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Selected properties of briquettes made from blends of bamboo and beech biomass

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Abstract: This study reported the experimental analysis on wood briquettes manufactured from Moso bamboo (*Phyllostachys pubescens*) and beech wood (*Fagus sylvatica*), regarded as an economically valuable fuel source. The following properties of briquettes: physical properties (density and moisture content); chemical properties (heating value, namely calorific value, and ash content); thermal properties (thermal conductivity and specific heat); and mechanical properties (breaking strength). These properties allowed the assessment of the efficiency of two species for using them in briquette manufacturing. The briquettes with higher fractions of bamboo wood showed enhanced characteristics as compared to the briquettes made of beech. This can be explained by the increase of the higher heating value of bamboo wood briquettes by 8.4% as compared to the beech wood briquettes. Similarly, bamboo briquettes had higher the breaking strength (2.1%) with respect to beech wood briquettes. The thermal conductivity of beech wood briquettes was 0.155 W/mK while it was determined as 0.177 W/mK for bamboo wood briquettes. The average densities of beech wood and bamboo wood briquettes were 780.9 kg/m^3 and 813.1 kg/m^3, respectively. The ash content difference between the bamboo wood briquettes and beech wood briquettes was minor. The advantage of using the bamboo wood in different mixture ratios with other wood species for briquettes manufacturing is that it is one of the fastest growing plants on the world as well as widespread around the world, predominantly in Asia. Based on the results of the present study, it was concluded that the bamboo wood biomass could be efficiently used in the production of lignocellulosic briquettes, regardless if individual or in combination with beech wood biomass.

Key words: Bamboo biomass, heating value, ash content, specific heat, thermal conductivity, breaking strength

1. Introduction

Currently, fossil fuels, such as oil, coal or natural gas are the main energy sources, which is approximately 80% of the annual total energy consumption (Krajnc, 2015). As estimated, these energy sources will deplete in the coming next 40–50 years; that is why new energy sources need to be discovered and employed. Among new energy sources there are the renewable energy sources such as geothermal energy, wind energy, solar energy, and the energy of lignocellulosic biomass. Biomass is the generic name for any organic substance, derived from plants, being the result of photosynthesis. The general category of biomass includes wood from forests, agricultural crops, marine algae, leftover from agricultural and forestry processes, industrial, human and animal residues and organic manure etc.

Wood biomass is a part of renewable energy sources and generally comprises remains of wood in different forms and dimensions. Wood has the ash content below 1 wt% and the heating value is normally between 18 MJ/kg and 20 MJ/kg (Ushakov et al., 2017). Any increase of the ash content with 1% determines the decrease of the heating value with 0.20 MJ/kg, since the ash does not substantially contribute to the heat developed during combustion, even if some mineral elements from the ash may represent catalysts for the thermal decomposition of the fuel (Ushakov et al., 2017). In addition, the increase of the ash content has an effect on the proportional decrease of the carbon content, the latter being the chemical element that determines the increase of the heating value of wood. Furthermore, they reported that any increase of the carbon content with 1% increased the heating value (0.39 MJ/kg). This result was obtained for the fuel wood from heavy species, such as beech and hornbeam. The cellulose has a lower heating value (17.3 MJ/kg) than lignin (26.7 MJ/kg) because of the higher degree of oxidation (Ushakov et al., 2017). As compared to the fossil coal, the carbon dioxide emissions coming from the combustion of biomass are decreased by 93%. Moreover, the alkaline ash derived from biomass retains a part of the sulfur dioxide and carbon

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dioxide is produced during combustion (Ushakov et al., 2017).

Briquettes made of wood biomass represent an ecological fuel, being produced by compressing sawdust or other wood particles without using binders or other chemical substances. The lignin as a natural binder is activated at temperatures of 80–100 °C during the compression in the machine. Wood briquettes have several advantages as compared to wood. The density of briquettes is higher than that of wood particles and accordingly, the heat generated by briquettes per unit volume is 3–5 times higher than that released during fuel wood combustion. Briquettes from wood biomass show also an economically advantage because they can be produced from wood leftover, tree barks or wood wastes originating from wood working factories. Moreover, briquettes have aconstant moisture content (around 10%) and can be kept for a long time by wrapping them.

Raw material characteristics and their effect on the properties of briquettes were investigated in previous studies. For example, Ushakov et al. (2017) have used fallen leaves from ornamental trees for producing briquettes. They studied the physical and mechanical characteristics of this new type of biofuel and finally, they indicated the ways in which the briquettes can be used and valorized. Olugbade et al. (2019) reviewed the main additives used to increase the physical and mechanical characteristics of briquettes obtained from biomass. They investigated the compatibility properties between binders and biomass finding that the additives based on phosphorus were the best. Regarding their compaction degree, it was demonstrated that the increase in briquette processing temperature determined the increase of density and the energy content of briquettes. Tanui et al. (2015) studied some physical and thermal properties of briquettes (moisture content, relaxed density, ash content, gross calorific value, and breakage index) produced at a pressure of 50–150 MPa, as well as the influence of molasses as additive on these properties. They reported that the pressure did not have a significant influence on the physical properties of briquettes. Obi and Okongwu (2016) investigated the physical and caloric properties of briquettes made from a blend of rice husk and sludge of palm oil factory. The briquettes with the density of 1045 kg/m^3 and the moisture content of 10% had 76% volatiles content, 15% ash content, and 9% fixed carbon.

The thermal properties of lignocellulosic briquettes such as thermal conductivity and specific heat, and the chemical properties such as the heating value, ash content, energy density, volatiles content or fixed carbon should be considered in the production of the briquettes. Guo et al. (2013) determined the effective thermal conductivity and specific heat of bulk pellets made from a mixture of spruce, pine and fir wood. The thermal conductivity of a single pellet was calculated by theoretical tools. Sjöström and Blomqvist (2014) determined experimentally the thermal properties (specific heat and thermal conductivity) of pine and spruce pellets at elevated temperatures (22–120°C) and different moisture contents (2.9%–11.7%). Vargas-Moreno et al. (2012) reviewed the heating values of different types of biomass, based on elemental analysis, proximate analysis, structural analysis, physical properties analysis, chemical analysis and other variables. Derčanet al. (2012) reported that the briquettes manufactured from wood particles represented the most economical solution for obtaining a solid fuel source and the cleanest way for domestic heating. By compressing the lignocellulosic material, the volume reduces approximate 10 times and thus the briquettes density ranges from 800 to 1200 kg/m^3. Derčan et al. (2012) determined the heating value of beech wood briquettes (1200 kg/m^3)with the moisture content 12%–15% was 21.68 MJ/kg while it was found to be 14.84 MJ/kg for the beech wood briquettes with a density of 720 kg/m^3. The research work performed by Dodić et al. (2012) showed that the higher heating value of dry wood biomass (0% moisture content) decreased from 19.8 to 12 MJ/kg for a moisture content of 70%.

Bamboo wood is easily recognized from its circular section with an interior large hole. The plant is able to take root in about 3 years and it grows very fast. Approximately, it can reach maturity in 5-–7 years and can be employed in the production of briquettes. Bamboo wood can be used in many applications because of its uniform structure and the leftover from its processing can be easily used for briquettes manufacturing. A solution proposed by Liu et al. (2014) is the carbonization of bamboo wood, thus reducing the moisture content and the volatiles content. They found that the carbonization occurred at high temperatures (200–300°C) and accordingly, about 10% of the energy potential was lost. The bamboo wood used in the research had the initial moisture content of 8.1% and the density of 600 kg/m^3. The higher heating value ranged between 19.44 MJ/kg for the wood carbonized at 200 °C and 26.93 MJ/kg for the wood carbonized at 300 °C. A similar research was performed on bamboo pellets (Liu et al., 2013). The bamboo wood samples with the initial moisture content of 6.13% and the density of 650 kg/m^3 were used in production of the pellets. Their subsequent carbonization temperatures ranged from 180 to 220 °C. The heating values measured were found to be 19.43 MJ/kg, 19.48 MJ/kg, and 19.71 MJ/kg for the pellets carbonized at 180 °C, 200 °C, and 220 °C, respectively.

