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# Bamboo Fiber and Sugarcane Skin as a Bio-Briquette Fuel

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**Abstract:** The present study deals with the issue of bio-briquette fuel produced from specific agriculture residues, namely bamboo fiber (BF) and sugarcane skin (SCS). Both materials originated from Thừa Thiên Huế province in central Vietnam and were subjected to analysis of their suitability for such a purpose. A densification process using a high-pressure briquetting press proved its practicability for producing bio-briquette fuel. Analysis of fuel parameters exhibited a satisfactory level of all measured quality indicators: ash content $A_c$ (BF—1.16%, SCS—8.62%) and net calorific value *NCV* (BF—16.92 MJ·kg$^{-1}$, SCS—17.23 MJ·kg$^{-1}$). Equally, mechanical quality indicators also proved satisfactory; bio-briquette samples' mechanical durability *DU* occurred at an extremely high level (BF—97.80%, SCS—97.70%), as did their bulk density $\rho$ (BF—986.37 kg·m$^{-3}$, SCS—1067.08 kg·m$^{-3}$). Overall evaluation of all observed results and factors influencing the investigated issue proved that both waste biomass materials, bamboo fiber and sugarcane skin, represent suitable feedstock materials for bio-briquette fuel production, and produced bio-briquette samples can be used as high-quality fuels.

**Keywords:** waste biomass; Vietnam; solid biofuel; calorific value; mechanical durability

## 1. Introduction

With the increasing prices and various environmental impacts created by the use of fossil fuels, the importance of biofuel production has subsequently increased. Such production has reached unprecedented volumes over the last 20 years [1]. In addition, the world's population is expected to continue growing, with the total population calculated to be almost ten billion by mid-2050 [2]. This population growth will lead to a deepening requirement for energy, and therefore, global energy demand will subsequently increase. Energy is considered a key source for the future and plays an important role in socioeconomic development because affordable energy is an essential ingredient for such development [3,4].

With deforestation comprising a major problem in many parts of the developing world, there is increasing demand for fuelwood for household cooking. This phenomenon particularly affects remote rural communities that have no access to fuels such as liquid petroleum gas (LPG) and that depend substantially on burning locally-collected biomass [5]. Such a demand for fuel could be covered by bio-briquettes, which may provide necessary energy from waste materials because biomass is globally recognized as a renewable and sustainable energy source [6]. In addition, agricultural residues have recently been posited as a major fuel source for many potential bio-energy projects in developing countries [1].

Biomass is now considered a primary global energy resource, providing 14% of the world's energy needs. It comprises at least one third of energy consumption in some developing countries. In addition, biomass combustion can be considered $CO_2$ neutral because during production, it removes $CO_2$ from the atmosphere by photosynthesis and is later released during combustion [7]; this aspect was however contradicted in Cherubini et al. [8], who analyzed $CO_2$ emissions from biomass combustion for bioenergy.

### *1.1. Bamboo and Sugarcane as a Source of Herbaceous Biomass*

Bamboo (*Bambusoideae* spp.) and sugarcane plants (*Saccharum officinarum*) are members of the grass family *Poaceae* (also known as *Gramineae)*. Both grasses are widely spread in tropical and subtropical climate regions. As a strongly growing species, their cultivation provides several advantages. Bamboo plants are the fastest growing plant species on Earth (approximately 91–122 cm per day); thus, significant potential for herbaceous biomass production is indicated. Moreover, the subfamily Bambusoideae contains 1100–1500 different bamboo species, with their classification and identification being complicated; approximately 69 naturally-occurring species were monitored in Vietnam alone [9,10].

Historically, bamboo is a traditional and widely-used plant in Asia; its utilization has lasted for centuries in different industries, for building various parts of houses, furniture production, as well as medicinal, food [10], clothing and home craft purposes, among others [11]. Concurrently, sugarcane plants cultivated for agricultural purposes provide 70% of sugar worldwide (having the most calories per unit area of cultivation of any plant), with a large amount of the herbaceous waste biomass being left behind after plant processing, for example sugarcane skin [12]. Such material is one of the by-products of the sugarcane processing industry [13]. Today, biological residues from sugarcane plants are a particular point of interest of different scientific fields [14,15]; thus, its potential seems significant. However, sugarcane skin reuse in Southeast Asia, namely in Vietnam, is not ensured; the open field burning or ejection into municipal waste is a common practice in rural areas when individuals or small processing plants are treating sugarcane crop. In an attempt to meet increasing energy demands and maintain an appropriate waste management strategy, waste biomass originated from processing of both mentioned grasses could be reused and utilized; for example, as a feedstock material for various biotechnological processes [13,16,17]. Bamboo plants commonly provide waste cuttings of bamboo logs or bamboo fiber (BF), while sugarcane processing results in the production of sugarcane bagasse. Utilization of such residues is not secured, and they are often left behind as useless waste or burned without a purpose. Occasionally, bamboo fiber is used as a fire starter and sugarcane skin for combustion purposes.

### *1.2. Biomass Availability in Vietnam*

In Vietnam, biomass is considered an important source of energy, comprising approximately 90% of domestic energy consumption in rural areas [18], as well as being an important source of energy for small industries and farms, often located in rural areas [19]. Further, it has significant potential as a renewable energy source, even though the agricultural sector currently accounts only for approximately 20% of the country's GDP [19]. Agricultural residues, as described in Schirmer [19], and animal waste, as described in Roubík et al. [20], are offering significant potential for the generation of electricity, sources that have so far been insufficiently tapped. Currently, biomass is mainly used by households, and waste biomass is usually not used at all, or very ineffectively and with potential harmful consequences.

Agricultural residues (including bamboo fiber and sugarcane skin) are important sources of biomass in Vietnam and can be taken from residues left directly on fields or from the processing of agricultural products. The wider use of such residues may be relatively difficult because this agricultural waste usually occurs locally (for example, rice husk residues are produced in large quantities only in the local rice mills). As mentioned by Schirmer [19], there is a need for a reliable supply of biomass, its efficient collection, transportation and storage, meaning well-established supply chains, which currently do not exist.

