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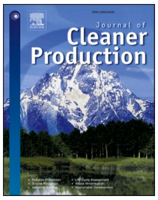

# Manual wooden low-pressure briquetting press: An alternative technology of waste biomass utilisation in developing countries of Southeast Asia

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## ABSTRACT

Although briquetting is an appropriate technology for the production of renewable energy, its widespreadness in Southeast Asia is limited. Especially due to the high initial investments and energy consumption of a high-pressure briquetting press. However, manual low-pressure briquetting presses (operating pressure <5 MPa) can represent a relevant alternative, regarding to their ease of use and modest energy consumption. The aim of the present research was to develop and verify a manual wooden low pressure briquetting press with a square-shaped pressing chamber, piston and a single lever as a pressing unit. In practice, press was designed, manufactured, and verified by successful bio-briquette samples production. Four different feedstock mixtures were prepared from coconut mesocarp fibre (CF), bamboo skin (BS), pineapple leaves (PL), sugarcane bagasse (SB); each mixed with external binding agent (wastepaper) in biomass:binder ratios of 1:1 and 2:1. The achieved bulk density $\rho$ ranged from 204.30 ± 15.73 kg m$^{-3}$ for 1:1 feedstock mixtures and 199.31 ± 23.13 kg m$^{-3}$ for 2:1 feedstock mixtures. The press efficiency, feasibility and practicability were positively evaluated within their possible utilisation in rural areas of developing countries. The importance of research increases constantly due to the worldwide need for a transition from fossil fuels to renewable energy sources, proper waste management, and reduction of environmental and health risks related to improper treatment of waste materials. The final idea of the article contributes to the development of the sector of clean green energy production, simultaneously with raising awareness about sustainable technologies for proper waste management within the wide public.

## 1. Introduction

> “Briquetting technology represents both, clean renewable energy production and proper waste management."

The current world situation shows enormous potential for waste biomass as a renewable energy source despite the fact that untreated raw waste biomass is characterised by a low energy potential. This issue can be solved through its conversion into solid biofuels, namely, bio-briquettes (Anggono et al., 2016). The bio-briquette fuel is produced by the densification process working with the application of high pressure on feedstock material (biomass) to increase its density. Compaction of raw biomass also eliminates its undesirable mechanical properties (low density, irregular shape, high moisture content), thereby providing its easier handling and transportation; further improves its chemical

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properties (more produced heat, higher calorific value, less smoke) (Emerhi, 2011; Bhattacharya et al., 2000).

### 1.1. Biomass utilisation

Various biomasses can be used for the production of bio-briquette fuel (prevalently waste biomass); thus, its mechanical and chemical parameters (directly related to the used feedstock) differ. Wood waste biomass represents the most commonly used kind due to its availability and suitable properties as a high content of natural binder, lignin (Emerhi, 2011). However, other types of waste biomass (herbaceous, fruit, or mixed) also provide suitable properties for bio-briquette production, thus representing a suitable source of renewable energy capable of competing with fossil fuels (Picchi et al., 2013; Obi and Okongwu, 2016; Romallosa and Kraft, 2017). Biomass waste in developing countries comes primarily from agriculture, that is, the cultivation, harvesting, and processing of palm oil, coconut, corn, bean, cassava, and sugar cane. These residues have already been investigated as a satisfactory fuel alternative (Suzuki et al., 2016; Nasrin et al., 2008; Rezania et al., 2016). As mentioned, the production of bio-briquette fuel represents not only the technology of clean renewable energy production but also the procedure of proper waste management, while this knowledge should be integrated into the wider public. It indicates the importance of subsequent utilisation of all types of waste biomass. However, the utilisation of alternative types of waste biomass requires a more extensive analysis of their suitability. The statement and application of suitable briquetting technology, feedstock materials, external binding agents, and their proper ratio improve the possible negative parameters of waste biomass and increase their potential for clean energy generation.