The heating value and the elemental composition of bamboo wood by using infrared spectroscopy was evaluated by Posom and Sirisomboon (2017). They reported that heating value of the bamboo wood ranged from 17.53 to 17.88 MJ/kg. In other study, FT-NIR spectrometry was used in assessing the heating value of bamboo chips with an average moisture content of 9.95% (Sirisomboon et al., 2020). They obtained the higher heating value as 18.77 MJ/kg and the lower heating value as 18.53 MJ/kg. Combustible characteristics of bamboo wood with initial moisture content of 6.23% were reported by Liu et al. (2016). The wood was exposed to the torrefaction at 300 °C for 2 h in a nitrogen environment. By torrefaction, the combustible characteristics of bamboo wood were improved, i.e. the volatiles content decreased from 80.84% (untreated wood) to 29.84% (torrefied wood), the moisture content decreased to 5.53%, the higher heating value increased from 18.52 to 27.09 MJ/kg, and the carbon content increased from 49.59 to 74.56%.

The properties of the lignocellulosic pellets are considerably affected by raw material characterisicts and production proses. Some properties of bamboo pellets were investigated by Liu et al. (2014). The moisture content and the density of the pellets were determined as 6.1% and 650 kg/m^3, respectively. The wood was shredded and then particles were compacted then in pellets. The particles were humidified up to 8%, 12% and 16% moisture contents. The measured higher heating value was 18.50 MJ/kg, regardless the moisture content of the pellets. Their study concluded that the bamboo pellets could be used as solid fuel with efficient combustible properties and could be marketed. Liu et al. (2016) investigated the combustible characteristics of bamboo wood (*Phyllostachys pubescens*). The initial moisture content and density of the wood were 10.1% and 600 kg/m^3, respectively. The wood was conditioned in climate room so that the moisture content of the tested samples was between 7.8% and 8.8%. The measured higher heating value ranged between 18.2 MJ/kg and 19.2 MJ/kg. The volatiles were in a large amount, namely 74.5%–83.2%. They concluded that the bamboo wood had good combustible characteristics, which were influenced by the content of C, H, O, N and S, moisture content and volatiles content.

A comparative research on the thermal properties of two bamboo species, *Phyllostachys pubescens* and *Phyllostachys heterocycla* was performed by Liu et al. (2013). The aim of their research was to obtain information regarding the energy production from biomass by gasification and pyrolysis. The moisture content of the wood samples was 8%. The measured lower heating value was 19.291 MJ/kg for *Phyllostachys pubescens* and 18.082 MJ/kg for *Phyllostachys heterocycla*. The differences were due to the different compositions and structures of two species. The lower heating value of *Phyllostachys heterocycla* was explained by the greater amount of energy required for the thermal decomposition of this species. Kumar and Chandrashekar (2014) analyzed the combustible properties of some bamboo species from India. Knowing the physical and chemical properties of the biomass source is very important for evaluating its energy potential. The measured heating value ranged from 18.8 to 19.6 MJ/kg. They concluded that the different bamboo species had energy potential that could be locally valorized. Cheng et al. (2018) determined the lower heating value of bamboo wood with the moisture content 9.54% is mentioned, namely 17.4 MJ/kg. The properties of the pellets produced from a blend of bamboo and rice straw were evaluated by Liu et al (2013). In order to improve the properties of rice straw pellets they were mixed with bamboo wood particles in different ratios. The initial moisture content of bamboo wood was 6.13% and the density 650 kg/m^3. The bamboo wood and rice straw were shredded and uniformly mixed in different mass ratios (5:0, 1:4, 2:3, 3:2, 4:1 and 0:5). The mixtures were conditioned and the moisture content ranged between 15.56% and 16.03%. The density of pellets obtained from biomass mixtures was considerably lower than that of bamboo pellets (1250 kg/m^3) and rice straw pellets (1350 kg/m^3), respectively. The heating value of bamboo pellets was higher than that of the rice straw pellets. This is due to the different composition of two biomass types. The higher heating value of rice straw pellets was lower than 15.5 MJ/kg, but it increased by mixing rice straw with bamboo wood particles. Mixing two biomasses contributed to the optimization of the combustible properties, allowing in this way the use also of rice straw for burning purpose. The heating value of bamboo wood pellets was 18.5 MJ/kg, hence bamboo wood had good combustible properties.

Since the bamboo wood pellets have a low bulk density, Liu et al. (2016) produced pellets from a mixture of bamboo wood and pine wood particles. The bulk density of the pellets increased from 540 kg/m^3 to 680 kg/m^3 with increasing the fraction of pine wood. The density of the pellets obtained from the wood mixtures was lower than that of the bamboo pellets (1250 kg/m^3) and the pine pellets (1300 kg/m^3), respectively. The bulk density of the bamboo pellets did not meet the requirements of the standard (ÖNORM M7135, 2000) for the use of pellets for domestic or commercial purpose (>600 kg/m^3). However, it increased with the increase of the pine wood fraction. In contrast, the lower heating value slightly decreased from 18.5 to 18.3 MJ/kg with the increase of the pine wood fraction. The carbon content of bamboo wood was higher than that of the pine wood, which resulted in a higher value of the lower heating value of the bamboo pellets. The addition of pine wood particles to bamboo wood particles optimized the properties of bamboo wood pellets. Although the lower heating value slightly decreased by adding pine wood, its values were still higher than the requirements of the ÖNORM M7135 standard (higher than17.5 MJ/kg).

As can be seen above there are constant concerns regarding the finding of new wood biomass sources for the production of lignocellulosic briquettes. Furthermore, there is an attempt in combining various biomass types in order to obtain improved properties of briquettes, but also to reduce their cost. The aim of the research work was to determine the selected properties of briquettes made from mixtures of bamboo and beech wood particles, such as physical properties (density and moisture content), chemical properties (heating value and ash content), thermal properties (specific heat and thermal conductivity), and one mechanical property (breaking strength).

2. Experimental

2.1. Wood and briquettes density and moisture content

Different mixture ratios of bamboo and beech wood samples were used in the production of briquettes. Industrial beech wood waste were used in the experiments. Bamboo short ends originating from previous processing were collected from Sasso Marconi, Bologna province, Italy. The short ends were cut along fiber by means of a circular-saw bench in the samples with lengths of approximate 40 mm (Figure 1a). After a visual assessment ten such bamboo samples were selected from the samples having the cross section which was very close to the circular section. In order to determine the bamboo density, the samples were weighed by using an analytical balance (Model: Kern-Ew) with 0.01 g accuracy. Two external diameters and two internal diameters were measured in perpendicular directions and also two lengths by means of an electronic caliper gauge (0.01 mm accuracy). The moisture content (oven-dry basis) measurements were performed on the five randomly selected specimens at 103 ± 2 °C.

The mass of the dried samples was determined after their cooling in the desiccators. The density of the bamboo wood (ρ_{bw}) was calculated as the ratio between the mass and the volume of the hollow cylindrical samples, as follows:

$$\rho_{bw} = \frac{m_{bw}}{\frac{\pi}{4}\cdot(D_e^2 - D_i^2)\cdot L}\left[\frac{kg}{m^3}\right] \qquad \text{(Eq. 1)}$$

where m_{bw} is the mass of the sample (kg), D_e and D_i are the average external and internal diameters of the sample (m), respectively, L is the average length of the sample (m).

