

Renewable Pellets Obtained from Aspen and Birch Bark

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In the industrial processing of logs, large amounts of bark can be utilized as pellets. This study sought to establish conditions for the efficient use of bark, in the form of pellets, as a solid, renewable fuel. First, the physical properties of the bark (10% moisture content, 618-kg/m³ density for aspen, and 749-kg/m³ density for birch) and pellets obtained from the shredded bark were determined. Then, the calorific properties (calorific value, calorific density, and ash content) of the shredded native bark and bark treated at 180 °C, 200 °C, and 220 °C for 1h, 2h, and 3 h were determined. The sawdust samples that underwent the torrefaction treatment were analyzed to find the mass loss. The mass losses of the birch bark were 20.0% (native bark) to 39.0% after a heat treatment at 220 °C for 3 h. An increased calorific value, up to 9.6%, showed that both the temperature and duration of the treatment improved the calorific properties of the bark. The findings of this paper highlighted the fact that bark can be used as a fuel source in log processing factories.

Keywords: Bark; Briquettes; Pelletizing; Calorific value; Ash content; Mass loss

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INTRODUCTION

Bark is the exterior layer of trees that protects them against insects and their larvae, the sun, cold, frost, and other external factors. Bark also protects two fragile tissues positioned immediately beneath it, the cambium, which is responsible for growth, and the leading tissue, which is responsible for transferring nutrients from the soil to the leaves (Şen *et al.* 2011). On average, the bark account for 10% of the trunk volume, but it varies based on the age and diameter of the tree (Quilhó and Pereira 2001). Typically, bark is made up of two layers, the outer and inner parts, which are indistinct microscopically (Rios *et al.* 2014). Similar to the rest of the tree, the bark has developmental growth tissue called vascular cambium. Bark has low contents of cellulose and hemicellulose, but a higher content of secondary substances, such as extractives and minerals (Calderón *et al.* 2017). The outer walls of bark contain a fatty substance called suberin, which protects it against the loss of moisture or attack from insects and xylophagous fungi. Although it has the same anatomical structure as wood, bark is more brittle, softer, less dense, and more colorful (Miranda *et al.* 2013). These reasons are why bark is easily transformed into small particles through processing and why its presence in products, such as timber, veneers, particleboards, fiberboards, *etc.*, is not accepted and is restricted.

When processed for veneer, medium density fiberboard (MDF), oriented strand board (OSB), and other products, logs are peeled, resulting in large amounts of bark as a byproduct. For example, the peeling of logs in a large OSB factory can result in enough bark that an entire factory warehouse would be filled in less than a year. In addition to bark being able to gridlock production, it is easily biodegradable and can create serious

environmental problems in a very short time. Therefore, in large woodworking companies, there must be quick and viable solutions to efficiently use bark from the manufacturing stream. Problems with the bark also occur within wood exploitation activities, especially during collection, intermediate storage, and primary processing of logs, where large amounts of bark are peeled off the trunk when the logs are handled.

The main uses of bark are as fuel and fertilizer in agriculture. Additionally, bark has other more specific uses, such as for masks, interior decorative items, fishing materials, and thermal insulation boards. Also, tannin can be obtained from Mediterranean oak (*Quercus suber*), which is scraped and collected every 10 years. Other uses for bark include flooring, gaskets, tannins, spices (cinnamon and quinine from *Cinchona* spp.), food, resin, latex, poisons, and aspirin. Historically, bark has also been used to make cloth, canoes, cordage, and ropes (Rios *et al.* 2014).

Bark is often used as a renewable fuel, especially in large OSB, MDF, and timber factories. Bark is obtained in bulk from the peeling process and is not dried. This is a simple and inexpensive method for utilizing bark, but the combustion efficiency is very poor because of the high and non-uniform moisture content of the bark and low density of the fuel material. The deficiencies of bark also include a high biodegradability when wet (requiring drying and sheltering against external elements) and it can be transformed into small particles during transportation, preparation, and transfer to a combustion installation.

The utilization of briquettes and pellets in the wood fuel industry has created an opportunity for the use of other lignocellulosic resources, such as grains (wheat straw, rye, barley, oat, *etc.*), agricultural plant stems (sunflower, hemp, flax, corn, *etc.*), marine algae, orchard and viticulture scraps, bark from seeds (sunflower, rice, pumpkin, *etc.*), pips from indigenous or exotic fruits, *etc.* (Lakó *et al.* 2008). Briquettes and pellets are usually created near large wood industrialization complexes, where there is a large amount of wood residues, including bark.

The torrefaction of sawdust obtained from bark is a drying heat treatment that can improve some properties, such as the hygroscopicity and calorific value (Esteves and Pereira 2009; Chen *et al.* 2012). Thermal treatment begins at 160 °C and concludes at the flammability limit of 210 °C to 260 °C (Wang *et al.* 1984). The treatment duration varies depending on the size of the raw material, and can range from a few hours (for sawdust) to a couple of days (for timber) (Esteves and Pereira 2009). The main advantages of torrefaction are improvements to the dimensional stability and hygroscopicity, and protection against rot and insect attack, which improves the calorific characteristics (Wang 2015). The calorific value of thermally treated woody materials is similar to that of coal and can be equally as profitable as fuel when is used in stoves and furnaces (Chen *et al.* 2011). Many researchers believe that during heat treatment up to 230 °C to 240 °C, hemicellulose is extensively degraded, cellulose less, and lignin little to not at all (Esteves and Pereira 2009). Researchers agree that all types of lignocellulosic biomass can be torrefied, including sawdust, wood chips, vegetal scraps, and marine algae (Chen *et al.* 2011; Chen *et al.* 2012). Some of them consider torrefaction the first step in total pyrolysis (Bridgwater 2012; Brue 2012).

This study observed the process of using pellets from birch and aspen bark as fuel. The physical (moisture content and density) and calorific (calorific value, calorific density, and ash content) properties of the briquettes and pellets obtained from the bark were studied. Also, the calorific properties for the pellets heat-treated at 180 °C, 200 °C, and 220 °C for 1 h, 2 h, and 3 h were determined to observe the influence of heat treatment on the calorific properties.

EXPERIMENTAL

Materials

Raw aspen (*Populus tremula*) and birch (*Betula pendula*) bark were obtained from peeled wood at the Kronospan OSB factory in Brasov, Romania. This bark was cleaned and dried at 105 °C until reaching a moisture content of up to 10%. Then, each type of bark was divided into polished rectangular pieces with straight edges to obtain a perfect parallelepiped shape from which the effective density (as a ratio between the mass and volume) was determined. Then, the raw bark was fed into a hammer mill (model SBM, Shibang Machinery, Shanghai, China) for shredding. The obtained shredded bark (Fig. 1b) was used as the raw material for the production of the briquettes and pellets.