### 1.2. Briquetting technology in developing countries

The use of waste biomass for direct combustion purposes ensures that in rural areas in developing countries primary energy consumption requirements for heating and cooking (Bhattacharya et al., 1999; Cabraal et al., 2005; Kaygusuz, 2012). However, the use of raw waste biomass in such regions is characterised by low energy efficiency and harmful indoor air pollution (ESCAP, 1999; Kaygusuz, 2012). Using densification technology (solid biofuel production), it is possible to minimise the undesirable impacts of waste biomass combustion (Saptoadi, 2008). With a particular focus on developing countries, briquetting technology is suitable for the reuse of various organic waste materials (Bhattacharya, 2001; Hood, 2010; Lohri et al., 2015). Many countries are endowed with an abundant amount of waste materials, both biological and non-biological, thus, their interest in proper waste management results in reusing of those waste materials in various production sectors (Bhattacharya and Kumar, 2000; Tunc, 2019). However, the implementation of densification technology in these countries encountered several limitations, directly related to the fact that densification technology operates with heavy machinery such as a high-pressure briquetting press, which represents high initial financial costs, regular repair service, high electrical energy consumption, and the need for properly trained operators (FCCC, 1999; Bhattacharya and Kumar, 2000; Lohri et al., 2015). Therefore, manual low-pressure briquetting technology could be an adequate and relevant alternative within the densification process related to the utilisation of biomass waste.

### 1.3. Low-pressure briquetting technology

The implementation of low-pressure briquetting technology in developing countries represents a challenge in its energy and economic savings related to its availability, and the viability technology needs to be simplified. Specifically, reduce the financial costs and electrical energy consumption and simplify machine operation. Such efforts can increase the applicability of briquetting technology, which is now limited (FCCC, 1999; Bhattacharya and Salam, 2001; Kaygusuz, 2012). Currently, there are several designs of manual low-pressure briquetting presses implemented in Asia and Africa using different pressing mechanisms (Abakr and Abasaeed, 2006; Ngusale et al., 2014; Yank et al., 2016). This alternative technology offers a variety of design options which differ in press size, construction materials (wood, metal), number of briquettes produced at a time, the shape of pressing chamber, thus the shape of briquettes (square, cylindrical, mold) or pressing mechanisms (piston, screw) (Stanley, 2003; Hite, 2016).

This diversity offers a significant opportunity to combine the technical specifications of the briquetting press with the properties of the feedstock material to manufacture the most efficient manual low-pressure briquetting press with respect to the local requirements and the chosen feedstock materials. Focused on the production of biological waste in Asia, the largest part of organic waste is formed by herbaceous biomass; waste from the production and processing of rice, corn, cassava, coconut, coffee, tobacco, sugar cane, and spice or simply sawdust (wood biomass) (Hood, 2010). Manual low-pressure presses work with operating pressure less than 5 MPa (Eriksson and Prior, 1990a,b; Abakr and Abasaeed, 2006; Yank et al., 2016), which is sufficient for the herbaceous biomass densification process (Pilusa et al., 2012; Ngusale et al., 2014; Yank et al., 2016). Within the use of this technology, it is necessary to use external binding agents for the agglomeration of feedstock materials; the ratio of feedstock material and binding agent differs according to their variety. This ratio represents an important factor influencing the final quality in the bio-briquette fuel produced. (Hood, 2010).

The technology mentioned is not well known or commonly used in the energy production sector today. Thus, the development and verification of such equipment is still in process worldwide. Moreover, research activities focused on manual low-pressure briquetting technology are mostly represented by the efforts and initiative of non-profit organisations or individuals. Thus, literature regarding such technology is quite limited; the majority of information is published on the organisation's websites or as content of specific handbooks intended for use in the field. However, several studies have already been published with satisfactory results (Eriksson and Prior, 1990a,b; Pilusa et al., 2012; Ngusale et al., 2014). Such a limitation represents the difficulties during the compilation of appropriate literature review compilation. On the other hand, it indicates that the topic has not yet been thoroughly investigated, thus, there is a possibility to perform original research and contribute to the development of the topic with primary data and completely new knowledge. Such efforts can result in an increase in awareness about the investigated topic in the general public.

The novelty of the presented research lies in the introduction of low-pressure briquetting technology to target groups in practice, as well as in obtaining specific data about low-pressure briquetting technology. Briquetting technology is not widely spread in rural areas of SE Asia due to its high costs for implementation and use, therefore, spreading awareness about a more suitable and affordable version of briquetting press can influence the wide public to reconsider their opinion about briquetting technology in general, but also reconsider their opinion about waste management. The novelty also lies in the collection of primary data within the production of low-pressure bio-briquette fuel, of which the amount of published data is very limited.

The main aim of the present research was to develop a manual low-pressure briquetting press designed with a piston unit as a pressing mechanism producing square-shaped briquettes. Furthermore, we verify its viability by the production of bio-briquette samples. Within the investigated target area for possible press implementation (rural areas of developing countries, specifically Southeast Asia), four different types of waste biomass originating from Vietnam, Indonesia, and Cambodia were used as feedstock material. The selection of suitable external binding agents and their ratios (biomass:binder) were also the subject of research. Qualitative analysis of the fuel parameters of the chosen feedstock materials and the mechanical parameters of the bio-briquette fuel samples produced were also performed.