In order to determine the density of solid beech wood, tencubic pieces of wood with dimensions of 20 mm × 20 mm × 20 mm were cut. Before measuring the dimensions, each surface of the sample was sanded to have straight edges and precise measurements. The bamboo wood was split in several pieces (usually 10–12 pieces), (Figure 1b), which were further cut by means of a laboratory hammer mill up to a grain of 1–3 mm (Figure 1c). Sieves with the mesh dimensions of 1mm × 1 mm and 3 mm × 3 mm were used and larger or smaller fractions than the mesh dimensions were removed. The hammer mill was connected to a mobile suction unit (Elektra Beckum SPA-1000) which collected the wood particles. Then they were stored in a plastic bag and maintained in the laboratory at constant atmospheric parameters (20 °Cand 45% relative humidity). Bamboo and beech wood particles were compressed in briquettes in different mass ratios. Briquettes were manufactured from bamboo and beech wood samples in the following; Bamboo(Ba)-Beech(Be)

a) b) c)

Figure 1. Bamboo wood. a) 40 mm long samples, b) shreds, c) particles (chips).

ratios; 100%Ba:0%Be, 75%Ba:25%Be, 50%Ba:50%Be, 25%Ba:75%Be, and 0%Ba:0%Ba, named 100B, 75B, 50B, 25B, and 0B. In order to achieve similar particle sizes, they were sorted using the same sieves as in the case of bamboo, namely those with mesh sizes of 1 mm × 1 mm and 3 mm × 3 mm. The fractions remained after sieving had the dimensions ranging between these two mesh sizes, were further used for briquetting.

The briquetting device was a hydraulic press type (MB4 Goldmark, Brasov, Romania) with the following technical characteristics: press power 4 kW, pressure 150 bar, capacity 40 kg/h, briquette diameter 40 mm, briquette length 30–75 mm, tank diameter 800 mm, and press dimensions of 1200 mm × 980 mm × 1300 mm (length × height × width). The wood particles were weighed by using an analytical balance in order to obtain the mass fractions used for briquetting. The bamboo and beech wood particles were very well mixed, thus obtaining uniform blends of two species. Cylindrical briquettes were then produced by compressing the wood particles. For each mixture a batch of ten briquettes were selected from all the briquettes, having similar shapes and dimensions. No binders or additives were used in briquetting since the lignin as structural component of both wood species had bonding properties in certain compression conditions, that was a pressure higher than 5 MPa and a temperature around 90–100 °C (Lunguleasa et al., 2008).

In order to determine the briquettes density, four diameters were measured in perpendicular direction and two lengths of each briquette. Average values of the length and diameter were calculated for each briquette and then the volume was obtained, considering that the briquettes had a perfect cylindrical shape. Also, the mass of the briquettes was obtained by weighing them using an analytical balance. The density of each briquette (ρ) was calculated as the ratio between mass and volume, as follows:

$$\rho = \frac{m}{\frac{\pi}{4} \cdot d^2 \cdot l} \left[\frac{kg}{m^3}\right] \qquad \text{(Eq. 2)}$$

where m is the mass of the briquette (kg), d is the average diameter of the briquette (m), l is the average length of the briquette (m).

The briquettes were stored in polyethylene bags at constant atmospheric conditions for further measurements of briquettes properties.

2.2. Heating value of briquettes

For the beginning, the higher and lower heating values were measured by using XRY-1C oxygen bomb calorimeter (Shanghai Geological, China). The heating value of briquettes, also called calorific value, was determined by measuring the temperature difference of a defined amount of water that cools the bomb calorimeter. Thus, the heat released during combustion by a known amount of solid fuel (a small sample of a briquette, in this case) was determined and then, the heating value. For the measurements, a small amount of material was detached from each briquette, having the mass below 1 g (usually, 0.4–0.8 g), that was burned in the bomb calorimeter. Ten measurements were performed for each briquette type. The experimental data were recorded when the temperature of the water within the calorimeter was uniform. The experiment comprised three distinct stages, called foreperiod, main period and after period. At the end, both higher and lower heating values were displayed.

2.3. Ash content of briquettes

In order to determine the ash content, shredded wood from both species was used. It was firstly sorted by means of a sieve with the mesh size 1 × 1 mm and the fraction that passed through the meshes was further used. The wood particles were dried for 30 minutes in a laboratory oven (Memmert, Germany) at 103 °C until they reached 0% moisture content. Then, 10 calcification crucibles made from heat-resistant (up to 750 °C) nickel-chromium alloy were prepared, that is, cleaning, sanding, burning for 3 min, cooling and weighing. Afterwards, three layers of the sorted and dried material were placed in each crucible and weighed together. They were burned until the flame and smoke disappeared in order to prevent the effects of soot on the calcination furnace (Protherm STS, Ploiesti, Romania).

By weighing the crucibles with the remaining material, the black ash content (AC_b) was determined with relation (3):

$$AC_b = \frac{(m_{cs} - m_{ec}) - (m_{cba} - m_{ec})}{m_{cs} - m_{ec}} \ [\%] \qquad \text{(Eq. 3)}$$

where m_{cs} is mass of the crucible with the dried sample (kg), m_{ec} is the mass of the empty crucible (kg), m_{cba} is the mass of the crucible with the black ash (kg).

Each crucible containing the burnt sample was then placed in the calcination furnace at the temperature 750 °C (ASTM E1755 (2020) and maintained for approximate 1 h, until the complete calcification of the ash is done. This was observed by the light-grey color of the ash and by the absence of sparkles on the table where the sample was placed. After the cooling in the desiccators provided with silica gel to the room temperature, the crucibles were weighed by using an analytical balance (0.001 g accuracy) in order to determine the calcined ash content by using relation (4):

$$AC_c = \frac{m_{cca} - m_{ec}}{m_{cs} - m_{ec}} \ [\%] \qquad \text{(Eq. 4)}$$

where m_{cca} is the mass of the crucible with the calcined ash (kg), m_{ec} is the mass of the empty crucible (kg), m_{cs} is the mass of the crucible with the dried sample (kg).

The statistical analysis of the experimental data was performed with Minitab 18 software (Minitab Inc., State College, PA, USA). All statistical parameters were obtained at 95% confidence level. In addtion, Excel software (Microsoft Corporation, Redmond, WA, USA) was used for graphical representation of data.

2.4. Specific heat and thermal conductivity of briquettes

In order to measure the specific heat and thermal conductivity of briquettes, four briquettes were selected from each type, which was drilled at one end for obtaining two orifices in parallel with the briquettes axis, having the dimensions 1.3 mm (diameter) and 30 mm (length). Two thermal properties were determined with KD2 Pro Thermal Properties Analyzer (Decagon Devices, Inc., Pullman, WA, USA) based on the transient line heat source method. A dual-needle sensor was used; one of the needles contains a line source heater and the other needle a temperature sensing k-type thermocouple. When introducing the sensor in the briquette, a short energy pulse of known power and duration is applied to the heating needle and the response of the thermocouple is monitored. From the response of the thermocouple several thermal properties of briquettes can be simultaneously determined, such as, volumetric heat capacity, thermal diffusivity and thermal conductivity. Three measurements were performed for each briquette and the final result was the arithmetic mean of the data for each briquette and the group of four briquettes per type.