Agricultural Waste Utilization through Briquetting

One technology for the utilization of agricultural wastes is biomass briquetting [21,22], which involves the densification of the biomass through the use of pressure [23,24]. The advantages of briquetting include the following: increased bulk density of the material, making it easier to transport and store, higher energy content per unit volume and the production of homogenous product fuel from various raw materials [22,25]. Therefore, as concluded by Chen et al. [23], densified solid biofuel (meaning bio-briquettes) could be an important route for efficient utilization of agro-residues.

## 2. Methodology

The present section details research activities performed for the collection of selected waste biomass (both materials represented by herbaceous biomass) in raw form and its initial processing in the target area of Huế city and surrounding villages in Thừa Thiên Huế province, central Vietnam. There is a detailed description of the investigated waste biomass laboratory preparation (drying, grinding) and laboratory testing of its fuel properties. Further, the utilization of selected waste biomass as a feedstock material for bio-briquette fuel production using a high-pressure briquetting press is described, together with the determination of their suitability for such a purpose. Finally, the complete evaluation of stated mechanical and chemical quality indicators of produced bio-briquette samples is performed.

In general, the production of bio-briquette fuel for commercial purposes is conducted to mandatory technical standards (stated by the country of bio-briquette fuel production) ensuring the quality and safety of such products. Thus, all procedures of experimental testing were performed in accordance to related European technical mandatory standards stated by the European Committee for Standardization, namely: EN 14918 (2010) [26], ISO 1928 (2010) [27], EN 15234-1 (2011) [28], EN ISO 16559 (2014) [29], EN ISO 17225-1 (2015) [30], EN ISO 17831-2 (2015) [31], EN ISO 18122 (2015) [32], EN ISO 18134-2 (2015) [33], EN ISO 16948 (2016) [34] and EN ISO 18123 (2016) [35].

### 2.1. Materials and Samples

Both investigated waste materials, bamboo fiber (*Bambusoideae* spp.) and sugarcane skin (*Saccharum officinarum*), were identified as herbaceous biomass due to their membership in the grass family *Poaceae*. Collection activities were performed at small processing plants in central Vietnam in June of 2017. Bamboo fiber samples originated from rural areas in Thừa Thiên Huế province; the collections were performed during several field trips; thus, samples originated from different villages, whereas sugarcane skin samples originated from one specific processing plant in Huế city. Nevertheless, unprocessed raw sugarcane stalks were harvested in surrounding rural areas of Huế city. The target area of the materials' collection is illustrated in Figure 1.

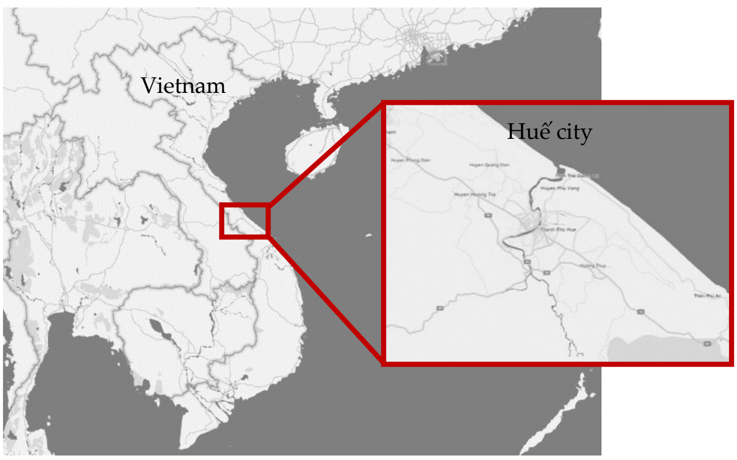



**Figure 1.** Area of sample collection: Huế district, Thừa Thiên Huế province.

Both investigated materials were chosen because they represented commodities frequently processed in large quantities in the target area, and their processing results in the production of a significant amount of waste biomass.

Bamboo stalks were already sundried prior to the fiber being manually separated in processing plants; thus, final waste biomass occurred in ideal conditions for combustion purposes (low level of moisture content); as shown in Figure 2.

(**a**) (**b**)

**Figure 2.** Bamboo processing in Thừa Thiên Huế province, central Vietnam: (**a**) manual removing of fiber; (**b**) produced waste biomass: bamboo fibers.

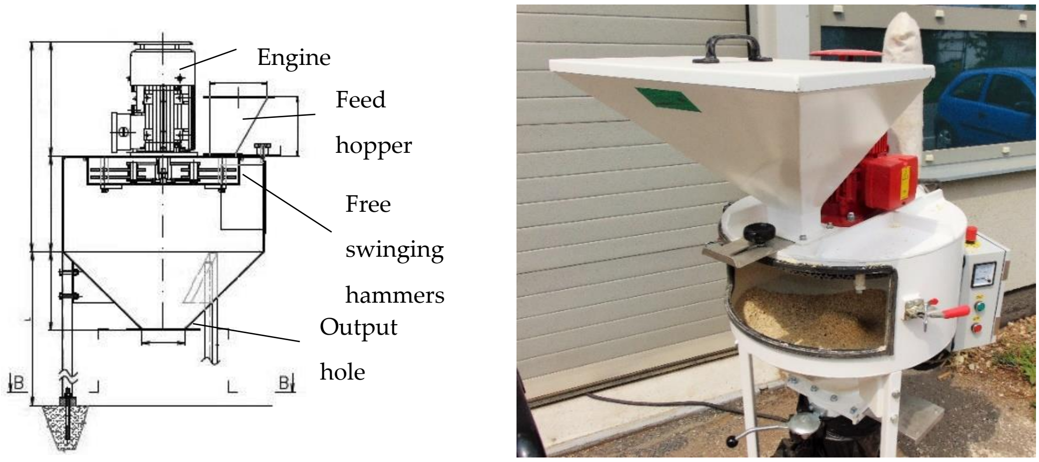
In contrast, sugarcane stalks occurred in the raw state before their skin was manually removed in the processing plant; thus, produced waste biomass occurred in its initial high moisture content, as shown in Figure 3.