The side objective of the performed research and subsequent research was to influence the reader's approach within the understanding a fact that bio-briquette production not only directly contributes to clean green energy production, but also supports utilisation of biological waste materials (waste biomass). Thereby, it validates negatively perceived waste as a commodity, reduces the amount of unused waste that can cause environmental harm, and changes the public opinions about the potential of waste. The whole research was carried out with this interdisciplinary thought, thus, authors would appreciate if readers get into the same mindset in the very beginning of the article reading.

## 2. Methodology

The processes performed and the specific steps described in the present chapter were based on the knowledge and requirements of the solid biofuel production and the testing background. The majority of the processes mentioned were performed within the mandatory technical standards related to bio-briquette fuel production and quality testing within commercial sale; the list of standards used is noted in Table 1.

### 2.1. Materials and samples

The materials investigated represented herbaceous waste biomass and were produced as agricultural residue; therefore, the level of their processing differed during collection, see Fig. 2.

The target areas of their origin represented rural areas of different Asian countries, namely, the Socialist Republic of Vietnam, the Kingdom of Cambodia and the Republic of Indonesia (detail characterisation is noted in Table 2).

Materials originating from the Republic of Indonesia were collected in Toba Samosir district, North Sumatra province, Sumatra island in years 2016 from July to September and 2017 in November). The materials collected in the Socialist Republic of Vietnam originate from Thừa Thiên Huế province, Central Vietnam. The collection was held in January and May 2017 and from March to April 2018. The last place to collect materials was the Kingdom of Cambodia, specifically, Battambang province in the northwestern part of the country. The materials were collected in March 2018. Areas of sample collection are expressed in Fig. 1.

**Table 1**
List of used technical standards.

| Code | Name | Year |
|---|---|---|
| EN ISO 16559 | Solid Biofuels - Terminology, Definitions and Descriptions | 2014 |
| EN 15234-1 | Solid Biofuels - Fuel Quality Assurance - Part 1: General requirements | 2011 |
| EN ISO 17225-1 | Solid Biofuels - Fuel Specifications and Classes - Part 1: General Requirements | 2015 |
| EN 14918 | Solid Biofuels - Determination of Calorific Value | 2010 |
| ISO 1928 | Solid Mineral Fuels - Determination of Gross Calorific Value by the Bomb Calorimetric Method, and Calculation of Net Calorific Value | 2010 |
| EN ISO 18122 | Solid Biofuels - Determination of Ash Content | 2015 |
| EN ISO 16948 | Solid Biofuels - Determination of Total Content of Carbon, Hydrogen and Nitrogen | 2016 |
| ISO 16994 | Solid biofuels - Determination of Total Content of Sulphur and Chlorine | 2016 |
| EN ISO 16993 | Solid biofuels - Conversion of Analytical Results from One Basis to Another | 2016 |
| EN ISO 18134–1 | Solid biofuels - Determination of Moisture Content - Oven Dry Method - Part 1: Total Moisture - Reference Method | 2015 |
| EN ISO 18134-2 | Solid Biofuels - Determination of Moisture Content - Oven Dry Method - Part 2: Total Moisture - Simplified Method | 2015 |
| EN ISO 17831-2 | Solid Biofuels - Determination of Mechanical Durability of Pellets and Briquettes - Part 2: Briquettes | 2015 |

**Table 2**
Description of investigated waste biomass feedstock materials.

| Sample type | Latin name | Sample's identification | Country of origin | Collection year |
|---|---|---|---|---|
| Coconut mesocarp fibres | *Cocos nucifera* | CF | Indonesia | 2016 |
| Bamboo skin | *Bambusoideae* spp. | BS | Vietnam | 2017 |
| Pineapple leaves | *Ananas comosus* | PL | Indonesia | 2017 |
| Sugarcane bagasse | *Saccharum officinarum* | SB | Cambodia | 2018 |

**Fig. 1.** Target provinces of the collection of materials investigated.

#### 2.1.1. Materials processing

All investigated waste biomass samples were collected in rural areas of the mentioned countries and partially processed immediately after collection. Initial processing consisted of drying (stabilisation of moisture content), cutting (particle size reduction) and subsequent preservation within materials transportation to Prague, Czech Republic, the target area of experimental testing. Specifically, materials were cut during or after collection and crushed with the use of a machete and a kitchen blender, with respect to the local conditions. Subsequently, the materials were dried by using solar energy in order to use available renewable energy. Materials were stored immediately after processing in hermetically sealed laboratory vessels and bags. In addition, the materials were transported to fully equipped laboratories in Prague, Czech Republic, where more extensive processing was performed.