2.5. Breaking strength of briquettes

The breaking strength of briquettes samples was measured according to EN ISO 17225-1(2014) standard. A universal testing machine (Model: IMAL 300, Italy) consisting of two compressing plates was used. The briquette was placed between two plates of the testing machine (Figure 2) (Spîrchez and Lunguleasa, 2016). The breaking strength (σ_b) was calculated with the following relation:

$$\sigma_b = \frac{F_{max}}{d \cdot l}\ [N/m^2] \quad \text{(Eq. 5)}$$

where F_{max} is the maximum breaking force (N), d is the diameter of the briquette (m), l is the length of the briquette (m). Ten tests were carried out for each briquette type.

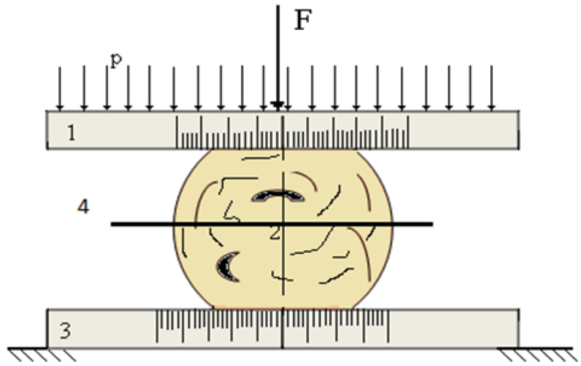

Figure 2. Superior platen. 2: Briquette. 3: Inferior platen. 4: Breaking section. P: Specific pressure. F: Force (Spîrchez and Lunguleasa, 2016).

3. Results and discussion

3.1. Density and moisture content of beech wood, bamboo and their briquettes

Bamboo wood density ranged from 549.1 to 614.4 kg/m^{3}with the standard deviation 19.67 kg/m^3 and the mean value 574.64 kg/m^3, as indicated in Figure 3. The mean density of beech wood calculated from the densities of ten samples examined was 710 kg/m^3 with the standard deviation of 5.76 kg/m^3. It was observed that the beech wood was more homogeneous than the bamboo wood with regard to the density of the species. Bamboo wood density was lower than the density of beech wood, which was 720 kg/m^3 at the equilibrium moisture content 12.15% (Lunguleasa et al. 2008). Liu et al. (2014) determined the density of bamboo wood with the moisture content of 6.13% as 650 kg/m^3.

It is important to know the density of both bamboo and beech wood since the density influences the compaction rate of wood particles in briquettes production, which is one of the most important parameters in briquetting. The moisture content (dry basis) of bamboo wood was determined with respect to the mass of the wet and oven-dry wood samples and it ranged from 6.65% and 8.01% with an average at 7.1%. The average moisture content of beech wood was 8%.The density of briquettes with different fractions of bamboo wood is presented in Figure 4. The density results showed that bamboo particles had better compaction capacity than beech particles. It can be observed that the increase of the bamboo wood fraction affected the increase of the briquettes density. The average densities of beech wood and bamboo wood briquettes were 780.9 kg/m^3 and 813.1 kg/m^3, respectively. The addition of the beech wood in the mixture did not have an important influence on briquettes density increase when comparing with the bamboo wood briquettes. Derčan et al. (2012) reported that by compressing biological material, the volume decreased approximately 10 times; thus the briquettes density ranged from 800 to 1200 kg/m^3. Although the briquettes were produced by using the same briquetting device and the same dimensions of the biomass, the different densities of bamboo wood briquettes and beech wood briquettes may be explained the different structure of two species, particularly their density.

3.2. Heating value of briquettes

The higher and lower heating values of bamboo wood briquettes and beach wood briquettes are presented in

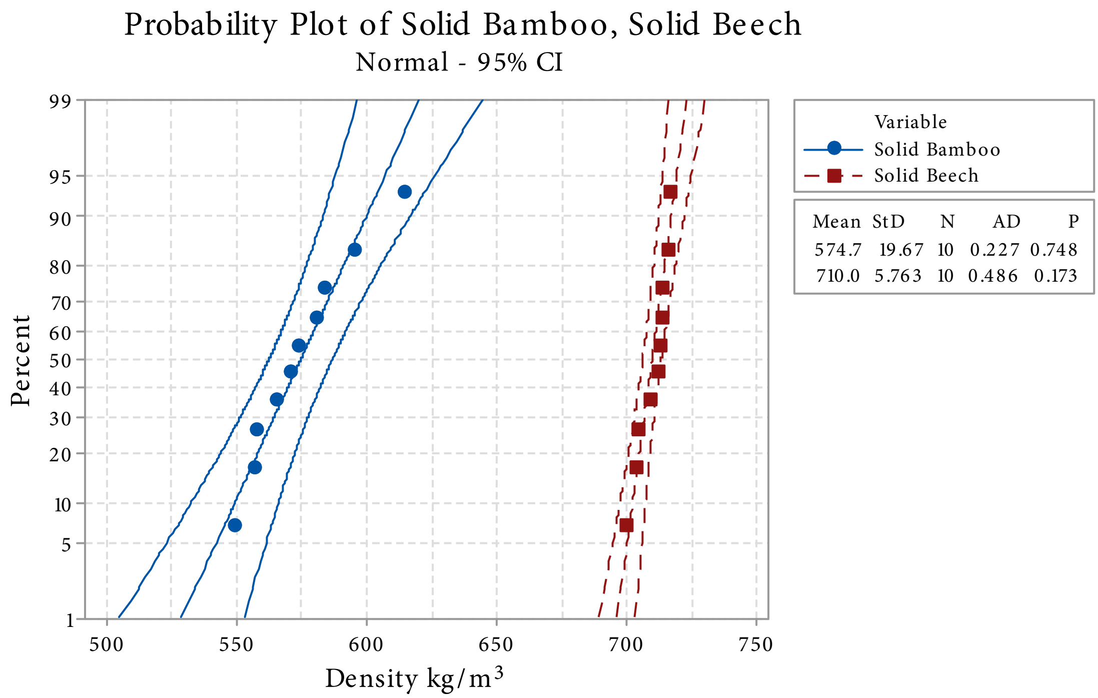

Figure 3. Densities of bamboo and beech wood.

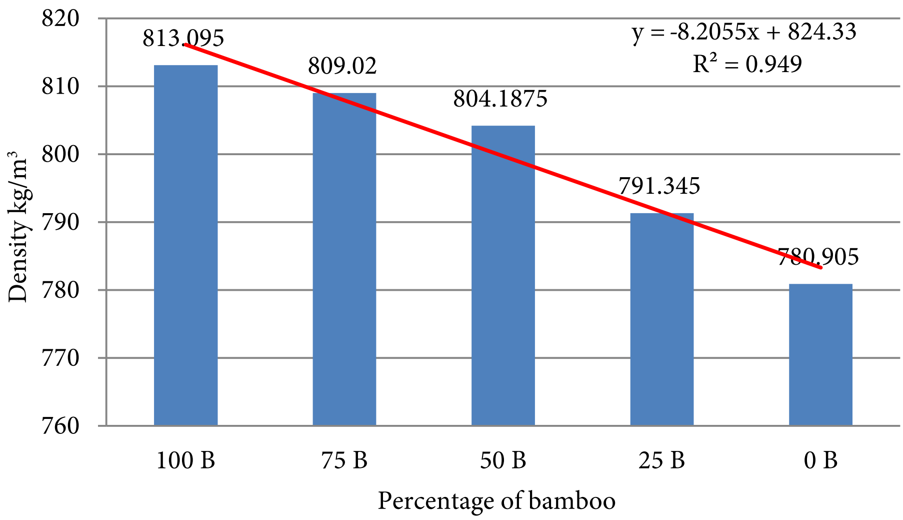

Figure 4. Density of briquettes with different bamboo wood fractions (B).

