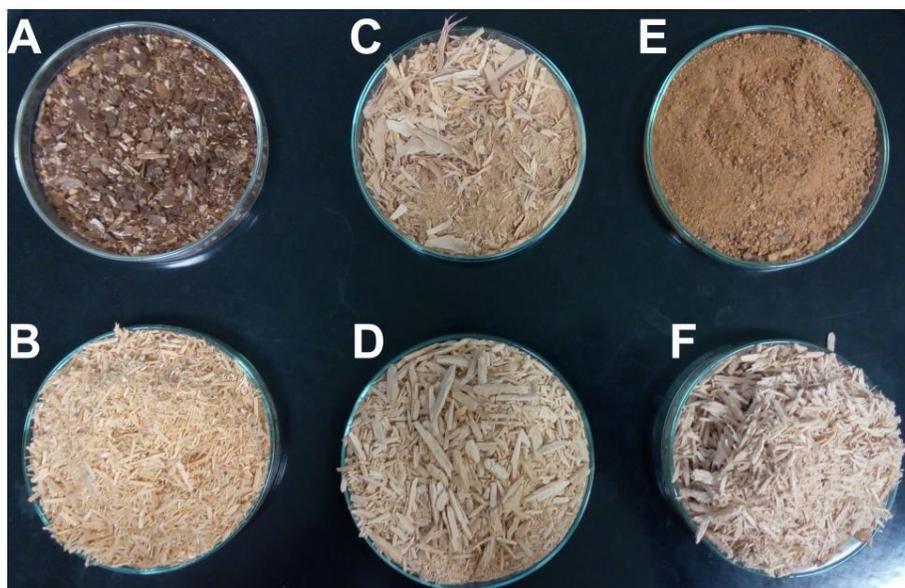


Fig. 1. Prepared samples of wood biofuels: A: Norway spruce – bark; B: Norway spruce without bark; C: Weeping birch – bark; D: Birch without bark; E: European beech – bark; F: European beech without bark

In accordance with ISO 1928 (2003), the values of combustion heat of the samples were determined using an LECO AC 500 calorimeter (Manufacturer- LECO; Manufacturer location-USA) and the following procedure: The prepared sample of dendromass was weighed to an accuracy of 0.1 mg using an analytical scale. The measured weight value was recorded into the program of the calorimeter. The weighed sample was placed on the crucible in a pressure vessel. The ignition wire was attached to the electrodes in a pressure vessel. The resistance of the ignition circuit of the pressure vessel did not exceed 5 to 10 Ω . The ignition wire was tied or firmly attached to the ignition substance, which was brought into contact with the sample of dendromass. The crucible was placed in the holder symmetrically in relation to the surrounding wall of the pressure vessel. The specified amount of distilled water was added to the pressure vessel. Its amount was exactly the same during calibration and determination measurements. The amount of distilled water added to the pressure vessel for biofuels was 10 ± 0.1 mL. The pressure vessel was charged with oxygen to a pressure of 3.0 ± 0.2 MPa. The water in the calorimeter was heated to a selected starting temperature in relation to the ambient temperature within the range ± 0.3 K. The amount of water in the calorimetric vessel was the same for all tests, to an accuracy of 0.5 g. The pressure vessel was mounted in the calorimeter vessel. After the start of measurement, the calorimeter measured the water temperature in the calorimeter vessel to an accuracy of 0.001 K. After the temperature stabilized, the sample was ignited by a resistive wire. A calorimeter recorded the temperature of the water in the calorimeter vessel to an accuracy of 0.001 K at regular intervals. A calorimeter determined the combustion heat of the dendromass sample from the increase in the water's temperature.

The relation of calorific value and combustion heat was determined using the following formula (Eq. 2),

$$Q_i = Q_S - 2.453 \cdot (M_{ar} + 9H_2)[MJ \cdot kg^{-1}] \quad (2)$$

where Q_S is the combustion heat of fuel in $MJ \cdot kg^{-1}$, M_{ar} is the relative humidity of fuel in $kg \cdot kg^{-1}$, and H_2 is the hydrogen content of fuel in $kg \cdot kg^{-1}$.