The materials were dried in laboratory LAC, type S100/03 (Rajhrad, Czech Republic) at 105 °C for 3–4 h until the weight of the material was constant. The process of grinding the materials consisted of more steps regarding the variety of the materials and the initial particle sizes. Materials of larger size, samples PL and CF, were mainly crushed by a hammer mill, type 9FQ-40C (Henan, China). Subsequently, all materials, samples BS, CF, PL and SB, were ground by a grinding hammer mill Taurus, Type VM 7,5 (Chrudim, Czech Republic). Its working unit was equipped with a vertical shaft with eight free-swinging hammers. A sieve with 8 mm diameter holes was used to homogenise the particle size of materials; thus, the final particle size of investigated materials was $<8$ mm. The form of the materials after the grinding process is shown in Fig. 2.

#### 2.1.2. Feedstock mixture preparation

The preparation of feedstock in the present research differed from the commonly used methodology of high-pressure briquetting.

**Fig. 2.** Investigated material samples before and after processing: a) coconut mesocarp fibre (CF), b) bamboo skin (BS), c) pineapple leaves (PL), d) sugarcane bagasse (SB).

Specifically, the need for external binding agents and the moisture content of the feedstock material *Mc* (%) differed. The moisture content of the feedstock materials *Mc* (%) must be less than 10% - 15 % within the high-pressure briquetting technology, while the feedstock materials for the low-pressure briquetting technology are soaked in water before use (Saeed et al., 2021). Furthermore, no binders are needed due to the extremely high operational pressure applied to the feedstock materials by the high-pressure briquetting press (>15 MPa). In contrast, low pressure briquetting technology operates with a pressure <5 MPa, which implies that the use of external binding agents is necessary to optimise the bio-briquette samples production. The combination of investigated materials with external binding agents in a suitable ratio represented the most important step in the preparation of feedstock mixtures for utilisation within a manual low pressure briquetting press. Various external binding agents (tapioca starch, waste paper, and waste cardboard) were tested for feedstock mixture preparation. Shredded waste paper with dimensions of 4 mm × 30 mm was chosen as a binding agent for the research carried out. Simultaneously, different mass ratios of investigated materials and a binding agent (material:binder) were tested, while mass ratios of 1:1 and 2:1 were chosen for subsequent bio-briquette samples production. Consequently, eight different feedstock mixtures were prepared and used for bio-briquette samples production; their designation is noted in Table 3.

As was mentioned, feedstock materials for low-pressure briquetting technology occurred in wet form, more precisely, they were soaked. During the preparation of the feedstock mixtures, water was used as the surrounding medium in which the investigated materials and the external binding agent were mixed. The feedstock mixtures were prepared in the mixing vessels in advance (>5 h) because of the mechanical properties of the wastepaper; to soften and dissolve. The examples of prepared feedstock mixtures before use are shown in Fig. 3.

### 2.2. Low-pressure briquetting technology

High-pressure briquetting technology is commonly intended for commercial purpose; thus, the methodology of its production, and especially the quality testing and requirements, are subjected to mandatory technical standards. On the contrary, low-pressure briquetting technology is commonly used in developing countries and was developed by non-profit organisations, volunteers, or individuals (Pilusa et al., 2012; Ngusale et al., 2014; Yank et al., 2016). Such a technology is still under development. Thus, low-pressure briquetting technology is not widespread and is considered as an alternative technology. As a consequence, there are no official requirements, limitations, and restrictions related to methodology, technology, or final products. Therefore, the methodology of low-pressure briquetting press design, manufacturing, and use, as well as production of bio-briquette samples and their evaluation, was based on knowledge from practice, previously performed experiments, and experiences of other authors.