(**a**) (**b**)

**Figure 3.** Sugarcane processing in Huế city, central Vietnam: (**a**) manual removing of skin; (**b**) produced waste biomass: sugarcane skin.

The drying process of sugarcane skin was thus necessary prior to its subsequent utilization, and therefore, the material was sundried in open fields in local conditions. Thereby, the drying process was ensured without the need for any other energy source investment. Moreover, local insects were not interested in such materials, which represents a significant advantage if considering that such materials contained residual sugars. Unfortunately, precise initial moisture content of both materials was not determined due to the fact that primary research activities were performed in conditions of rural areas of Vietnam without proper measuring equipment. Further, both materials were properly stabilized and stored in special hermetically-sealed bags for transportation.

After the materials' transportation to the laboratories at the target destination of Prague, Czech Republic, both materials were appropriately prepared for subsequent experimental measurements; their particle size and moisture content were modified to the required form. Primarily, both materials were dried in a laboratory dryer LAC, Type S100/03 (Rajhrad, Czech Republic), for 24 hours at a temperature of 105 °C until their moisture content was constant. Disintegration of feedstock materials was also performed using a grinding hammer mill Taurus, Type VM 7,5 (Chrudim, Czech Republic), with a vertical shaft with eight hammers as a working unit (see Figure 4).




(**a**) (**b**)

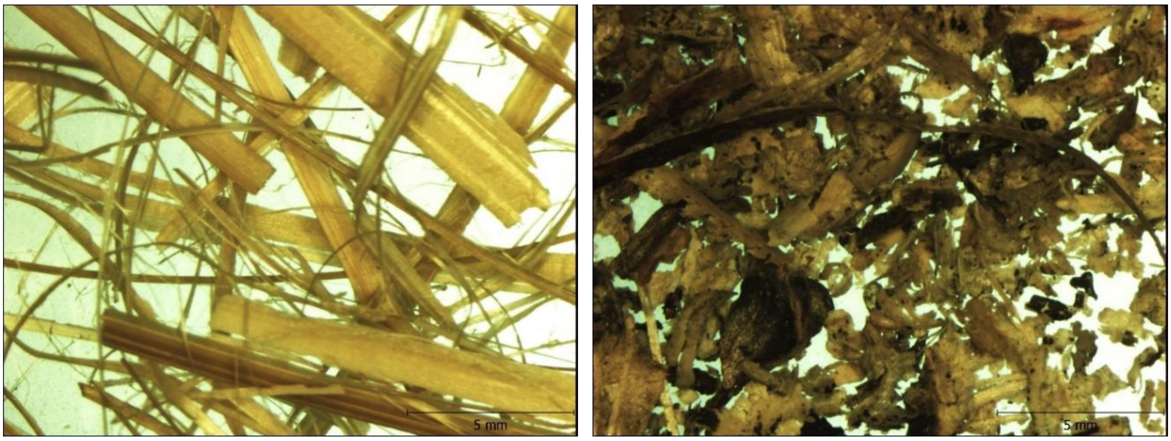
**Figure 4.** The disintegration device used, the hammer grinding mill: (**a**) scheme; (**b**) in practice.

A sieve with holes of 8 mm in diameter was used to unify the faction of both disintegrated feedstock materials. The final form of properly prepared samples is expressed in Figure 5.

(**a**) (**b**)

**Figure 5.** The form of samples prepared for chemical and mechanical analysis: (**a**) bamboo fiber; (**b**) sugarcane skin.

Nevertheless, the bamboo material occurred in the fibrous form, and hence, the fibers that fell through sieve holes were prevalently slightly longer than 8 mm. In contrast, sugarcane skin (SCS) material also contained tiny particles in the form of dust; thus, the prevalent particle size was smaller than 8 mm. Due to such differences between the investigated materials, brief microscopic measurements were performed to describe the particle size and shapes of investigated materials (measurement scale 5 mm). A stereoscopic microscope Arsenal, Type 347 SZP 11-T Zoom (Prague, Czech Republic) was used for image analysis; the resulting images are shown in Figure 6.




(**a**) (**b**)

**Figure 6.** Microscopic analysis of investigated samples: (**a**) bamboo fiber; (**b**) sugarcane skin.

Despite the fact that both investigated materials were represented by the top layer of plant stem (the epidermis), the variability in materials' behavior during disintegration and particle size were detected during microscopic analyses (Figure 6); such variability was related to the taxonomy of processed plants.

### *2.2. Fuel Analysis of Feedstock Materials*

Samples were subjected to analysis of their fuel properties, which defined their basic chemical parameters, energy potential and elementary composition. Such measurements were performed to determine the materials' suitability for the process of direct combustion. At least two or three repetitions of all of the following tests were performed for all investigated samples to ensure the correctness of measurement processes and observed data; data were recorded and evaluated using supporting software. Final data exhibited in the Results and Discussion Section are expressed as average values of all observed data with standard deviations.

#### 2.2.1. Basic Parameters and Energy Potential ($M_c$, $A_c$, $GCV$, $NCV$)

Samples were initially milled into the required particle size (<0.1 mm) using a cutting mill. Moisture $M_c$ (%) and ash content $A_c$ (%) analysis was performed with a thermogravimetric analyzer LECO, Type TGA 701 (Saint Joseph, MO, USA). Experimental tests complied with related standards, namely EN 18134-2 (2015): Solid biofuels—Determination of moisture content—Oven dry method—Part 2: Total moisture-Simplified method and ISO 18122 (2015): Solid biofuels—Determination of ash content.