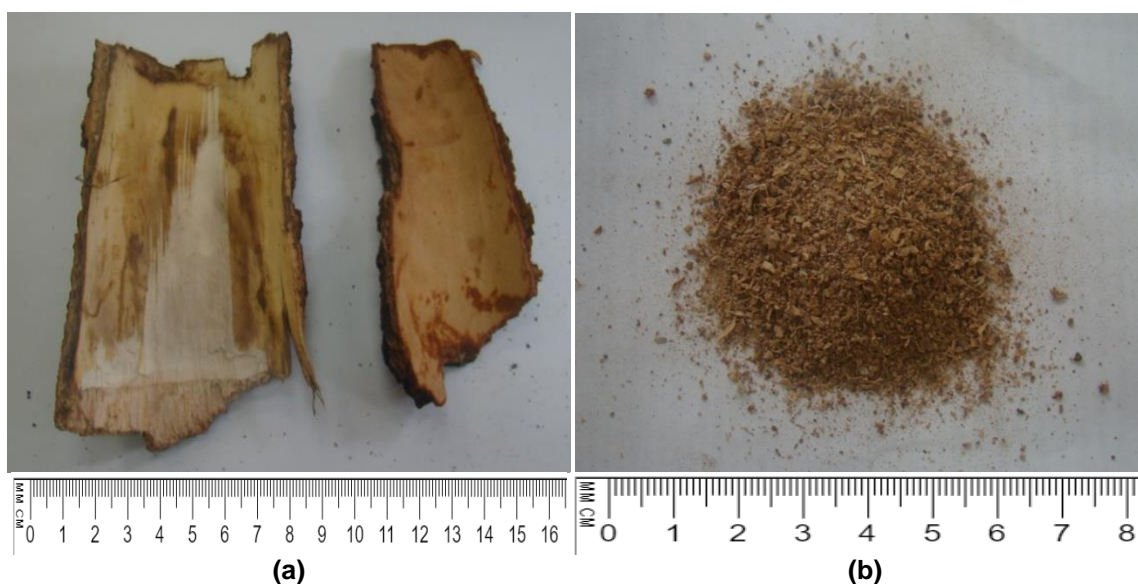


Fig. 1. (a) Raw and (b) Shredded aspen bark

Methods and Equipment

Certain methodologies and equipment were used to obtain briquettes and pellets from the shredded bark and to determine their physical and calorific properties to evaluate their potential use as renewable fuels. The shredded raw aspen and birch bark were compacted into briquettes with a 40-mm diameter in a Gold Star hydraulic press (Brasov, Romania), and into pellets with a pelletizing device (XRY, Changji Geological Instrument, Shanghai, China). A complex installation (XRY-1C calorimeter, Shanghai Changji Geological Instrument Co., China) was used to determine the calorific value of the bark.

The briquettes and pellets were conditioned in a conditioning chamber (with 20 °C and 55% air humidity), until a moisture content of 10% was reached. Afterwards, they were placed in sealed polyethylene sheets to maintain this moisture content throughout the experiments. For drying, a Memmert MM laboratory oven (Schwabach, Germany) was used at 105 °C and maintained a constant temperature within ± 2 °C. The density of the briquettes and pellets, as the ratio between their mass and volume, was determined individually for a group of 20 samples (EN 323 1993). To obtain a precise length, the ends of the briquettes and pellets were carefully sanded using a vertical disk sanding machine (TS 305, Domo, Iasi, Romania) with a grain of 80.

The shape of the briquettes was a cylinder, and the mathematical equation to determine the effective density (ρ) is given as Eq. 1,

$$\rho = \frac{4m}{\pi d^2 l} \cdot 10^{-6} \text{ (kg/m}^3\text{)} \quad (1)$$

where m is the briquette (pellet) mass (g), d is the briquette (pellet) diameter (mm), and l is the briquette (pellet) length (mm).

Calcined Ash and Fixed Carbon (Black Ash)

To determine the ash content, a calcination furnace (STC 18.26, Supertherm, Ploiesti, Romania) capable of reaching temperatures over 650 °C was used. For this process, 4 g to 6 g of shredded material were picked and sorted with an electric sorting device (SBM, Shibang Machinery, Shanghai, China) with a 1-mm ×1-mm mesh sieve. Only the fraction that was able to pass through the sieve was used. For calcination and obtaining the ash, nickel-chromium (Ni-Cr) alloy crucibles with a diameter of 60 mm, a flat base surface, and resistance to high temperatures were used. First, the crucibles were dried and calibrated in an oven at 650 °C, until a constant mass was reached, and then they were cooled in desiccators. Approximately 2 g to 3 g of sorted material were placed inside the vessel in thin and uniform layers with up to two rows of particles for complete burning.

To eliminate the influence of humidity, the shredded bark was dried in a laboratory oven until reaching a constant mass, at which point it was weighed to obtain the initial mass of the sample. To protect the calcination oven, the sample in the crucible was first burned over a butane gas lamp until smoke and flames disappeared completely. After cooling, the samples were weighed on an analytical balance, which was noted as the mass for the determination of the fixed carbon (black ash) and volatile substances contents (Verma *et al.* 2009; ASTM D2866-11 2011). The crucible with the sample was transferred to the calcination furnace with a temperature of 650 °C, which was maintained for 3 h and was periodically checked every 20 min after 2 h.

The calcination was considered complete when sparks in the crucible were no longer observed. At that time, the crucible was cooled and weighed on an analytical balance to obtain the final mass of the calcined ash. Based on the masses obtained during the experiments, the fixed carbon and calcined ash contents were determined using Eqs. 2 and 3, respectively,

$$C_{ba(fc)} = \frac{m_{ba} - m_c}{m_s - m_c} \cdot 100\% \quad (2)$$

$$C_a = \frac{m_{ca} - m_c}{m_s - m_c} \cdot 100\% \quad (3)$$

where $C_{ba(fc)}$ is the fixed carbon (black ash) content(%), C_a is the ash content(%), m_s is the sample dry mass with the crucible(g), m_c is the crucible mass (g), m_{ca} is the mass of the calcined ash(g), and m_{ba} is the mass of the fixed carbon (black ash) (g).