**Table 3**
Investigated feedstock mixtures identification.

| Material | Sample's identification | Mass ratio with the binder (material:binder) | |
|---|---|---|---|
| | | 1:1 | 2:1 |
| Coconut mesocarp fibers | CF | CF (1:1) | CF (2:1) |
| Bamboo skin | BS | BS (1:1) | BS (2:1) |
| Pineapple leaves | PL | PL (1:1) | PL (2:1) |
| Sugarcane bagasse | SB | SB (1:1) | SB (2:1) |

#### 2.2.1. Design of manual wooden low-pressure briquetting press

The design of the investigated manual wooden low pressure briquetting press was based on models first made by Hite and Smith (2011) presented on the website of the non-profit organisation Hands-on Engineering managed by Leland Hite (http://leehite.org/). Their photo documentation served as an initial patter (template) for the creation of press drawings and technical documentation. Furthermore, for press components design and manufacturing of investigated manual wooden low pressure briquetting press. The design used for the manual briquetting press was updated and modified according to the needs for construction and use due to the achievement of the highest practicability and efficiency of the press.

#### 2.2.2. Construction, use and operational pressure of manual wooden low-pressure briquetting press

Briquetting presses constructed within low-pressure briquetting technology (<5 MPa) operate mostly with a single or double lever and use a piston as a pressing unit (Yank et al., 2016). The manual low-pressure press manufactured within present research was constructed mainly from wood components (see all components in Fig. 4); assembled parts were screwed together by screws.

Construction of such a design also allows easy dismantling of the press in the event that there is a need for easy transportation or exchangeability of wood components. A pressing chamber was square-shaped (see Fig. 5, b)); thus, the bio-briquette samples came out in the form of blocks. The chamber was equipped with a mechanism for water drainage - with respect to the fact that feedstock material for low-pressure briquetting presses occurs in wet base (Pilusa et al., 2012; Ngusale et al., 2014; Yank et al., 2016) and the piston was pressed by single lever powered by manpower. The drainage system (drainage pipe) resulted in a hole in the middle of the final product which

**Fig. 3.** Prepared feedstock mixtures: a) coconut fibre (2:1), b) bamboo skin (1:1).

**Fig. 4.** Components of the investigated press: a) wooden parts, b) metal parts.

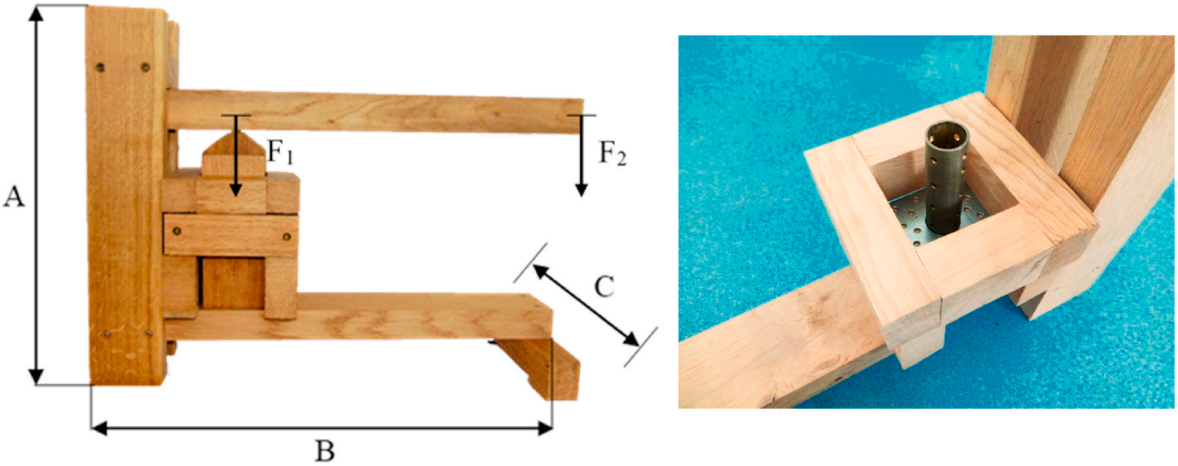

**Fig. 5.** Investigated manual wooden low-pressure briquetting press: a) dimensions of equipment: A = 47 cm, B = 61 cm, C = 25 cm, b) pressing chamber.

improved the porosity and combustion properties of bio-briquette samples due to better Oxygen flow (Shrivastava et al., 1989).

The manufactured manual wooden low-pressure briquetting press produced one bio-briquette sample at the time. After filling of pressing chamber with feedstock material mixture, the piston was placed into the pressing chamber and pushed down with the lever (densification process). After the densification process, the lever was removed, as well as detachable drainage pipe and pressing chamber, while produced bio-briquette sample was manually pushed out from topper part of the pressing chamber. Regarding the using of wet feedstock mixtures, the produced bio-briquette samples occurred in wet form; therefore, their drying process was necessary. The previously mentioned laboratory dryer LAC, type S100/03 (Rajhrad, Czech Republic) was used for samples drying.