Figures 5a and 5b, respectively. The average higher and lower heating values obtained from the experiments performed on the ten samples taken from the bamboo wood briquettes were 20.6 MJ/kg and 20.2 MJ/kg, respectively, while the average heating values of the beech wood briquettes were 18.9 MJ/kg and 18.6 MJ/kg, respectively. It can be observed that the higher heating value of bamboo wood briquettes is by 8.4% higher than the higher heating value of beech wood briquettes, and the lower heating value is by 8.6% higher than the corresponding heating value of beech wood briquettes. These findings could be explained by the different chemical composition of two species, that is, the higher carbon content of bamboo wood than that of beech wood. The statistical analysis of the heating values of the briquettes showed that the variance in the case of beech wood briquettes was much higher than the variance in the case of bamboo wood briquettes. This difference could be explained by the processing of different beech wood timbers in the faculty workshop where the chips were collected.

The density of briquettes made from the mixtures in different ratios obeyed the mixture ratio of two species.

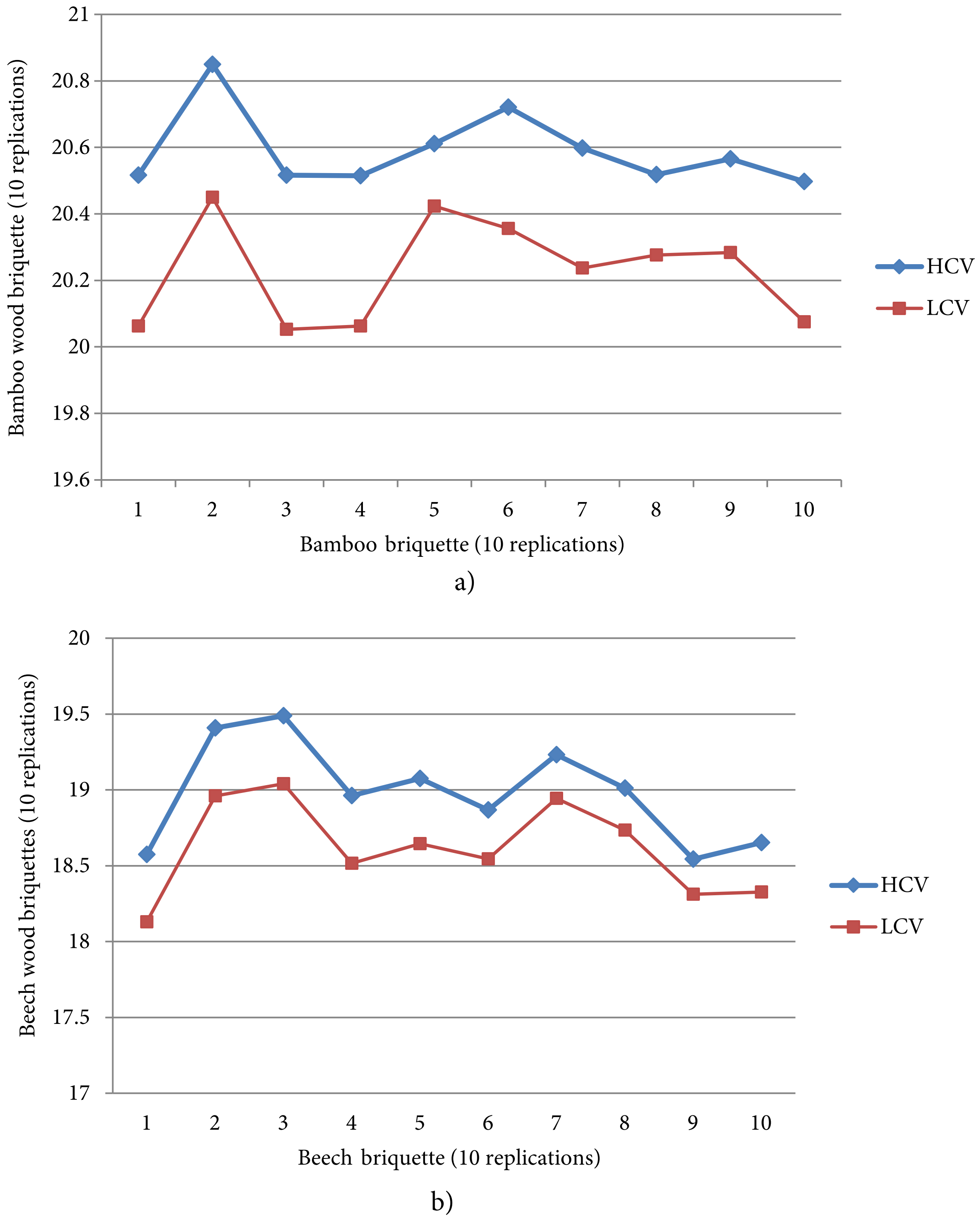

Figure 5. Higher (HCV) and lower (LCV) heating (calorific) values of briquettes a) Bamboo wood briquettes, b) beech wood briquettes.

Considering the fractions of bamboo wood in the mixture (100%, 75%, 50%, 25%, and 0%), Figure 6 indicates the variation of the average heating values of the briquettes. The heating values of the briquettes made from the mixtures of the biomass were between the calorific (heating) values of bamboo wood briquettes and beech wood briquettes, decreasing with the decrease of the bamboo wood fraction. The higher heating value of all the briquette types was higher than 17.50 MJ/kg, which was the requirement of the standard DIN 51731 for pellets in order to be marketed. Previous studies reported that the higher heating value of bamboo wood ranged from

18.5 to 19.2 MJ/kg and depended on the wood moisture content (Sirisomboon et al., 2020; Liu et al., 2016). The heating value of the beech wood densified in the form of briquettes was 21.68 MJ/kg, as indicated in the research work of Derčanet al (2012).

3.3. Ash content of briquettes

The black ash contents of bamboo and beech biomasses are presented in Figure 7. The average value of the black ash content was 27.15% for the beech biomass and 24% for the bamboo biomass. It can be noticed that the black

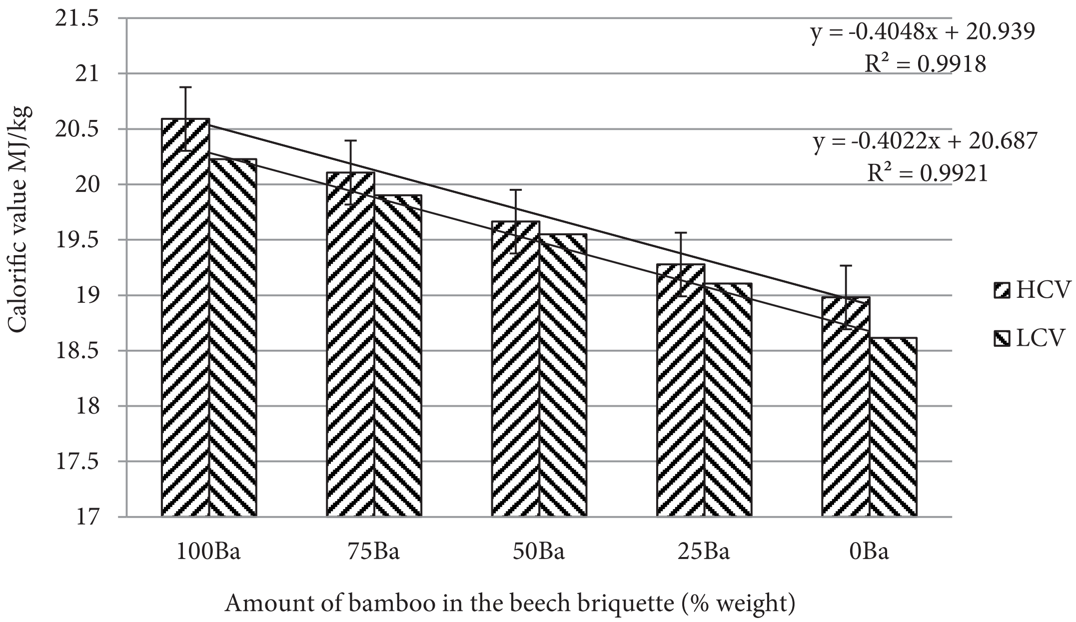

Figure 6. Higher calorific value (HCV) and lower calorific value (LCV) of briquettes with different fractions of bamboo wood.