Thermal Treatment

The sawdust of both species was torrefied at 180 °C, 200 °C, and 220 °C for 1 h, 2 h, and 3 h. As a heat treatment support, Ni-Cr alloy crucibles that are resistant to high temperatures were used. The crucibles were burned, cooled, and weighed with a precision of 0.002 g. The sawdust was dried to a constant mass in a laboratory oven at 105 °C (EN 323 1993). This was considered the initial mass of the bark (sawdust) sample, which was then treated thermally. Next, the torrefaction treatment was performed in an electric

furnace without air circulation. The atmosphere inside the furnace was poorly oxygenated due to the closure of the air intake flaps, making possible the thermal treatment of the sawdust without its self-ignition. When the heat treatment was finished, the shredded bark was cooled in desiccators and weighed again to obtain the final mass of the bark sample. Using the two masses obtained, the mass loss (ML , %) was determined using Eq. 4,

$$ML = \frac{m_i - m_f}{m_i} \cdot 100\% \quad (4)$$

where m_i is the initial mass of the bark sample (g) and m_f is the final mass of the bark sample (g).

Because the treatment was done in crucibles with a certain mass (m_c), the previous mathematical equation became Eq. 5,

$$ML = \frac{m_{i+c} - m_{f+c}}{m_i - m_c} \cdot 100\% \quad (5)$$

where m_{i+c} is the mass of the initial sample plus that of the crucible calibrated by burning (g), m_{f+c} is the final mass of the torrefied sample plus the mass of the crucible (g), and m_c is the mass of the empty and well-dried crucible (g).

Calorific Value

The calorific value of the briquettes and pellets from the bark was determined using the XRY-1C calorimeter with a calorimetric bomb and its own calculation software to record and display the results. Thus, during the experiment, the calorimeter displayed the temperature change in the three distinct periods of “fore”, “main”, “after”, and “end” also indicated the moment the wood material ignited. The calorimetric installation consisted of the calorimeter body, water tank, calorimetric bomb, computer, and oxygen tank with a pressure regulator (ISO 1928 2009).

Pieces of briquettes and pellets weighing 0.5 g to 0.8 g, weighed within 0.0001g, were dried completely in an oven at 105 °C. They were then prepared to determine the calorific value by cleaning the side fringes and chips, which could negatively influence subsequent weightings. The calorimetric installation was calibrated using a benzoic acid pill purchased from Parr Instrument Company (Moline, IL, USA) with a known and verified calorific value of 26454 kJ/kg (ASTM D5865-00 2000; DIN 51900-1 2000). This calibration made it possible to obtain the calorimetric coefficient (k), which was used in Eq. 6 to determine the calorific value (CV , MJ/kg):

$$CV = \frac{k \cdot (t_f - t_i)}{m} - Q_s \quad (MJ/kg) \quad (6)$$

where t_f is the final temperature at the end of the combustion period (°C), t_i is the initial temperature in the bomb before ignition (°C), m is the mass of the dried sample (g), and Q_s is the amount of energy released by burning the nickel wire and cotton thread (MJ/kg).

After inserting the pellet into the crucible of the calorimetric bomb, a 10-mm nickel wire was fastened between the two arms of the lid and an 8-mm cotton thread connected the material and nickel wire to send aflame to the bark or pellet samples.

Each procedure lasted between 30 min and 50 min, depending on the mass of the pellet. For each sample, eight to ten replications were performed, for a total of 40 to 50 replications. The arithmetic mean of the results was used in the discussion below. The calorific density of the briquettes and pellets was also obtained from the shredded bark, both before and after the heat treatment, and was compared with that of the original bark.

Using Eq. 7, the calorific density (CD) was determined,

$$CD (MJ/m^3) = CV \cdot \rho \quad (7)$$

where CV is the calorific value (MJ/kg) and ρ is the density of the material (kg/m^3).

RESULTS AND DISCUSSION

Bark has always been considered a lignocellulosic biomass with multiple uses, but for this study, only its viability as a renewable fuel source was evaluated (Calderón *et al.* 2017). The moisture content of the bark after drying was $10\% \pm 0.5\%$ and was maintained throughout the experiment by keeping the raw bark, shredded material, briquettes, and pellets in sealed polyethylene sheets. The effective density was 618 kg/m^3 for the aspen bark and 749 kg/m^3 for the birch bark (21.19% higher) (Fig. 2a). Similar values have been found for other woody species, such as *Eucalyptus grandis* (Wang *et al.* 1984).

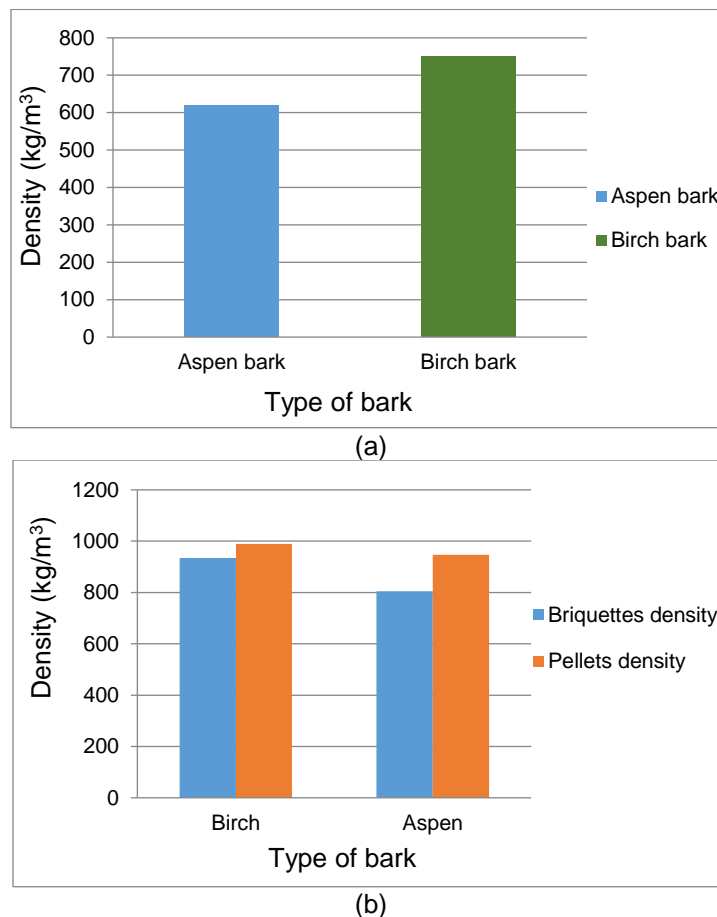


Fig. 2. Density of the (a) raw bark and (b) experimental briquettes and pellets

The densities of the briquettes and pellets obtained from the bark were between 800 kg/m^3 and 990 kg/m^3 (Fig. 2b). The average was $934 \pm 41 \text{ kg/m}^3$ for the birch briquettes and $804 \pm 37 \text{ kg/m}^3$ for the aspen briquettes. The density of the pellets was higher than that of briquettes by 5.7% for the birch bark and 17.7% for the aspen bark. A higher density for briquettes and pellets can be obtained with a helical feeder or hammer press (Kaliyan and