The principal parameters of fuel properties, gross calorific value ($GCV$) (MJ·kg$^{-1}$) and net calorific value $NCV$ (MJ·kg$^{-1}$) express the energy potential of the investigated materials. Gross calorific values ($GCV$) (MJ·kg$^{-1}$) were primarily measured using an isoperibol calorimeter LECO, Type AC 600 (Saint Joseph, USA) and secondarily analyzed by related software. Net calorific values ($NCV$) (MJ·kg$^{-1}$) were calculated using relations between those two parameters. The complete process of analyses used standards EN 14918 (2010): Solid biofuels—Determination of calorific value and ISO 1928 (2010): Solid mineral fuels—Determination of gross calorific value by the bomb calorimetric method and calculation of NCV.

#### 2.2.2. Elementary Composition (*C*, *H*, *N*, *S*, *O*)

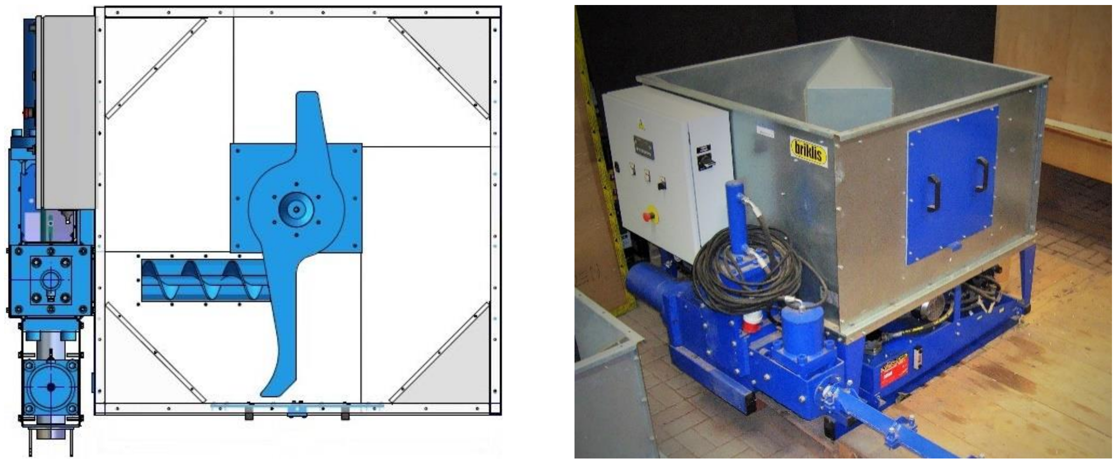
Materials content of carbon *C* (%), hydrogen *H* (%), nitrogen *N* (%), sulfur *S* (%) and oxygen *O* (%) represented the last measured fuel parameters. Experimental testing was performed using laboratory equipment LECO, Type CHN628+S (Saint Joseph, MO, USA), while the testing process corresponded to requirements stated by related standard EN ISO 16948 (2016): Solid biofuels—Determination of total content of carbon, hydrogen and nitrogen.

### *2.3. Mechanical Analysis of Bio-Briquette Samples*

When the suitability of investigated materials for the process of direct combustion was proven, they were utilized as a feedstock for bio-briquette fuel production. Subsequently, the produced bio-briquette samples were subjected to the determination of their mechanical quality represented by the following indicators: bulk density $\rho$, mechanical durability *DU* and rupture force *RF*. Specific methods of the mentioned experimental measurements are described in the following sections. The present section is divided into four sections: The first section is related to the production factors of the densification process and to the entire process of bio-briquette sample production. The remaining three sections describe bio-briquette sample quality testing and determination of specific mechanical quality indicator results.

#### 2.3.1. Bio-Briquette Sample Production

As mentioned previously, high-pressure briquetting technology was used for densification of two different types of herbaceous waste biomass: bamboo fiber and sugarcane skin. Namely, a laboratory hydraulic piston high-pressure briquetting press Briklis, Type BrikStar 30-12 (Malšice, Czech Republic), was used as a pressing device (shown in Figure 7).



(**a**) (**b**)

**Figure 7.** Briklis high-pressure briquetting press: (**a**) scheme; (**b**) in practice.

This press was operated with an automatic setting during feedstock compression with a specific focus on ensuring a similar level of bulk density $\rho$ of all produced bio-briquette samples. However, such settings resulted in different lengths of final products. The device is equipped with a pressing chamber and matrix with a diameter of 50 mm, thus producing bio-briquette samples (expressed in Figure 8) of a diameter equal to approximately 50 mm; the dimensions of bio-briquette samples are provided in Table 1.

(a) (b)

**Figure 8.** Produced bio-briquette fuel samples from: (**a**) bamboo fiber; (**b**) sugarcane skin.

**Table 1.** Basic mechanical properties of investigated briquette samples (±standard deviation).

| Sample | Weight (g) | Height (mm) | Diameter (mm) |
|---|---|---|---|
| Bamboo fiber | 79.68 ± 20.71 | 37.73 ± 10.61 | 51.55 ± 0.37 |
| Sugarcane skin | 120.61 ± 12.85 | 53.35 ± 5.55 | 51.96 ± 5.40 |

In general, the dimensions of bio-briquette fuel influence its final mechanical quality. Thus, its monitoring represents an important production parameter that needs to be considered.