Combustion heat and calorific value were determined five times for each sample, and the resulting value is the average of these five measurements.

The ash content of the prepared samples of dendromass was determined according to standard EN 14775 (2010), which is used to determine the ash content of solid biofuel, and according to standard ISO 1171 (2003), which is used to determine the content of solid fuel ash. In order to compare the results of ash content with results from previous manuscripts, the procedure in accordance with standard ISO 1171 was also used in this research. Before determining the ash content, the samples of dendromass were dried in an oven at a temperature of $105 \text{ }^\circ\text{C} \pm 2 \text{ }^\circ\text{C}$. After drying, the samples were temporarily placed in a desiccator. Subsequently, the empty alumina bowl, which had been recently heated to $550 \text{ }^\circ\text{C} \pm 10 \text{ }^\circ\text{C}$ and then cooled to ambient temperature, was weighed with an accuracy of 0.1 mg. Approximately 10 g of crushed-mixed sample was evenly placed in the bottom of the bowl. Subsequently, the bowl was weighed to an accuracy of 0.1 mg and placed in the cold muffle furnace, which was heated in compliance with standard EN 14775 (2010), according the following procedure: Over 30 min, there was a steady increase in oven temperature to $250 \text{ }^\circ\text{C}$ at a rate of approximately $7.5 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$. A temperature of $250 \text{ }^\circ\text{C}$ was maintained for 60 min to release the volatiles from the sample before combustion. Over 30 min, the constant increase of the temperature continued up to $550 \text{ }^\circ\text{C}$ at a rate of approximately $10 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$. A temperature of $550 \text{ }^\circ\text{C}$ was maintained for at least 120 minutes. According to the standard ISO 1171 (2003), the sample was first heated at a rate of $7.5 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$ to $500 \text{ }^\circ\text{C}$. The sample remained at this temperature for 60 min, and then the temperature in the muffle furnace increased at a rate of approximately 5 to $7.5 \text{ }^\circ\text{C} \cdot \text{min}^{-1}$ up to $815 \text{ }^\circ\text{C}$. The sample remained at this temperature for 360 min. The bowl and its contents were removed from the muffle furnace, and after cooling were weighed with an accuracy of 0.1 mg. The ash content was determined using Eq. (3),

$$A_d = \frac{(m_3 - m_1)}{(m_2 - m_1)} \cdot 100 [\%], \quad (3)$$

where m_1 is the weight of the empty bowl in grams, m_2 is the weight of the bowl with the test sample in grams, and m_3 is the weight of the bowl with ash in grams.

RESULTS AND DISCUSSION

The resulting values of the parameters of each sample of dendromass, including moisture, combustion heat, calorific value, and ash content obtained at a maximum temperature of $550 \text{ }^\circ\text{C}$ and the ash content obtained at a maximum temperature of $815 \text{ }^\circ\text{C}$ are given in Table 1.

Based on the obtained results, it can be concluded that bark content significantly affects several parameters of dendromass.

Ash formation was also predicted using a simple mathematical model. To obtain a correlation for calculating ash content (A_{dM}), the proposed mathematical model uses a linear regression, which examines the relationship between two variables. It was necessary to choose the method of least squares to minimize the sum of squares of residues.

Table 1. Moisture, Gross Calorific Value, Calorific Value, and Ash Content of Tested Wood Biofuels *