Morey 2009). The mass loss was the main parameter used to assess the thermal treatment and is dependent on the intensity, temperature, and duration of the thermal treatment. The mass losses ranged from 4.9% to 36.8% for the aspen bark and 9.02% to 39.01% for the birch bark. The mass losses of the shredded bark (Fig. 3) increased linearly with an increase in the temperature and duration, regardless of the species, with a Pearson coefficient (R^2) (obtained with Excel Microsoft software) of over 0.9.

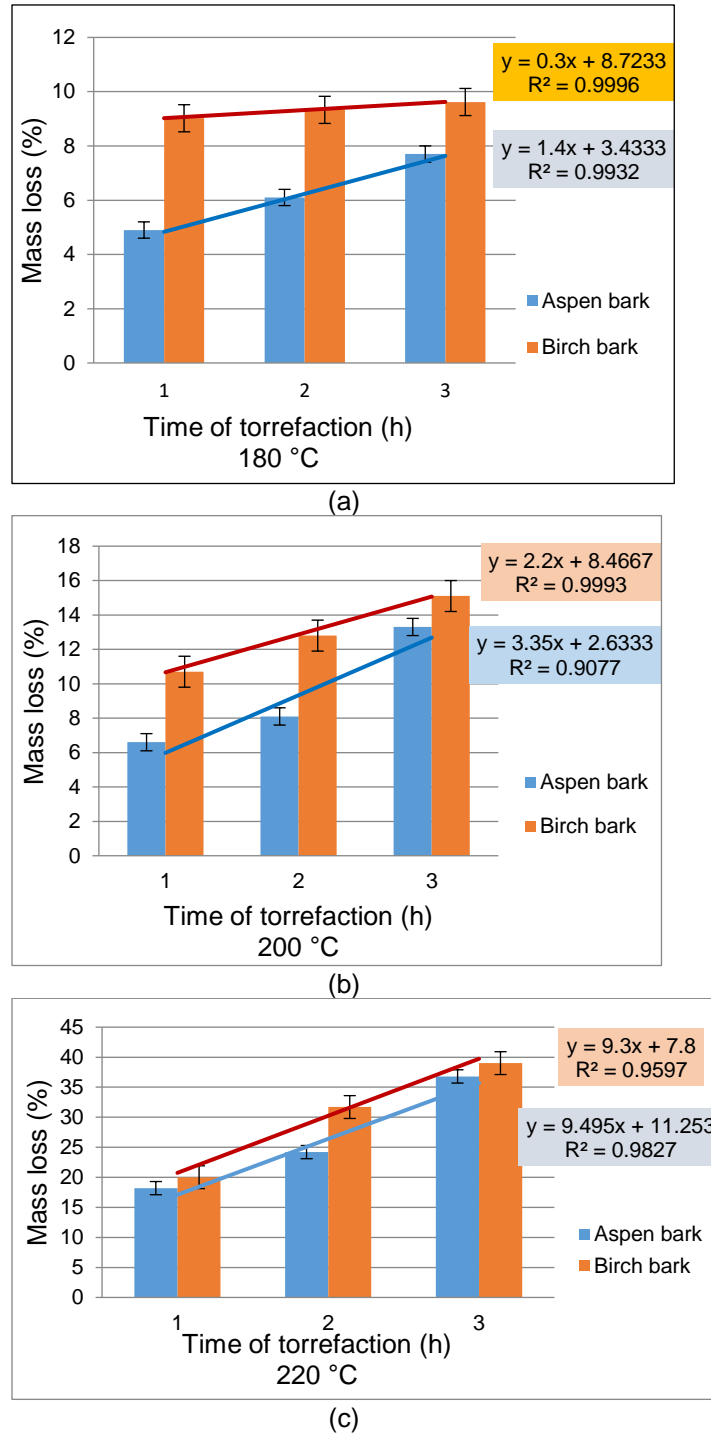


Fig. 3. Mass losses of shredded bark during torrefaction at (a) 180 °C, (b) 200 °C, and (c) 220 °C

Large differences were observed between the curves at 180 °C; however, they flattened at 220 °C, which meant that at high temperatures, the wood species and biomass type did not have an overwhelming influence on the thermal treatment process. The same trend was noticed for the 3-h treatment time. Generally, the birch bark underwent treatment better than the aspen bark, and it had mass loss values that were higher by at least 2%. As was expected, the greatest mass losses were obtained at the highest temperature (220 °C), with values of 36.8% for the aspen bark and 39.01% for the birch bark. However, using both the highest temperature and longest duration is not recommended, as some samples (which were discarded from this analysis) started burning without a flame during the thermal treatment, even when the air intake was null. Other research has shown that in a nitrogen atmosphere, the temperature can increase considerably to over 240 °C to 260 °C, and thus cause a stronger degree of thermal treatment (Esteves and Pereira 2009; Chen *et al.* 2011; Lunguleasa *et al.* 2015).

Influence of the Moisture Content and Torrefaction on the Calorific Value

For a moisture content of 0%, it was not possible to determine the calorific value because the equipment requires 2 mL of distilled water to be placed in the bomb to replace the volume of HNO₃, which the installation software considers the addition of 40J (Fig. 4).