#### 2.3.2. Bulk Density $\rho$

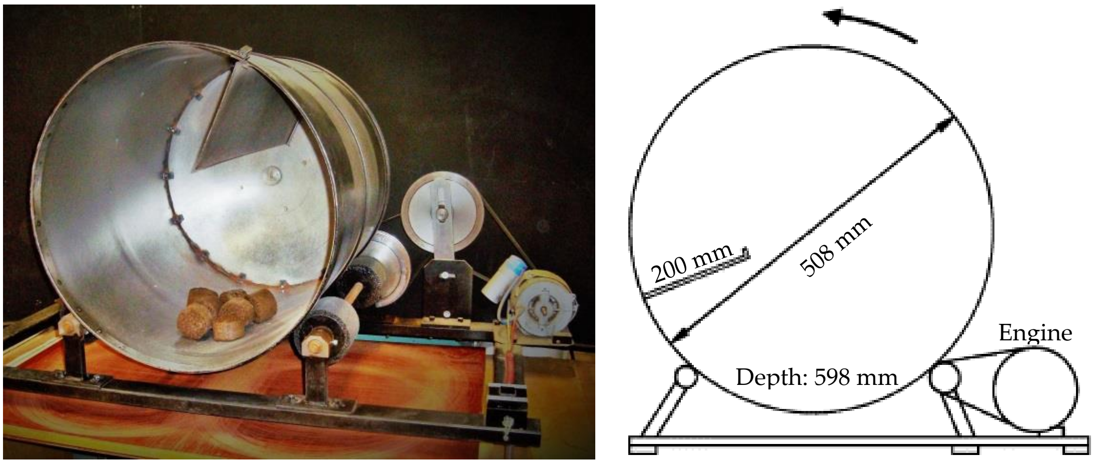
The first investigated indicator, bulk density $\rho$, describes both the final mechanical quality of produced bio-briquette samples, as well as the ability of tested feedstock materials to be densified. Thus, it evaluates the efficiency of the densification process in the case of such specific feedstock materials. Calculation of bio-briquette sample bulk density $\rho$ (kg·m$^{-3}$) used its dimensions, namely its volume $V$ (m$^3$) and mass $m$ (kg), and the following Equation (1).

$$\rho = \frac{m}{V} \tag{1}$$

where $\rho$ is the bulk density (kg·m$^{-3}$), $V$ the bio-briquette samples' volume (m$^3$) and $m$ the bio-briquette sample mass (kg).

#### 2.3.3. Mechanical Durability $DU$

The produced bio-briquette samples were subjected particularly to the determination of mechanical durability $DU$ (%), which is the main indicator of bio-briquette fuel mechanical quality and which is defined by standard EN ISO 17831-2 (2015): Solid biofuels—Determination of mechanical durability of pellets and briquettes—Part 2: Briquettes. This standard states several quality levels of bio-briquette fuel and establishes the lowest acceptable level ($DU$ > 90%) for commercial bio-briquette fuel production. Experimental observation and measurements were performed repeatedly using an electrically-powered special dust–proof rotating drum (Figure 9) with a rectangular steel partition. The principle of such a test consists of projected impacts of tested bio-briquette samples in the rotating drum; thereby, the samples prove their durability.




(**a**) (**b**)

**Figure 9.** Equipment used for the determination of mechanical durability: (**a**) in practice; (**b**) scheme.

In practice, several groups of bio-briquette samples of a specific weight (2 ± 0.1 kg) were separately placed inside the drum and subjected to controlled impacts for a specific time (4 minutes 17 seconds), which was equal to the specific number of rotations (105 ± 5 rotations). Subsequently, bio-briquette samples were weighed prior to and after such testing, and their final resistance was determined by Equation (2).

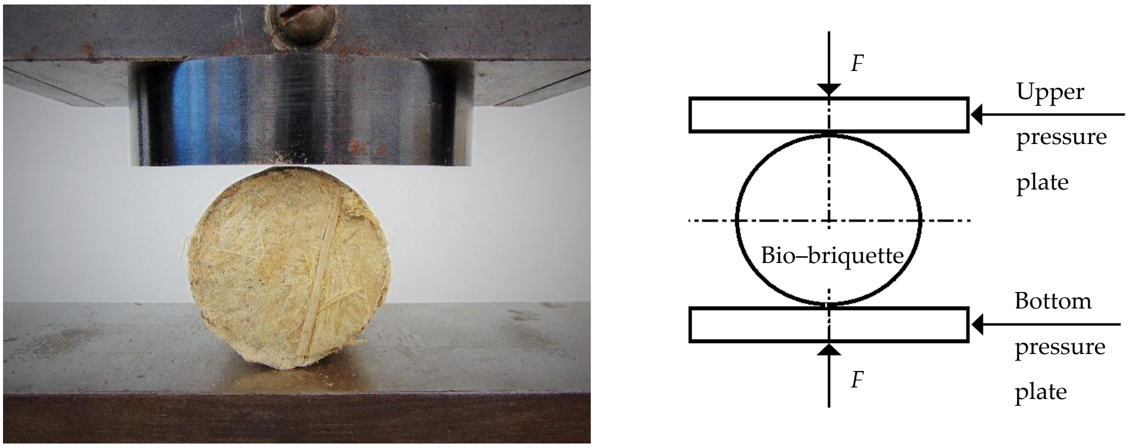
$$DU = \frac{m_a}{m_e} \cdot 100 \quad (2)$$

where $DU$ is mechanical durability (%), $m_e$ the sample weight before testing (g) and $m_a$ the sample weight after testing (g).

2.3.4. Rupture Force *RF*

The methodology of the last tested mechanical quality indicator, the rupture force *RF*, does not correspond to any mandatory technical standard. It was developed on the basis of previous scientific research focused on the pressing technology and measurement of the physical and mechanical properties of pressed items [36–38]. The stated methodology determined the hardness of tested bio-briquette samples, thus simulating their possible damage in practice.

The principle of measurement lies in the plate-loading test (Figure 10), which was performed using a universal hydraulic machine WPM, Type ZDM 5 (Leipzig, Germany) with a loading speed $v$ equal to 20 mm·min$^{-1}$. The measurement ended when bio-briquette samples disintegrated due to the influence of force loading; thus, the maximal force loaded to the samples before their disintegration was noted. The number of tested bio-briquette samples was equal to 64 in the case of bamboo fiber and to 57 in the case of sugarcane skin.




(**a**) (**b**)

**Figure 10.** The equipment used for the determination of rupture force *RF*: (**a**) in practice; (**b**) plate, loading test principle (*F* compressive force (N)).