Sample	Moisture (%)	Higher Heating Value (MJ.kg ⁻¹)	Lower Heating Value (MJ.kg ⁻¹)	Ash Content (550 °C) (%)	Ash Content (815 °C) (%)
N1	9.55±0.36	17.910±0.087	16.289±0.079	0.240±0.017	0.168±0.012
N2	9.71±0.21	17.782±0.049	16.177±0.043	0.495±0.024	0.356±0.019
N3	9.94±0.19	17.712±0.073	16.077±0.067	0.731±0.047	0.551±0.039
N4	12.36±0.31	15.596±0.091	14,034±0.082	5.253±0.172	3.874±0.128
B1	6.97±0.18	18.661±0.102	17.101±0.093	0.401±0.021	0.277±0.019
B2	6.94±0.11	18.886±0.098	17.324±0.091	0.438±0.042	0.332±0.025
B3	6.87±0.17	19.291±0.158	17.731±0.147	0.492±0.033	0.412±0.027
B4	6.24±0.15	23.554±0.134	22.011±0.125	1.136±0.112	0.943±0.099
E1	10.13±0.09	17.772±0.069	16.155±0.062	0.472±0.015	0.306±0.007
E2	10.12±0.24	17.699±0.084	16.084±0.072	0.721±0.046	0.514±0.041
E3	9.94±0.13	17.786±0.073	16.173±0.063	1.224±0.111	0.785±0.074
E4	9.12±0.31	17.857±0.099	16.263±0.090	7.804±0.152	5.022±0.067

* (N1 - Norway spruce without bark, N2 - Norway spruce with 5% bark content , N3 - Norway spruce with 10% bark content, N4 - Bark of Norway spruce (100%), B1 - Weeping Birch without bark, B2 - Weeping Birch with 5% bark content, B3 - Weeping Birch with 10% bark content, B4 - Bark of Weeping Birch (100%), E1 - European beech without bark, E2 - European beech with 5% bark content, E3 - European beech with 10% bark content, E4 - Bark of European beech (100%))

The prediction of ash content was calculated according following equation,

$$A_{dM} = b_0 + b_1 \cdot B_d \quad (4)$$

where b_0 is a constant, b_1 is a regression coefficient, and B_d is bark content. Input data for prediction of A_{dM} are presented in Table 2.

Table 2. Regression Coefficients for Prediction of Ash Content

Symbols	Indication	Norway Spruce: N1-N4	Weeping Birch: B1-B4	European Beech: E1-E4
b_0	constant	0.238134	0.406846	0.43701
b_1	regression coef.	5.014317	0.7301008	7.367791
R	correlation index	0.999996647	0.999709622	0.999853209
σ [%]	standard deviation	0.00758218	0.010275713	0.073720283

Calculated values of ash content by the Eq. 4 and correlation coefficients in Table 2 indicate high accuracy, since the standard deviation σ of all samples was less than 0.0737%. High accuracy of the mathematic model confirms high levels of correlation index R exceeding the value of 0.99.

The high accuracy of the model is also confirmed by comparison of measured results (A_d) and calculated results by the mathematical model (A_{dM}) in the Table 3.

Table 3. Comparison of Measured and Predicted Ash Content

Samples	A_d [%]	A_{dM} [%]	Residues [%]
N1	0.24	0.238133822	0.00187
N2	0.495	0.488849679	0.00615
N3	0.731	0.739565536	0.0086
N4	5.253	5.252450962	0.00055
B1	0.401	0.406846013	0.00585
B2	0.438	0.443351054	0.00535
B3	0.492	0.479856095	0.01214
B4	1.136	1.136946838	0.00095
E1	0,472	0.437010082	0.03499
E2	0,721	0.805399633	0.0844
E3	1,224	1.173789184	0.050211
E4	7,804	7.8048011	0.0008

In the case of spruce wood, isolated bark contained approximately 2.81% more moisture compared with wood without bark. Mass fractions of 5% and 10% bark, alternatively, resulted in respective increases in humidity. The combustion heat and calorific value of the tested samples of spruce wood was relatively low compared with the results mentioned in various works (Jandacka *et al.* 2007; Malat'ák and Vaculik 2008; Dzurenda and Jandačka 2010; Dzurenda *et al.* 2014), given that it was older spruce wood of lower quality. The bark of the tested spruce wood also had a lower calorific value by approximately 2.26 MJ.kg^{-1} , which is inconsistent with previous works (Ivask 1999; Jandacka *et al.* 2007; Garcia *et al.* 2012; Owens and Cooley 2013), which state that the combustion heat of bark of softwoods is higher than the combustion heat of softwoods without bark. The addition of bark in the amount of 5% to 10% proportionally reduced the combustion heat and calorific value of individual samples. The measurement of ash content confirmed the results of previous works (Kurschner 1952; Filbakk *et al.* 2010; Martiník *et al.* 2014), that ash content in the bark of spruce wood is about 20 times higher than in spruce wood without bark. The mass fraction of bark in spruce wood of 5% and 10%, alternatively, proportionally increased ash content in comparison with the ash content in samples of spruce without bark.