### *2.2.3. Operation pressure*

Within the determination of the operation pressure *P* (MPa) developed by the investigated manual low-pressure briquetting press, the quantities described further were determined. The dimensions and placement of the lever during bio-briquette samples production is visible in Fig. 5.

The forces distribution proved force $F_2$ (N) applied by the manual work equal to approximately 500 N. After proper calculation was force $F_1$ stated equal to 2.94 N; such force was during bio-briquette samples production applied to the piston, and further, to the feedstock material. In consequence, the operation pressure $P$ (MPa) was calculated equal to 0.516 MPa.

#### 2.2.4. Technical documentation

The manufactured equipment was completed with technical documentation and an interactive 3D model (see Fig. 6 and Annex A). The interactive 3D model was created by SolidWorks software (Waltham, Massachusetts, United States) for better expression and understanding of press functions and construction for the users and manufacturers. Such software offers a 360°-degree view of the 3D model of the press and contains a set of views, stack disasters, visualizations, animation of clusters or movements of the press assembly. Using the present software, each part of the 3D model can be converted to an invisible form; thus, the internal construction of the press is visible. Within the transfer of observed knowledge into practice, two illustrated handbooks for practical use by end-users were produced. The first handbook contained illustrations and dimensions of press components, and the second handbook contained illustrations of press manufacturing and use.

### 2.3. High-pressure briquetting technology

A hydraulic high-pressure briquetting press Briklis, type BrikStar 30-12 (Malšice, Czech Republic) was used as a representative of high-pressure briquetting technology for subsequent comparison with investigated low-pressure briquetting technology. The mentioned high-pressure briquetting press (expressed in Fig. 7) was chosen on the basis that it uses piston as a pressing unit as well as the developed low-pressure briquetting press.

The comparison of monitored briquetting presses was performed according to machine properties (operation pressure, power consumption, productivity, dimensions or weigh and others), bio-briquette properties (dimensions, moisture content, volume density and others) and feedstock requirements (particle size, moisture content, addiction of binder). The price and other related investments were also evaluated. Chosen high-pressure briquetting press is commonly used as a part of whole briquetting plant containing intended for 24-h operation in large-scale industry.

### 2.4. Fuel parameter analysis

As a feedstock material for the production of bio-briquette fuel intended for direct burning investigated, materials had to be subjected to the experimental testing, which determined their safety, efficiency, and suitability for such purpose.

#### 2.4.1. Chemical parameters

Material samples were ground into powder (particle size <0.1 mm), pressed into the form of small pellet samples and subsequently used to test their moisture content $Mc$ (%) and ash content $Ac$ (%). The methods used corresponded to requirements defined by the mandatory technical standards EN 18134-2 (2015) and EN ISO 18122 (2015). The samples were burned in the LECO TGA 701 thermogravimetric analyser (Saint Joseph, United States) at 107 °C within the moisture content $Mc$ (%) and at 550 °C within the $Ac$ (%) determination. Subsequently produced bio-briquette samples were subjected to a similar process of moisture content $Mc$ (%) determination because they were produced in wet form and their moisture content $Mc$ (%) represented important indicator of stated methodology efficiency.

#### 2.4.2. Energy potential

The main indicator of the energy potential of waste biomass is the CV calorific value $CV$ (MJ•kg$^{-1}$), which describes the amount of energy released during the burning of the materials. Both the gross calorific value ($GCV$) and the net calorific value ($NCV$) were determined. Gross calorific value $GCV$ (MJ•kg$^{-1}$) was determined by using of isoperibol calorimeter LECO, type AC 600 (Saint Joseph, United States), while requirements of mandatory technical standard EN 14918 (2010) was followed. Net calorific value $NCV$ (MJ•kg$^{-1}$) was calculated by using the relationship between $GCV$ (MJ•kg$^{-1}$) and $NCV$ (MJ•kg$^{-1}$) defined by mandatory technical standard ISO 1928 (2010). The following formula (Equation (7)) was used:

$$NCV = GCV - 24.42 \bullet (M_c + 8.94 \bullet H) \qquad \text{(Eq. 7)}$$

where: $NCV$ - net calorific value (MJ•kg$^{-1}$), $GCV$ - gross calorific value (MJ•kg$^{-1}$), 24.42 - coefficient of 1% of the water in the sample at 25 °C (MJ•kg$^{-1}$), $Mc$ - moisture content in the analytical sample (%), 8.94 - coefficient of Hydrogen to water conversion, $H$ - Hydrogen content in the analytical sample (%)