## 3. Results and Discussion

The complex evaluation of the investigated bio-briquette production efficiency was based on the set of quality indicators of both feedstock materials and produced bio-briquette samples. All chosen indicators described the suitability of the investigated bio-briquette fuel for commercial production. Therefore, required indicator levels occurred at a high level in an attempt to ensure the highest quality of produced bio-briquette fuel. Nevertheless, mandatory requirements for solid biofuel commercial production differ within each country; the obtained results were compared with the European standards.

The present research aimed to answer the question of whether the chosen waste materials were suitable for bio-briquette production. In general, it was a complex process containing several necessary steps and could be influenced by many factors. Thus, before answering the main question posed, the following specific issues must be answered: (a) Is there a sufficient amount of such waste materials? Is there any functional existing way of its subsequent utilization? (b) Are those materials suitable for direct combustion processes? Is their fuel analysis positive for such purposes? (c) Are the materials suitable for drying and disintegration processes or do such steps involve difficulties? Is it possible to produce bio-briquette fuel from those materials? What is the final mechanical quality of such biofuel?

Answers to all of these questions are noted in the following sections or were explained in the Methodology Section.

### 3.1. Feasibility and Practicability of Production

The conditions of investigated materials production and potential reuse were primarily monitored in the target area. Both materials originated from plants that abundantly grow and are processed in the target area, with the only difference being that sugarcane plants are purposely cultivated as an agriculture crop, while bamboo plants grow wildly throughout the target area. Specifically, processed bamboo culms originated from the forests in the surrounding areas.

Both plants were nevertheless processed in the target area at a large-scale. Sugarcane plants were used for juice production by individual sellers; plants stems were skinned before squeezing of juice, which resulted in the production of sugarcane skin. Dried bamboo stems were manually skinned by small storekeepers and subsequently used for the production of various commercial items. As observed, both produced waste materials, bamboo fiber and sugarcane skin, were not reused properly in the target area (Figure 11).

(**a**) (**b**)

**Figure 11.** Untapped waste biomass potential in the target area: (**a**) sugarcane skin in municipal waste; (**b**) bamboo fiber in a fireplace.

Bamboo processing plants were located in rural areas. Thus, bamboo fiber was burned as waste without any purpose in the fields or individuals used it as a fire lighter at a small-scale. Sugarcane plants were processed directly in the streets of Huế city, thus leading to part of the produced sugarcane skin ending up in garbage bins for municipal waste (Figure 11). It is worth mentioning that the generation and amount of monitored waste materials were considerable and daily. In contrast, subsequent utilization of materials was rarely observed.

Bamboo plant populations or their cultivation were difficult to monitor because prevalent parts of the population are growing wildly. Focused on sugarcane plants, specific data of its production in Vietnam were available and are shown in Table 2. Meanwhile, according to a statistical database of the United Nations Food and Agriculture Organization (FAO), world sugarcane crop cultivation in 2016 provided the following data: harvested area 26,774,304 ha, production quantity 1,890,661,751 t and yield 706,148 hg·ha$^{-1}$.

**Table 2.** Sugarcane production in Vietnam in 2010–2014.

| Year | Harvested Area (ha) | Production Quantity (t) | Yield (hg·ha$^{-1}$) |
|---|---|---|---|
| 2016 | 256,322 | 16,313,145 | 636,432 |
| 2015 | 284,262 | 18,337,227 | 645,083 |
| 2014 | 304,969 | 19,822,851 | 649,996 |
| 2013 | 310,264 | 20,131,088 | 648,757 |

t, tonne; ha, hectare; hg, hectogram. Source: FAO, 2018.

As observed in this table, sugarcane production in Vietnam has occurred at a high level in recent years. Thus, the production of sugarcane residues has also increased. Sugarcane plants are prevalently used for production of juice or sugar in Vietnam, and thus, sugarcane skin represents a considerable percentage ratio of produced waste biomass.

### *3.2. Fuel Analysis of Feedstock Materials*

The present section describes the chemical parameters of the investigated materials, the required levels of which must be respected in practice, otherwise their burning (in the form of bio-briquette fuel) could cause environmental pollution. With respect to the data expressed in Table 3, it is clear that moisture content $M_c$ (%) during experimental measurements occurred at a suitable level for bio-briquette production (i.e., $M_c$ < 15%) [30]. Mentioned values of moisture content $M_c$ do not represent a material's moisture content in their initial form (at the moment of creation or collection) due to the necessary treatment within their transportation. However, as mentioned in the Methodology Section, bamboo fiber was removed from already sundried culms; thus, their (required) lower level of moisture content $M_c$ was expected. Such a factor evaluated the amount of energy input positively within the entire process of bio-briquette production, which in contrast to others, also contains feedstock drying. Moreover, if moisture content $M_c$ exceeds the suitable level, it complicates the densification process or makes it completely impossible to realize it.

**Table 3.** Basic chemical parameters of waste biomass samples (in w.b.) (± standard deviation).

| Sample | $M_c$ (%) | $A_c$ (%) | $GCV$ (MJ·kg$^{-1}$) | $NCV$ (MJ·kg$^{-1}$) |
|---|---|---|---|---|
| Bamboo fiber | 7.62 ± 0.47 | 1.16 ± 0.13 | 18.15 ± 0.03 | 16.92 |
| Sugarcane skin | 8.05 ± 0.52 | 8.62 ± 0.18 | 18.47 ± 0.50 | 17.23 |

$M_c$, moisture content; $A_c$, ash content; *GCV*, gross calorific value; *NCV*, net calorific value; w.b., wet basis.

When comparing the values of ash content $A_c$ (%), it is clear that bamboo fiber exhibited a good result, while sugarcane skin exhibited a result that was at the margin of tolerance (i.e., $A_c < 10\%$) [30]. Such a result represents a disadvantage of sugarcane material; however, it is still accepted by the mandatory requirements. Commonly, when a high level of ash content is detected, it can be caused by contamination of material due to external impurities (dust, soil). Nevertheless, sugarcane skin samples tested in the present research did not contain any impurities. Table 4 provides a comparison of fuel property data obtained within the present research with data from other studies.