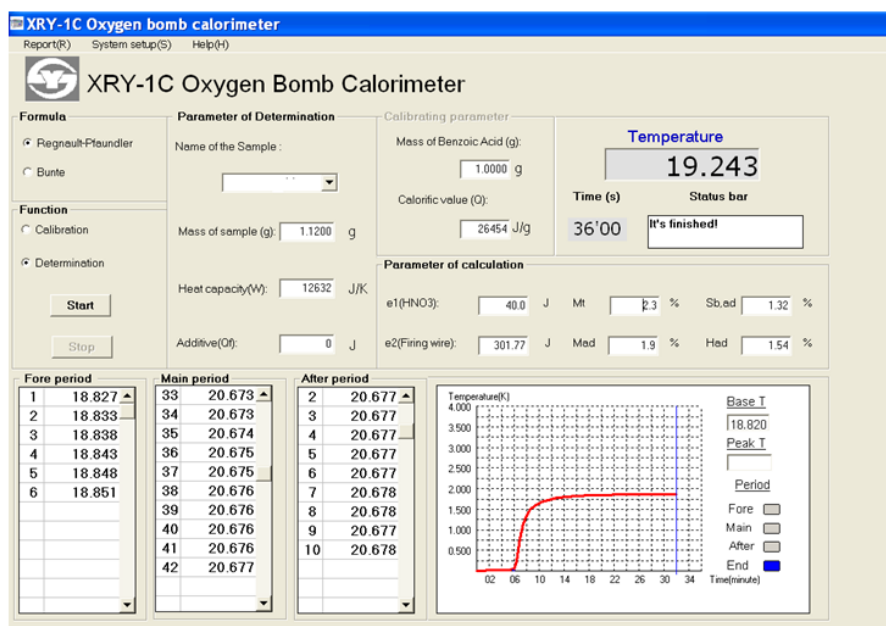


Fig. 4. Software interface for obtaining the calorific value of the bark

Therefore, after drying in an oven to a 0% moisture content, the absolute mass (m_0) was determined. Based on that value, the masses at the moisture contents (MC , %) of 10% and 20% (m_{MC}) were determined using Eq. 8:

$$m_{MC} = m_0 \left(1 + \frac{MC}{100} \right) [g] \quad (8)$$

For example, for a pellet with an absolute dry mass of 1.2 g, masses of 1.32 g and 1.44 g were calculated for the 10% and 20% moisture contents, respectively. Thereafter, the pellets were conditioned to a moisture content of 10% and 20%, using the mass as a monitoring criterion. Based on these two pellets with different moisture contents, Table 1

shows the two different points in the xOy plane (MC-O-CV), linear regression equations, calorific values for a 0% moisture content, and limitative moisture contents. Limitative moisture content represents that MC when heat obtained by burning is equal with heat consumed for eliminate entire moisture content.

Table 1. Calorific Value Related to the Moisture Content

Species		Points (MC; CV)	Equation	CV (MJ/kg)	Limitative MC (%)
Aspen bark	LCV	(10;16.697); (20; 14.294)	$LCV=19.1(1-0.011MC)$	19.1	80
	HCV	(10;16.999); (20; 15.290)	$HCV=19.1(1-0.01258MC)$		111
Birch bark	LCV	(10;19.205); (20;16.611)	$LCV=21.8(1-0.0119MC)$	21.8	84
	HCV	(10; 19.92); (20; 18.04)	$HCV=21.8(1-0.00862MC)$		116

LCV – low calorific value; HCV – high calorific value; MC –moisture content (10% and 20%)

The low calorific value (LCV) and high calorific value (HCV) were determined, and both decreased as the moisture content increased, which is shown in Fig. 5.

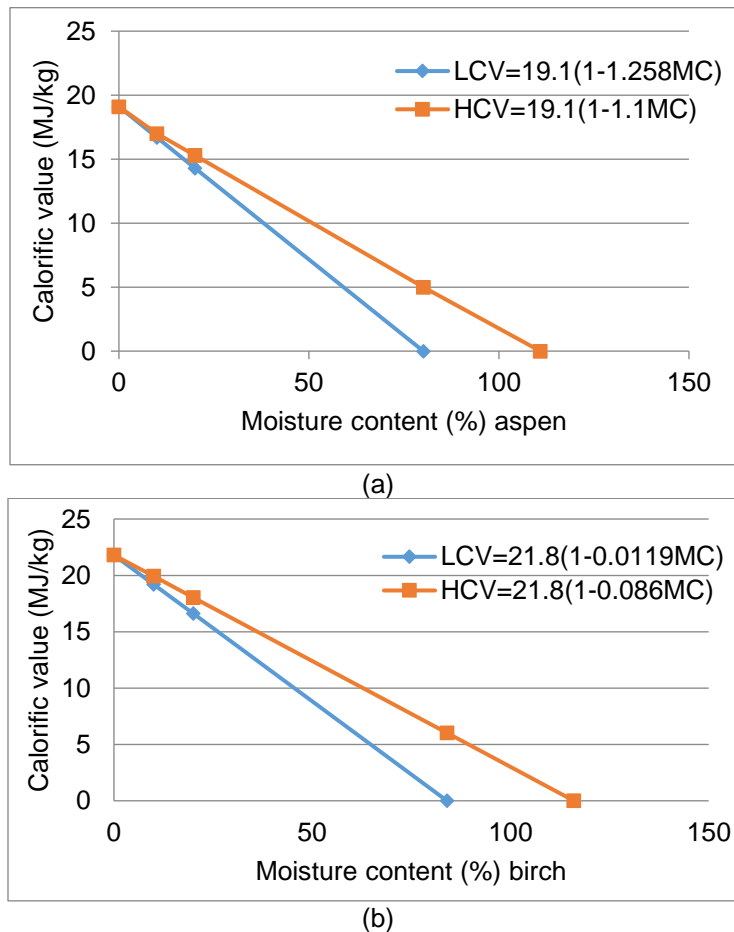
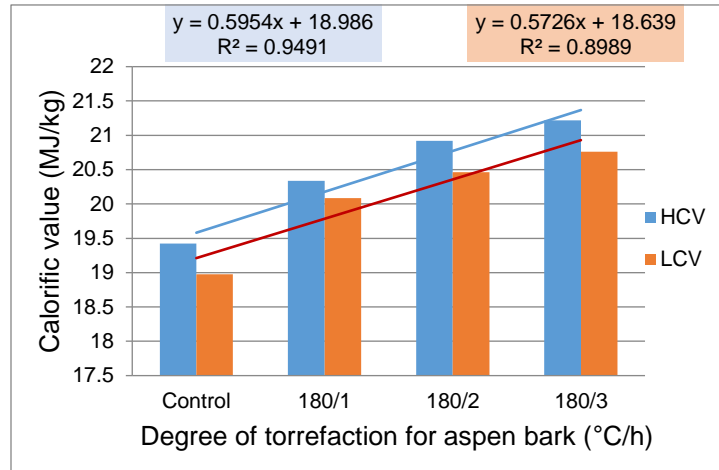
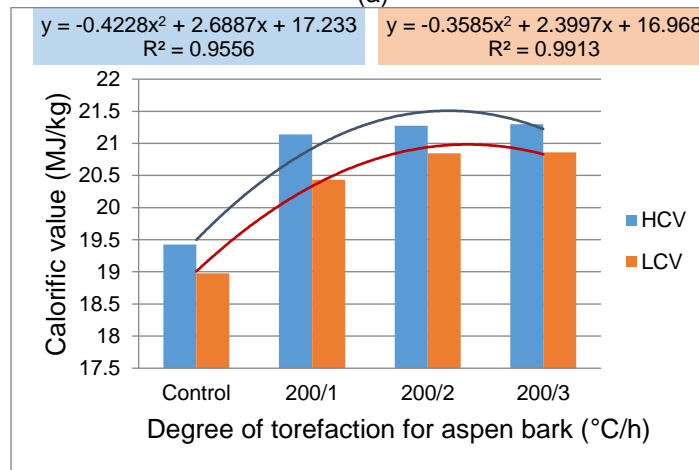