The bark of weeping birch in comparison with the wood of weeping birch without bark contained 0.73% less moisture. The humidity of weeping birch wood and the bark of weeping birch were very similar, and the mass fraction of bark of 5% and 10%, alternatively, did not have a significant effect on the moisture of biofuels. The combustion

heat and calorific value of the test samples of weeping birch wood were comparable with the results described in previous works (Jandacka *et al.* 2007; Walle *et al.* 2007; Dzurenda and Jandačka 2010). The bark of tested birch wood in comparison with birch wood without bark had a higher calorific value by approximately 4.28 MJ.kg^{-1} . The addition of bark in the amount of 5 to 10% increased the calorific value of individual samples from $17.101 \text{ MJ.kg}^{-1}$ to 17.32 to 17.73 MJ.kg^{-1} . The measurement of ash content confirmed the results of previous works (Kurschner 1952; Garcia *et al.* 2012; Owens and Cooley 2013); that the ash content of birch bark is about three times higher than the ash content of birch wood without bark. The mass fraction of birch bark of 5% and 10%, alternately, proportionately increased ash content compared with samples of birch wood without bark.

Testing of beech wood revealed that parameters such as humidity, combustion heat, and the calorific value of beech wood with bark and the bark of beech wood differed only slightly. The same trend was observed for samples of beech wood with a portion of bark. The measurements of ash content confirmed the results of previous works (Kurschner 1952; Jandacka *et al.* 2007; Garcia *et al.* 2012; Owens and Cooley 2013), and confirmed that the ash content in the bark of beech wood is about 16 times higher compared with beech wood without bark. The mass fraction of beech bark of 5% and 10%, alternately, proportionately increased ash content compared with ash content in samples of beech wood without bark.

Experimental measurements of the ash content of individual samples of dendromass confirmed the results of previous works (Pňakovič 2014). Ash content determined in accordance with standard ISO 1171 (2003) was lower by approximately 28% than ash content determined in accordance with standard EN 14775 (2010). This was caused by the weight loss of ash caused by the decomposition of carbonates of calcium, magnesium, and potassium under temperatures higher than $600 \text{ }^{\circ}\text{C}$. Based on these differences in results, depending on the method used, it is necessary to compare the obtained results only with results obtained by the same method (Pňakovič 2014).

A higher proportion of bark significantly increased the ash content, which can negatively affect the combustion process, especially in the context of the lower melting temperature of ash of bark compared with the melting temperature of ash from the combustion of wood. Ash in combustion boilers can cause various problems. It can inhibit heat transfer in heat exchangers, which can cause corrosion of heat transfer surfaces. In the case of biofuels, compounds such as potassium, sodium, sulphur, and chlorine are monitored. These particles change into the molten phase at around $700 \text{ }^{\circ}\text{C}$ and become sticky ash, which decreases heat flux of the heat exchange surface (Holubcik *et al.* 2015).

CONCLUSIONS

1. From the resulting qualitative parameters, it can be concluded that a higher proportion of bark in softwoods, such as Norway spruce (*Picea abies*), may result in a lower calorific value than spruce wood without bark, especially in the case of older wood. A higher proportion of bark significantly increases the ash content, which can negatively affect the combustion process, especially in the context of the lower melting temperature of ash of spruce bark compared with the melting temperature of ash from the combustion of spruce wood.

2. Based on these results, it can be concluded that a higher proportion of bark in hardwoods, particularly birch (*Betula pendula* - Roth), increases combustion heat and calorific value. A higher proportion of bark also significantly increases ash content, therefore it is necessary to adjust the combustion device.
3. In view of the negative characteristics of the bark of trees, in most wood processes it is removed and treated as a waste component. In view of its relatively high calorific value, it would be appropriate to make use of its energy with respect to its negative characteristics, in particular its higher ash content and the low melting temperature of its ash.

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