#### 2.4.3. Elementary composition

Within the analysis of the elemental composition of the investigated materials, the content of Carbon $C$ (%), Hydrogen $H$ (%), Nitrogen $N$ (%), Sulphur $S$ (%) and Oxygen $O$ (%) was determined. Laboratory instrument LECO CHN628+S (Saint Joseph, United States) was used for the experimental procedures, while helium was used as a carrier gas. Material samples were burnt in Oxygen and resulting flue gases were analysed. Infrared absorption cells were used to determine the $C$ (%), Hydrogen $H$ (%), and Sulphur $S$ (%) contents. Content of $N$ (%) was determined by using a thermal conductivity cell. Measurements were performed within mandatory technical standard EN ISO 16948 (2016).

### 2.5. Mechanical parameters of bio-briquette samples

To determine the mechanical quality of produced bio-briquette

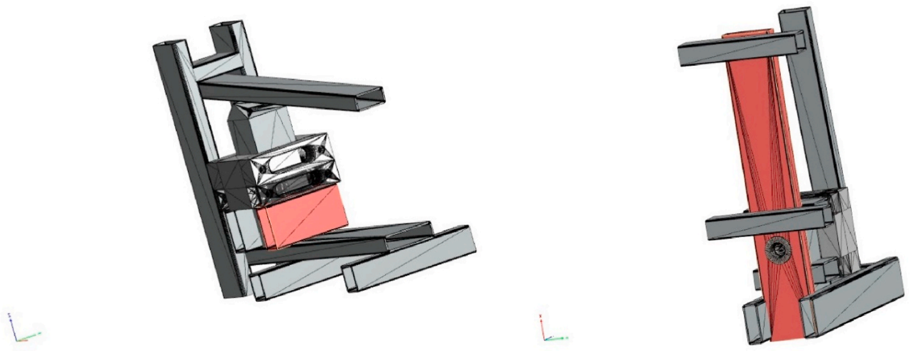

**Fig. 6.** Preview of interactive 3D technical documentation of investigated low-pressure briquetting press.

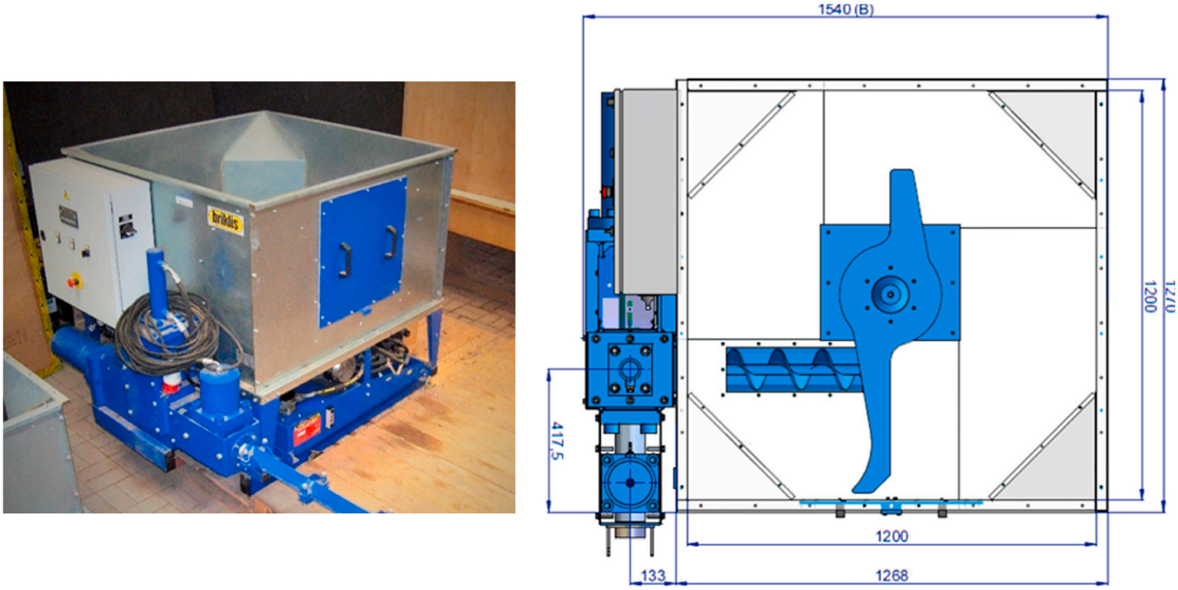

**Fig. 7.** Chosen high-pressure briquetting press: a) in practice, b) scheme of pressing unit from above (dimensions in mm).