Fig. 5. Calorific value of the (a) aspen (b) and birch bark depending on the moisture content

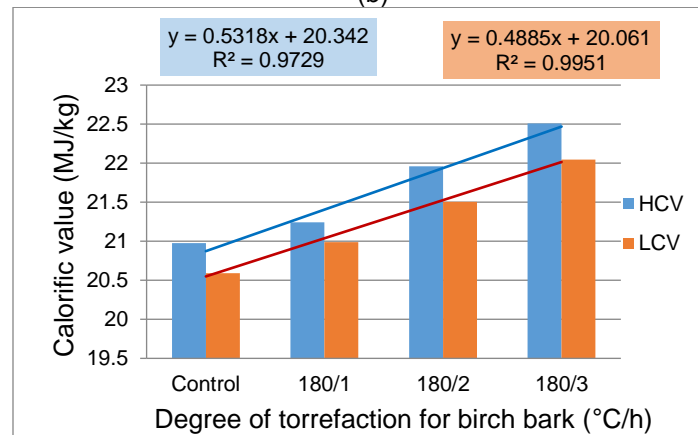
Figure 5 shows that as the moisture content increased, the calorific value consumed to draw the moisture out of the bark exceeded the calorific value of the combustion. Therefore, it was observed that a bark moisture below 20% led to an acceptable calorific value of over 15 MJ/kg. Also, the calorific value of the birch bark was slightly higher than that of the aspen bark because of its higher carbon content, which is 50.7% and 49.1%, respectively (Wang 2015).



(a)



(b)



(c)

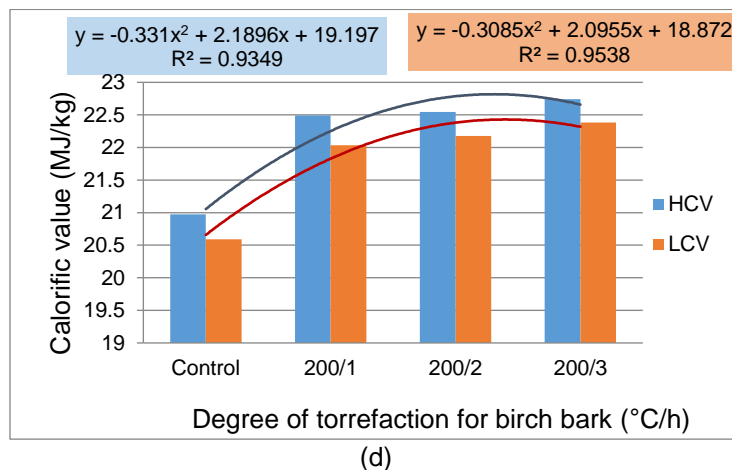


Fig. 6. Influence of the torrefaction degree on the calorific value for: (a) aspen bark at 180 °C; (b) aspen bark at 200 °C; (c) birch bark at 180 °C; and (d) birch bark at 200 °C

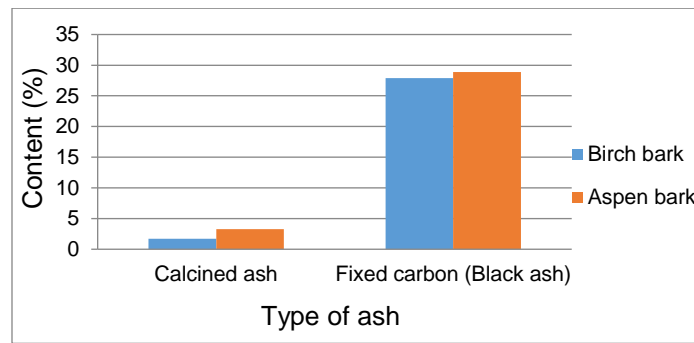
The influence of the thermal treatment on the calorific value was weak, but relevant, and can be seen in Fig. 6. The high calorific value of the aspen bark increased from 19.4 MJ/kg for the control sample to 21.2 MJ/kg after torrefaction at 180 °C for 3 h, which was an increase of 9.2%, and to 21.3 MJ/kg after torrefaction at 200 °C for 3 h, which was an increase of 9.6%. The high calorific value of the birch bark increased from 21.0 MJ/kg for the control sample to 22.5 MJ/kg after torrefaction at 180 °C for 3h, which was an increase of 7.3%, and to 22.7 MJ/kg after torrefaction at 200 °C for 3 h, which was an increase of 8.4%. Figure 6 shows that at 180 °C thermal treatment, the variation in the calorific value was linear. Compared with the control sample treated at 180 °C for 1 h, the increase in the calorific value was poor (4.7% for the aspen bark and 1.2% for the birch bark); meanwhile, after treatment at 200 °C for 3 h, the variation in the calorific value had a polynomial equation because the increase was high (9.6% for the aspen bark and 8.4% for the birch bark).

During the experiments, it was also observed that a temperature over 200 °C for 2 h lead to self-ignition of the sawdust, which limited the possibilities of expanding the heat treatment of the shredded bark.