**Table 4.** Fuel properties of bamboo and sugarcane residues.

| | $A_c$ (%) | $GCV$ (MJ·kg$^{-1}$) | Research |
|---|---|---|---|
| Bamboo culm | 3.74 | 19.62 | [39] |
| | 3.70 | 18.32 | [40] |
| Sugarcane bagasse | 6.16 | 18.20 | [41] |
| | 11.27 | 17.33 | [42] |

$A_c$, ash content; *GCV*, gross calorific value.

A higher level of ash content $A_c$ is commonly related to complications during biomass burning, which can result in low burning efficiency or damage to burning devices. In general, both materials represented herbaceous biomass, which prevalently exhibited a higher level of ash content $A_c$ in comparison to wood biomass [43,44]. However, the results of bamboo fiber samples were very good, thus proving the significant potential of such material, which were qualitatively comparable with wood biomass [45,46].

Energy potential expressed by calorific value is the most important indicator of fuel chemical quality, which indicates the amount of energy released from fuel during burning [47]. The obtained *NVC* data for both tested materials exhibited a high level of such an indicator; thus, these results were satisfactory. For commercial sale, bio-briquette fuel must exhibit *NVCs* of at least 14.50 MJ·kg$^{-1}$ for non-woody bio-briquette fuel and at least 15.00 MJ·kg$^{-1}$ for woody bio-briquette fuel [30]. Every biomass kind exhibits different levels of calorific value, as well as the requirements on each specific biomass kind of bio-briquette fuel differing (Table 5).

**Table 5.** Comparison of various biomass kind energy potential.

| Biomass Kind | Feedstock Material | *NCV* (MJ·kg$^{-1}$) | Research |
|---|---|---|---|
| Woody | Vine pruning | 19.19 | [48] |
| | Pine sawdust | 18.14 | [46] |
| | Sycamore wood | 15.62 | [49,50] |
| | Wild cherry wood | 15.55 | |
| Herbaceous | Banana leaf | 17.76 | [41] |
| | Wheat straw | 17.30 | [45] |
| | Bamboo leaf | 16.71 | [51] |
| | Rice straw | 15.07 | [41] |
| Fruit | Grape seeds | 20.39 | [52] |
| | Oil palm empty fruit bunch | 18.16 | [53] |
| | Banana peel | 18.89 | [54] |
| | Durian peel | 17.61 | [55] |
| Aquatic | Water hyacinth | 16.65 | [41] |
| Mixed | Rice husk, oil palm sludge | 21.68 | [56] |
| | Tropical hardwood sawdust | 18.94 | [57] |
| | Rice straw, sugarcane leaves | 17.83 | |

*NCV*, net calorific value.

The results of elementary composition (Table 6) primarily proved the higher level of oxygen content *O* (%) in the case of bamboo fiber, which is undesirable, while results for sugarcane skin were at a satisfactory level. In general, biomass elementary composition can influence final calorific value of produced biofuel, as well as influencing biofuel behavior during combustion. Higher levels of oxygen *O* (%) influence consumption of air during biofuel burning and production of flue gas [58].

**Table 6.** Elementary composition of waste biomass samples (in w.b.) (±standard deviation).

| Sample | *C* (%) | *H* (%) | *N* (%) | *S* (%) | *O* (%) |
|---|---|---|---|---|---|
| Bamboo fiber | 46.31 ± 0.14 | 6.19 ± 0.03 | 0.44 ± 0.02 | 0.04 ± 0.03 | 42.15 |
| Sugarcane skin | 45.85 ± 0.11 | 6.36 ± 0.02 | 0.96 ± 0.03 | 0.18 ± 0.01 | 34.02 |

*C*, carbon; *H*, hydrogen; *N*, nitrogen; *S*, sulfur; *O*, oxygen; w.b., wet basis.

Observed values were also converted into dry ash-free state to express results without the influence of ash presence (Table 7).

**Table 7.** Composition of samples in dry ash-free state (d.a.f.).

| Sample | *C* (%) | *H* (%) | *N* (%) | *S* (%) | *O* (%) | *GCV* (MJ·kg$^{-1}$) | *NCV* (MJ·kg$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Bamboo Fiber | 51.01 | 5.82 | 0.49 | 0.04 | 42.65 | 20.00 | 18.73 |
| Sugarcane Skin | 54.95 | 6.46 | 1.15 | 0.21 | 37.23 | 22.14 | 20.73 |

*C*, carbon; *H*, hydrogen; *N*, nitrogen; *S*, sulfur; *O*, oxygen; *GCV*, gross calorific value; *NCV*, net calorific value; d.a.f., dry ash-free state.

### 3.3. Mechanical Analysis of Briquette Samples

Both investigated materials proved their suitability for bio-briquette production. For the densification process, it was possible to produce bio-briquette samples from them. Such a statement may not be a matter of course because the success of bio-briquette sample production is not guaranteed in advance.

Specific data evaluating the efficiency of the densification process were observed immediately following bio-briquette sample production. Thus, their bulk density $\rho$ (kg·m$^{-3}$) was stated. The results of the first investigated mechanical quality indicator are noted in Table 8, together with the results of other investigated indicators.

**Table 8.** Mechanical quality indicators of the investigated bio-briquette samples (±standard deviation).

| Sample | $\rho$ (kg·m$^{-3}$) | *DU* (%) | *RF* (N·mm$^{-1}$) |
|---|---|---|---|
| Bamboo fiber | 986.37 ± 181.18 | 97.80 ± 0.04 | 143.30 ± 1.70 |
| Sugarcane skin | 1067.08 ± 39.08 | 97.70 ± 0.08 | 46.50 ± 0.80 |

$\rho$, bulk density; *DU*, mechanical durability; *RF*, rupture force.