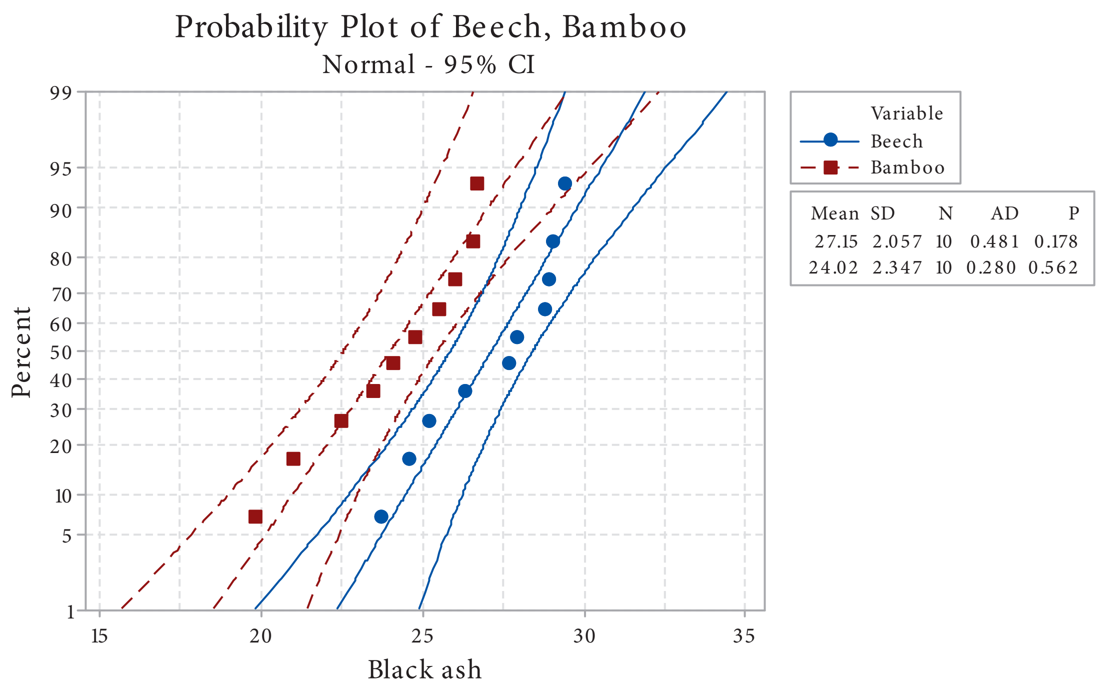

Figure 7. Black ash content of beech and bamboo biomasses.

ash content of beech wood was by almost 13% higher than that of bamboo wood. The average calcined ash content of the bamboo wood biomass (1.88%) was approximately 4% higher than that of beech wood biomass (1.34%), as shown in Figure 8. The homogeneousness of the calcined ash content of the bamboo wood, characterized by the standard deviation (0.28%), was better than that of the beech wood (0.5%). This homogeneousness is specific to the structure of the bamboo wood. Sharma et al. (2018) determined that the lignin content of the bamboo wood was significantly higher than that of other species, which could explain the high heating value and the ash content was similar to that of other species. Although other results regarding the ash content are contradictory (Bodîrlău et al., 2008), the calcined ash content depending on the wood maturity, our findings correspond to the values reported by many other researchers (Josephat et al., 2018; Passialis et al., 2008).

3.4. Specific heat and thermal conductivity of briquettes

The average specific heat of briquettes in relation to the briquettes type was displayed in Figure 9. The specific heat ranged from 1.71 to 2.51 kJ/kg.K. The relation between the specific heat and bamboo briquettes density was depicted in Figure 10. A slight decrease in the specific heat as a function of increasing briquette density (inclination angle, 0.229°) was observed. In a previous study, the specific heat of beech wood was determined as 2 kJ/kg.K at 20 °C and the equilibrium moisture content of 12% while it decreased to 1.6 kJ/kg.K in oven-dry conditions (Stelte et al., 2012).

The relationship between the thermal conductivity and density of beech briquettes is presented in Figure 11. A slight increase (inclination angle, 0.005°) in the thermal conductivity was observed when the briquettes density increased.

The thermal conductivity of the briquettes increased from 0.155 to 0.177 W/mK when their density increased from 740 to 865 kg/m^3. The incorporation of the bamboo wood into the beech wood briquette increased the thermal conductivity, and thus a better heat transfer, which is useful in the case of briquettes storage, where due to high temperatures they can self-ignite. Guo et al. (2013) produced briquettes from mixtures of beech wood and spruce wood in variable amounts. The thermal conductivity ranged between 0.11 W/mK and 0.195 W/mK at the average equilibrium moisture content of 5.95%. For beech wood, the thermal conductivity was 0.16 W/mK. It was determined an inverse variation trend of thermal conductivity versus specific heat. Therefore, a high thermal conductivity indicates a good heat transfer capacity and a poor capacity of heat accumulation, that is, a reduced specific heat of the material.

3.5. Breaking strength of briquettes

The breaking strength of bamboo and beech briquettes is displayed in Figure 12. The average breaking strength of bamboo briquettes was found to be 0.504 N/mm^2 with a standard deviation 0.13 N/mm^2 while the average breaking strength of beech briquettes was 0.493 N/mm^2 with a standard deviation of 0.11 N/mm^2. There was a slight

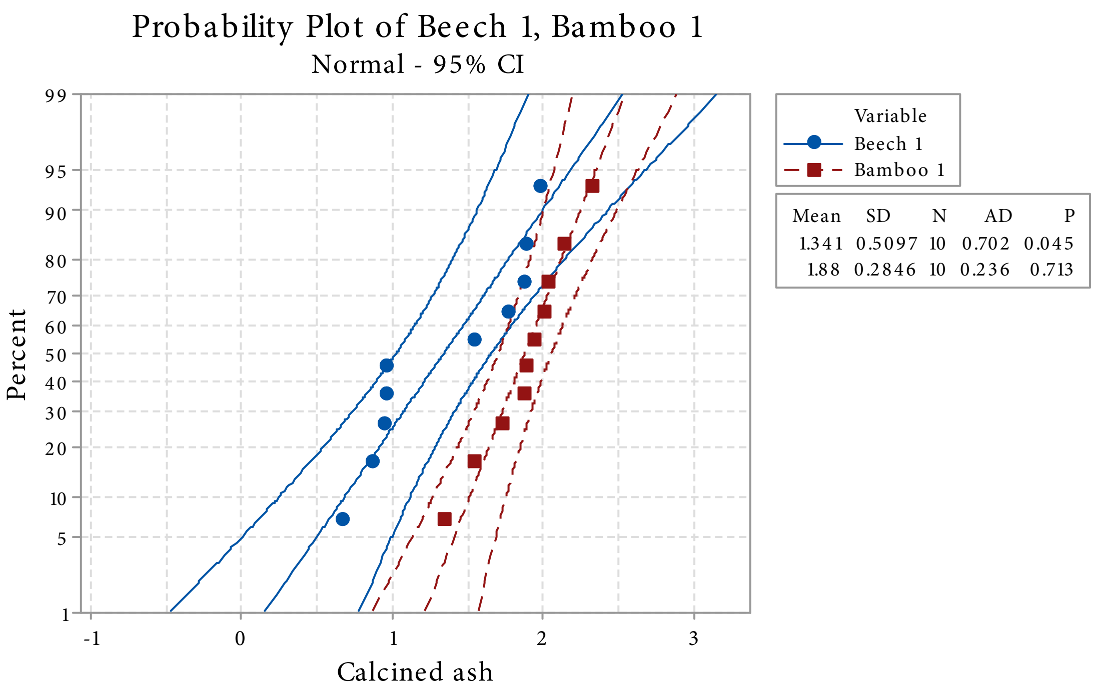

Figure 8. Calcined ash content of beech and bamboo biomasses.