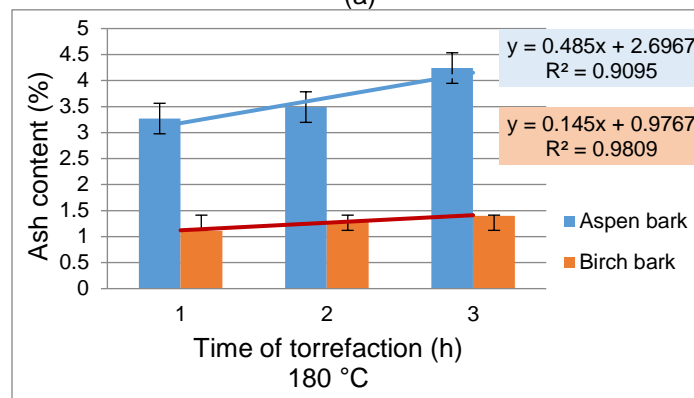
Ash Content

The ash content differs from one species to another. Bark is known to have an ash content higher than in wood from the same species (Brožek *et al.* 2012). In addition to its frequent use in agriculture, medicine, metallurgy, and various industries, bark influences the removal of ash from stoves and other heating installations. The calcined ash content (obtained at 650 °C after over 2 h) was closely related to the contents of the volatile substances (1.7% for the aspen bark and 3.3% for the birch bark) and fixed carbon (27.9% for the aspen bark and 28.9 for the birch bark) from the bark (Fig. 7a) (Etiégni and Campbell 1991; Krutul *et al.* 2014).

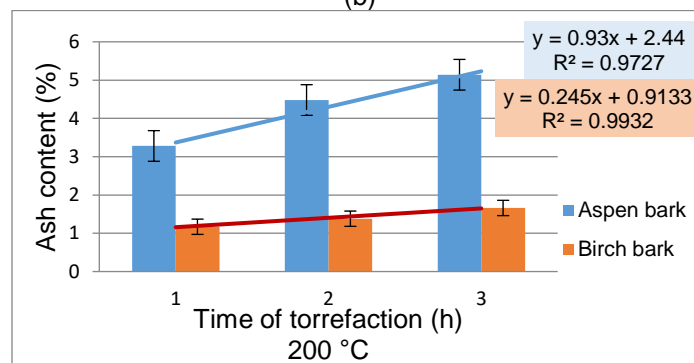
The torrefaction thermal treatment had some influence on the ash content by stripping away volatile substances. Thus, a directly proportional increase in the ash content with the torrefaction degree was observed (Fig. 7), which increased from 1.11% to 1.9% for the birch bark (71% increase) and from 3.27% to 8.57% for the aspen bark (162% increase). However, the maximum ash content of 8.57% for the aspen bark after treatment at 220 °C for 3 h did not exceed that of other wood species (Hytönen and Nurmi 2015).



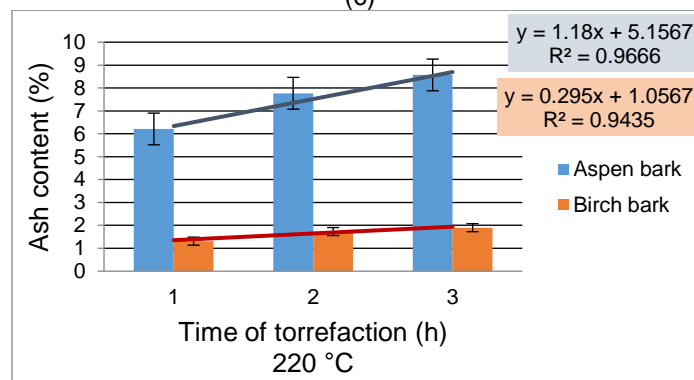
(a)



(b)



(c)



(d)

Fig. 7.(a) Calcined ash and fixed carbon contents from the bark; ash content related to the bark species and torrefaction time for the torrefaction temperatures of (b) 180 °C, (c) 200 °C, and (d) 220 °C

The same influence from the increase in the ash content was observed in the analysis with linear regression equations ($y=mx+n$), especially for the m coefficient, which had values of 0.485, 0.93, and 1.18 for the aspen bark and 0.14, 0.24, and 0.29 for the birch bark. The R^2 was over 0.9 (Fig. 7), and the standard deviation of ash content was under 5%, which represents a real value of 0.08%.

Modeling the Influence of the Ash and Moisture Contents on the Calorific Value

To observe the combined influence of the moisture and ash contents on the calorific value, two HCV equations were generated for the general case of the moisture content and real ash contents (1.7% for aspen and 3.3% for birch) (Table 2).

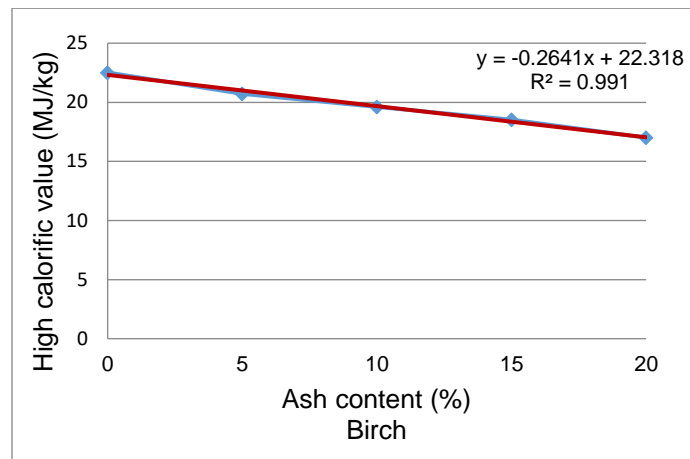
Table 2. Influence of the Ash Content on the Calorific Value

Species		Formulas	CV	Lineal equation
1		2	3	4
Aspen HCV=19.1 (1-1.1 MC)	Ash=1.7%	-----	19.100	HCV=- 0.264As+22.31
	Ash=0%	$19.1(1+1.7/100)$	19.424	
	Ash=5%	$19.1-(19.424-19.1)\cdot 5/1.7$	18.147	
	Ash=10%	$19.1-(19.424-19.1)\cdot 10/1.7$	17.194	
	Ash=15%	$19.1-(19.424-19.1)\cdot 15/1.7$	16.241	
	Ash=20%	$19.1-(19.424-19.1)\cdot 20/1.7$	15.288	
Birch HCV=21.8(1- 0.862 MC)	Ash=3.3%	-----	21.800	HCV = -0.203As + 19.29
	Ash=0%	$21.8-(1+3.3/100)$	22.519	
	Ash=5%	$21.8-(22.519-21.8)\cdot 5/3.3$	20.710	
	Ash=10%	$21.8-(22.519-21.8)\cdot 10/3.3$	19.621	
	Ash=15%	$21.8-(22.519-21.8)\cdot 15/3.3$	18.531	
	Ash=20%	$21.8-(22.519-21.8)\cdot 20/3.3$	17.006	