Observed bulk density $\rho$ data proved satisfactory results in both cases, which indicates high quality bio-briquette fuel. As noted previously, bio-briquette fuel mechanical quality increases with increasing bulk density $\rho$ [49,59,60] because it indicates bio-briquette fuels' longer burning time and larger amount of produced heat [61]. According to other published research, the level of bulk density $\rho$ of high quality bio-briquette fuels should occur at approximately 1000 kg·m$^{-3}$ [56,62,63].

The results of the next investigated indicator, bio-briquette sample *DU* (%), were obtained during experimental laboratory testing. A statement regarding bio-briquette fuel *DU* (%), also termed abrasion resistance, is necessary and required within commercial production and represents a major deciding factor [49,62,64]; thus, its performance was a pivotal point of mechanical analysis. Data noted in Table 8 expressed extremely good results; measured *DU* exceeded 97% for both materials, while the mandatory required level is a DU $\geq$ 90% [31]. Figure 12 illustrates the conditions of bio-briquette samples after abrasion testing.

(**a**) (**b**)

**Figure 12.** Bio-briquette fuel samples after mechanical durability testing: (**a**) bamboo fiber; (**b**) sugarcane skin.

As observed in Figure 12, tested bio-briquette samples were in very good condition; only the edges of their bodies were abraded. Such positive results were caused by the structural characteristics of the materials, which were able to create strong bonds between particles.

Such excellent results correspond to the highest level of *DU* stated by related standards (i.e., DU $\geq$ 95%). Table 9 shows a comparison of the result values of other investigated bio-briquette fuels sorted according to specific mechanical durability levels.

**Table 9.** Mechanical durability *DU* of different bio-briquette fuel kinds.

| *DU* (%) | Feedstock Material | Research |
|---|---|---|
| <90 | Big bluestem sawdust<br>Canola straw | [59] |
| | Switchgrass<br>Corn stover | [65] |
| >90 | Pine sawdust | [66] |
| | Canary grass | [67] |
| | Rice husk<br>Corncob | [64] |
| ≥95 | Eucalyptus sawdust, paper | [68] |
| | Soybean stalk | [69] |
| | Cotton stalk | [70] |
| | Digestate | [71] |

*DU*, mechanical durability.

The level of *DU* is prevalently influenced by the specifications of pressed feedstock materials, but also, a considerable influence of the forming pressure used was proven. *DU* clearly increased with increasing forming pressure applied by pressing the briquetting press into the feedstock material [65]. Applying such a process in practice could improve the unsuitable lower levels of other specific bio-briquette's *DU*.

The last monitored indicator was rupture force *RF*, which is not defined by any mandatory standard. Thus, the evaluation of the observed results was performed only by comparison between the investigated materials. Data in Table 9 indicate the marked differences observed. BF bio-briquette samples had an $RF$ = 143.30 N·mm$^{-1}$, while sugarcane skin bio-briquette samples exhibited an $RF$ equal to 46.50 N·mm$^{-1}$. The conditions of bio-briquette samples after *RF* testing are visible in Figure 13.

(**a**) (**b**)

**Figure 13.** Bio-briquette fuel samples after rupture force testing: (**a**) bamboo fiber; (**b**) sugarcane skin.

The considerably better strength of bamboo fiber bio-briquette samples was caused by the positive behavior of fibers during pressing; above that, fibers made strong bonds already during feedstock preparation. Thus, it can be concluded that fibrous materials have significant potential for bio-briquette production. In addition, the overall evaluation of both tested materials proved satisfactory when compared with other published data [72–74].

## 4. Conclusions

The main question investigated in the present research was to determine whether specific agriculture waste residues, namely bamboo fibers and sugarcane skin, are suitable for bio-briquette fuel production. The answer to this question, based on all observed results, is 'Yes'. Both investigated materials proved suitable as complete feedstocks for bio-briquette fuel production. Monitoring of their production (quantity) and poor practice in terms of their reuse (in local conditions of the target area) indicated high potential of such waste biomass for any further meaningful utilization.

Fuel parameter analysis found satisfactory levels of all tested quality indicators; the only identified limitation was observed in the case of sugarcane skin ash content ($A_c$ = 8.05%), but even that result is acceptable. Comparatively good results were obtained during determination of bio-briquette fuel mechanical quality indicators. Extremely high levels of mechanical durability (DU > 97%) strongly supported the statement that utilization of investigated materials for bio-briquette fuel production will result in high quality biofuel production.

In general, all measurements and tests performed within the present research provided satisfactory results, and hence, the utilization of bamboo fiber and sugarcane skin for bio-briquette fuel production can be highly recommended.

It is hoped that this research will also extend knowledge regarding appropriate waste management principles and reuse of all potential waste biomass for the production of environmentally-friendly solid biofuels.

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## Nomenclature

| | |
|---|---|
| $A_c$ | Ash content (%) |
| $\rho$ | Bulk density of bio-briquette samples (kg·m$^{-3}$) |
| $C$ | Carbon (%) |
| $DU$ | Mechanical durability (%) |
| $F$ | Compressive force (N) |
| $GCV$ | Gross calorific value (MJ·kg$^{-1}$) |
| $H$ | Hydrogen (%) |
| $m$ | Mass of bio-briquette samples (kg) |
| $m_a$ | Mass of bio-briquette samples after *DU* testing (g) |
| $M_c$ | Moisture content (%) |
| $m_e$ | Mass of bio-briquette samples before *DU* testing (g) |
| $N$ | Nitrogen (%) |
| $NCV$ | Net calorific value (MJ·kg$^{-1}$) |
| $O$ | Oxygen (%) |
| $RF$ | Rupture force (N·mm$^{-1}$) |
| $S$ | Sulfur (%) |
| $V$ | Volume of bio-briquette samples (m$^3$) |
| $v$ | Loading speed (mm·min$^{-1}$) |

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