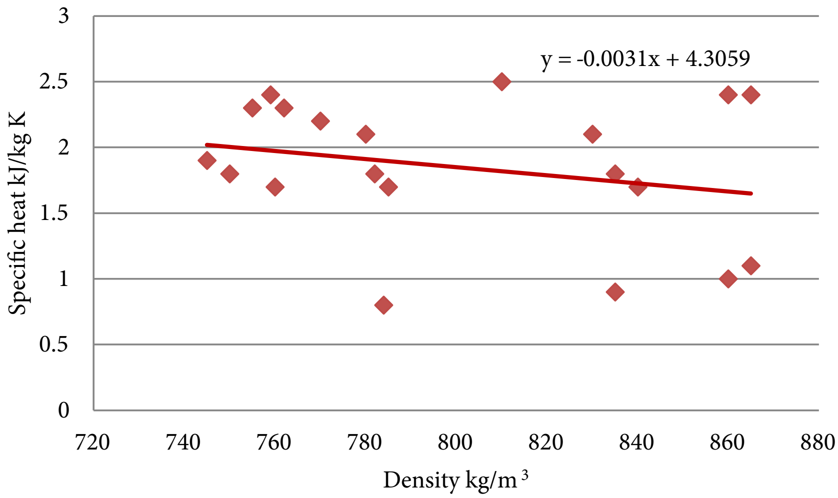

Figure 9. Specific heat related to briquettes type.

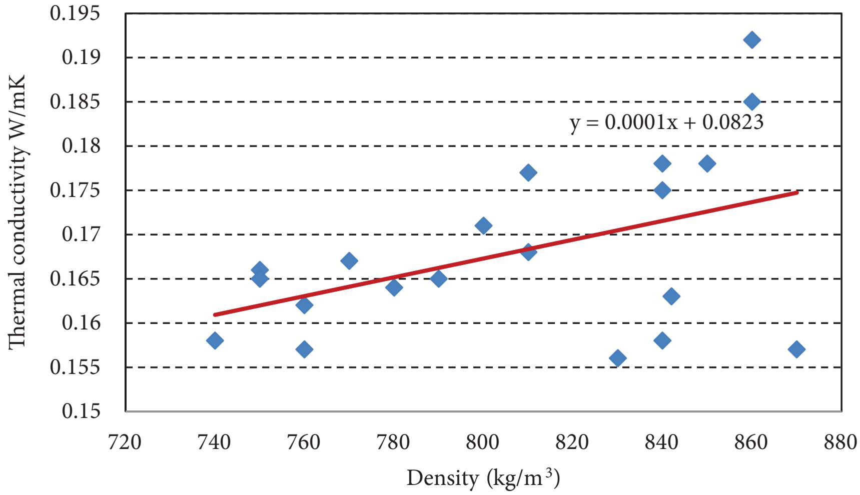

Figure 10. The relationship between specific heat and bamboo briquettes density.

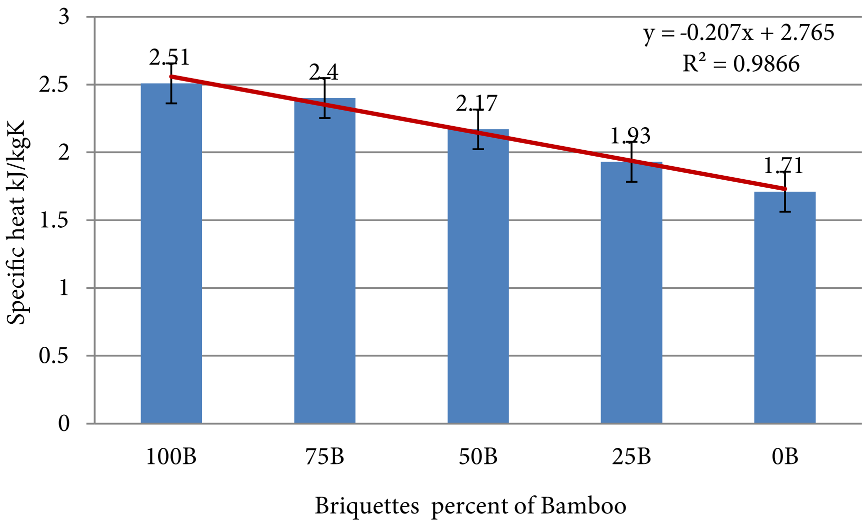

Figure 11. Relationship of the thermal conductivity and beech briquettes density.

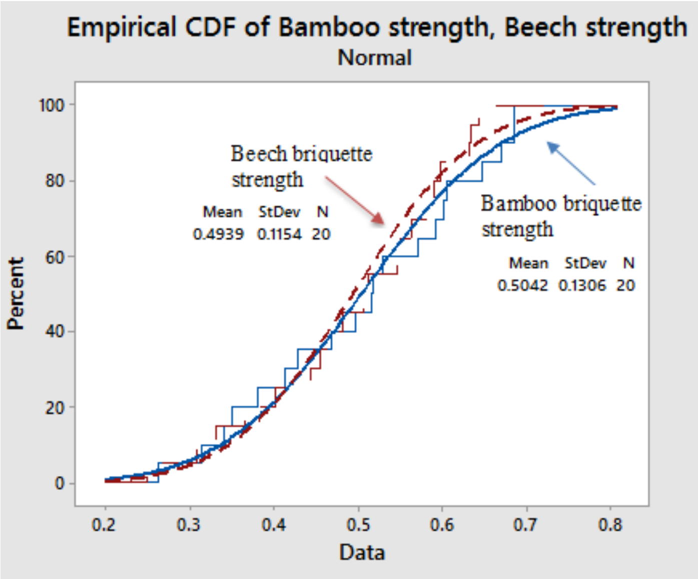

Figure 12. Empirical cumulative distribution function (CDF) of the breaking strength of bamboo and beech briquettes.

increase in the breaking strength of bamboo briquettes as compared to beech briquettes, which could be explained by the higher density of bamboo briquettes. The small difference (2.1%) in the breaking strength in comparison to the density difference (4%) can be explained by the homogeneousness of the bamboo wood and its low density, which makes possible a good compaction of the wood particles.

4. Conclusion

This study showed that bamboo particles could be efficiently used in the production of beech wood briquette. This was demonstrated by the increase of the higher heating value of bamboo wood briquettes by 8.4%as compared to beech wood briquettes. Similarly, bamboo briquettes had higher the breaking strength (2.1%) with respect to beech wood briquettes. The thermal conductivity of beech wood briquettes was 0.155 W/mK while it was 0.177 W/mK for bamboo wood briquettes. The average densities of beech wood and bamboo wood briquettes were 780.9 kg/m^3 and 813.1 kg/m^3, respectively. The ash content difference between the bamboo wood briquettes and beech wood briquettes was minor. Although beech wood is one of the most commonly used solid fuels, this study showed that the addition of bamboo wood particles into beech wood briquette improved the selected physical, chemical, thermal, and mechanical properties of beech wood briquettes.