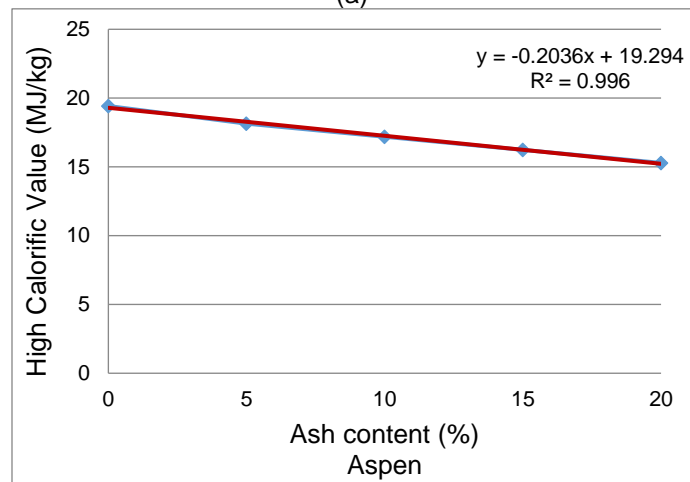
Using the equations from column 2 of Table 2 for an ash content of 0% (it was taken into consideration that the ash content reduces the calorific value), column 2 equations and the effective calorific values (column 3) were determined for the 5%, 10%, 15%, and 20% ash contents. Two of the five points were used and dependency equations (column 4) were obtained. The regression equations of the two points, from the orthogonal plane xOy , were used to create two influence diagrams (Fig. 8).

Other researchers have previously stated that the value of the ash content in bark is higher, sometimes by more than 7% to 8%, for some wood species, which is why it was important to analyze its general influences (Passialis *et al.* 2008; Brožek *et al.* 2012). The influences on the calorific value from the moisture (Fig. 5) and ash (Fig. 8) contents are shown as a combined influence in Fig. 9.

The calorific density, which was found using Eq. 7, was dependent on both the calorific value (which generally increased slightly during the heat treatment process) and density of the fuel product (which generally decreased during the torrefaction treatment). This occurred for the bark, briquette, and pellet samples. Table 3 shows lower values for the aspen bark (12000 ± 502 MJ/m³ to 13000 ± 532 MJ/m³) and higher values for the birch bark (15000 ± 640 MJ/m³ to 17000 ± 780 MJ/m³). The values were much higher for the briquettes and pellets. For example, values of over 18300 MJ/m³ for the aspen bark pellets and over 20700 MJ/m³ for the birch bark pellets were obtained. This was an increase of over 33% for the pellets compared with that of wood briquettes.



(a)



(b)

Fig. 8. Influence of the ash content of (a) birch and (b) aspen on the HCV from the modeling process

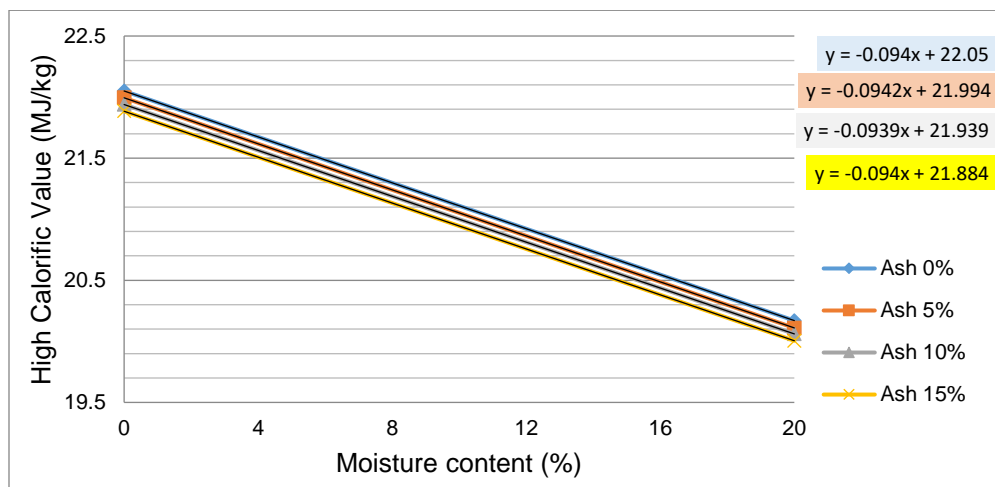


Fig.9. Combined influence of the moisture and ash contents on the HCV of the birch bark

Similar values have been reported by other researchers, such as 14000 MJ/m³ to 15000 MJ/m³ for wood briquettes and 13000 MJ/m³ to 14000 MJ/m³ for firewood (Usta and Kara 1997).

Table 3. Calorific Density of the Torrefied Bark, Briquettes, and Pellets

Torrefaction Degree	Calorific Density of Aspen Bark (MJ/m ³)			Calorific Density of Birch Bark (MJ/m ³)		
	Bark	Briquette	Pellet	Bark	Briquette	Pellet
Control	12008.54	15621.59	18397.42	15718.665	19607.43	20742.178
180/1	12572.95	16355.82	19262.12	15918.005	19856.087	21005.225
180/2	12932.13	16823.06	19812.38	16456.824	20528.208	21716.244
180/3	13115.73	17061.91	20093.67	16867.495	21040.478	22244.317
200/1	13069.98	17002.4	20023.59	16857.004	21027.391	22244.317
200/2	13150.35	17106.94	20146.71	16895.223	21075.066	22294.751
200/3	13166.42	17127.85	20171.34	17041.356	21257.352	22487.586

CONCLUSIONS

1. On average, the calorific values were 19.1 MJ/kg for the aspen bark and 21.8 MJ/kg for the birch bark, which were similar to those for firewood and coal.
2. The ash contents of the birch (3.3%) and aspen (1.7%) bark were not greater than that in other wood species, and its influence on the calorific value was low.
3. The torrefaction treatment showed some sensitivity to a temperature of 220 °C, and there was a noticeable increase in the calorific value. For example, the calorific values of the aspen bark increased by 9.6% and that of the birch bark increased by 8.4%.
4. The density of the birch bark pellets (989 kg/m³) was similar to that of other wood materials, and this led to an increase in the calorific density of over 33% compared with wood briquettes.
5. The obtained results suggested that birch and aspen bark are viable options for use as solid fuels.

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Article submitted: April 24, 2018; Peer review completed: July 12, 2018; Revised version received: July 17, 2018; Accepted: July 24, 2018; Published: July 31, 2018.

DOI: 10.15376/biores.13.3.6985-7001