References

ASTM E1755 - 01 (2020). Standard test method for ash in biomass. West Conshohocken, PA, USA: ASTM International.

Bodîrlău R, Teacă CA, Spiridon I (2008). Chemical modification of beech wood: effect on thermal stability. BioResources 3 (3): 789-800. doi: 10.15376/biores.3.3.789-800

Chaney J (2010). Combustion characteristics of biomass briquettes. PhD dissertation, University of Nottingham, Nottingham, UK.

Cheng J, Zhou F, Si T, Zhou J, Cen K (2018). Mechanical strength and combustion properties of biomass pellets prepared with coal tar residue as a binder. Fuel Processing Technology 179: 229-237. doi: 10.1016/j.fuproc.2018.07.011

Derčan B, Lukić T, Bubalo-Živković M, Đurđev B, Stojsavljević R et al. (2012). Possibility of efficient utilization of wood waste as a renewable energy resource in Serbia. Renewable and Sustainable Energy Reviews 16: 1516-1527. doi: 10.1016/j.rser.2011.10.017

Dodić SN, Zelenović Vasiljević T, Marić RM, Radukin Kosanović AJ, Dodić JM et al. (2012). Possibilities of application of waste wood biomass as an energy source in Vojvodina. Renewable and Sustainable Energy Reviews 16: 2355-2360. doi: 10.1016/j.rser.2012.01.079

EN ISO 17225-1 (2014). Solid biofuels - fuelspecificationsandclasses - Part 1: General requirements. . Brussels, Belgium: European Committee for Standardization.

Guo W, Lim CJ, Bi X, Sokhansanj S, Melin S (2013). Determination of effective thermal conductivity and specific heat capacity of wood pellets. Fuel 103: 347-355. doi: 10.1016/j.fuel.2012.08.037

Hytonen J, Nurmi J (2015). Heating value and ash content of intensively managed stands. Wood Research 60 (1): 71-82.

Krajnc N (2015). Wood Fuel Handbook. Pristina, Republic of Kosovo: Food and Agriculture Organisation of the United Nations.

Kumar R, Chandrashekar N (2014). Fuel properties and combustion characteristics of some promising bamboo species in India. Journal of Forestry Research 25 (2): 471- 476. doi:10.1007/s11676-014-0478-6

Liu Z, Fei B, Jiang Z, Liu X (2014). Combustion characteristics of bamboo-biochars. Bioresource Technology 167: 94-99. doi: 10.1016/j.biortech.2014.05.023

Liu Z, Fei B, Jiang Z, Cai Z, Yu Y et al. (2013). A comparative study of thermal properties of sinocalamusaffinis and moso bamboo. Journal of Thermal Analysis and Calorimetry 111: 393-399. doi: 10.1007/s10973-012-2266-x

Liu Z, Jiang Z, Cai Z, Fei B, Yu Y et al. (2013). Effects of carbonization conditions on properties of bamboo pellets. Renewable Energy 51: 1-6. doi: 10.1016/j.renene.2012.07.034

Liu Z, Liu X, Fei B, Jiang Z, Cai Z et al. (2013). The properties of pellets from mixing bamboo and rice straw. Renewable Energy 55: 1-5. doi: 10.1016/j.renene.2012.12.014

Liu Z, Fei B, Jiang Z, Cai Z, Liu X (2014). Important properties of bamboo pellets to be used as commercial solid fuel in China. Wood Science and Technology 48: 903-917. doi: 10.1007/s00226-014-0648-x

Liu Z, Hu W, Jiang Z, Mi B, Fei B (2016). Investigating combustion behaviors of bamboo, torrefied bamboo, coal and their respective blends by thermogravimetric analysis. Renewable Energy 87: 346-352. doi: 10.1016/j.renene.2015.10.039

Liu Z, Mi B, Wei P, Jiang Z, Fei B et al. (2016). Combustion characteristics of moso bamboo (*Phyllostachys pubescens*). European Journal of Wood Products 74:255-259. doi: 10.1007/s00107-015-0997-7

Liu Z, Mi B, Jiang Z, Fei B, Cai Z et al. (2016). Improved bulk density of bamboo pellets as biomass for energy production. Renewable Energy 86: 1-7. doi: 10.1016/j.renene.2015.08.011

Lunguleasa A, Ciobanu V, Costiuc L (2008). Ecological Combustion of Wooden Biomass. Brașov, Romania: Transilvania University of Brașov Press.

Obi OF, Okongwu KC (2016). Characterization of fuel briquettes made from a blend of rice husk and palm oil mill sludge. Biomass Conversion and Biorefinery 4: 449-456. doi: 10.1007/s13399-016-0206-x

Olugbade T, Ojo O, Mohammed T (2019). Influence of binders on combustion properties of biomass briquettes: a recent review. BioEnergy Research 12: 241-259. doi:10.1007/s12155-019-09973-w

ÖNORM M7135 (2000). Pellets and Briquettes - Requirements and Test Conditions. Vienna, Austria: Austria Standards Institute.

Posom J, Sirisomboon P (2017). Evaluation of lower heating value and elemental composition of bamboo using near infrared spectroscopy. Energy 121:147-158. doi: 10.1016/j.energy.2017.01.020

Passialis C, Voulgaridis E, Adamopoulos S, Matsouka M (2008). Extractives, acidity, buffering capacity, ash and inorganic elements of black locustwood and bark of different clones and origin. Holzals Rohund Werkstoff 66: 395-400. doi: 10.1007/s00107-008-0254-4

Sharma B, Shah DU, Beaugrand J, Janecek ER, Scherman OA et al. (2018). Chemical composition of processed bamboo for structural applications. Cellulose 25: 3255-3266 doi: 10.1007/s10570-018-1789-0

Sirisomboon P, Funke A, Posom J (2020). Improvement of proximate data and calorific value assessment of bamboo through near infrared wood chips acquisition. Renewable Energy 147: 1921-1931. doi: 10.1016/j.renene.2019.09.128

Sjöström J, Blomqvist P (2014). Direct measurements of thermal properties of wood pellets: elevated temperatures, fine fractions and moisture content. Fuel 134: 460-466. doi: 10.1016/j.fuel.2014.05.088

Șova D, Porojan M, Bedelean B, Huminic G (2018). Effective thermal conductivity models applied to wood briquettes. International Journal of Thermal Sciences 124: 1-12. doi: 10.1016/j.ijthermalsci.2017.09.020

Spîrchez C, Lunguleasa A (2016). Shear and crushing strengths of wood pellets. Drewno 59 (198): 87-97. doi: 10.12841/wood.1644-3985.170.04

Stelte W, Shang L, Holm JK, Ahrenfeldt J (2012). Recent developments in biomass pelletization-a review. BioResources 7(3): 4451-4490.

Tanui JK, Kioni PN, Kariuki PN, Ngugi JM (2018). Influence of processing conditions on the quality of briquettes produced by recycling charcoal dust. International Journal of Energy and Environmental Engineering 9: 341-350. doi: 10.1007/s40095-018-0275-7

Ushakov DE, Karelin DV, Bychkov AL, Korobeinichev OP, Shmakov AG (2017). Preparation of fuel briquettes from plant biomass, Solid Fuel Chemistry 51: 238-242. doi: 10.3103/S0361521917040103

Vargas-Moreno JM, Callejón-Ferre AJ, Pérez-Alonso J, Velázquez-Martí B (2012). A review of the mathematical models for predicting the heating value of biomass materials. Renewable and Sustainable Energy Reviews 16: 3065-3083. doi: 10.1016/j.rser.2012.02.054