samples, their basic mechanical parameters were measured and calculated. Their dimensions as a height *h* (mm), diameter $\phi$ (mm) and mass *m* (g) were measured by sliding scale, and their bulk density $\rho$ (kg·m$^{-3}$) was calculated by using observed result values and the following formula (Equation (8)):

$$\rho = \frac{m}{V} \quad \text{(Eq. 8)}$$

where: $\rho$ - volume density (kg·m$^{-3}$); *V* - bio-briquette samples volume (m$^3$); *m* - bio-briquette samples mass (kg)

### 2.6. Statistical analysis

The obtained data were sorted in Microsoft Excel (version 2013, Microsoft, Redmond, United States) and subsequently analysed by using Statistica software (version 13.5 TIBCO Software Inc., Palo Alto, United States). To compare mechanical quality of produced bio-briquette samples of different feedstock material mixtures and binder ratios, the observed results of volume density $\rho$ (kg·m$^{-3}$) were statistically analysed by the factorial analysis of variance (ANOVA) with significance level α 0.05, was used. Assumptions' fulfilment for ANOVA application - normality (Shapiro Wilk test, p-value = 0.62917 > 0.05) and homoscedasticity of variance (Levene's test, p-value = 0.58904 > 0.05) was verified prior to the testing. The means were compared by using post-hoc Tukey HSD tests at 95% significance level for all parameters evaluated in the ANOVA.

## 3. Results and discussion

The present chapter was divided into three separated parts. First one is related to the fuel parameters of investigated feedstock materials and their mixtures in an attempt to define their suitability for combustion purposes; their environment harmlessness and burning efficiency (the perspective of their using for bio-briquette fuel production). Second part of Result chapter focuses on the mechanical properties of subsequently produced bio-briquette samples within the statement of their strength and resistance during their using, transportation, and handling. Additionally, the measurements that were performed described the efficiency of the tested feedstock materials within their utilisation for clean and renewable energy generation. The last part focused on evaluation of the investigated low-pressure densification technology, thus, the practicability and viability of the designed, manufactured, and verified manual wooden low-pressure briquetting press.

### 3.1. Feedstock materials and mixtures testing

Primarily, this sub-chapter analyses the suitability of the feedstock materials for energy generation by combustion methods. Specifically, basic chemical parameters as a moisture content *Mc* (%), ash content *Ac* (%) were determined, while energy potential of investigated feedstock materials was expressed in the form of calorific values *CV* (MJ•kg$^{-1}$). The desired low level of ash content *Ac* (%) and directly related high level of calorific values *CV* (MJ•kg$^{-1}$) were desired to be obtained. Ash content *Ac* (%) of potential biomass feedstock material for bio-briquette production intended for energy generation by direct combustion should be lower than 3% and *CV* (MJ•kg$^{-1}$) should exceed level of 18 MJ kg$^{-1}$ to be considered high-quality and suitable (de Sousa Santos et al., 2020; Tomen et al., 2023).

Secondary, the necessity of external binder use was proved during the production of bio-briquette samples, and this issue is discussed in the present sub-chapter. Several studies reported that level of calorific value *CV* (MJ•kg$^{-1}$) of biomass bio-briquettes was influenced if external binder was used for feedstock material mixture production in attempt to improve the mechanical properties of produced bio-briquette samples (Muraina et al., 2017; Sing and Aris, 2013). Therefore, all the indicators mentioned must be in balance to produce a high-quality sustainable safe biofuel.

#### 3.1.1. Feedstock materials fuel parameters

The detailed result values obtained during the experimental measurements are listed in Table 4. Ash content *Ac* (%) of investigated feedstock materials occurred at a satisfactory level in cases of all samples. However, a higher undesired level was observed in the case of the PL sample (6.71%); Other samples expressed better *Ac* (%) results, specifically, CF (1.29%), BS (3.12%) and SB (1.31%). High level of *Ac* (%) can be considered as a biomass limitation within the combustion purposes, if higher than 15%. However, all the observed results on ash content *Ac* (%) indicated suitability of the investigated feedstocks for combustion purposes. Obtained results of calorific values *GCV* (MJ•kg$^{-1}$) noted in Table 4 proved desired high-quality level of such energy indicator (Tomen et al., 2023). The highest level (best result) was achieved by PL sample (20.40 MJ kg$^{-1}$), followed by CF sample (19.83 MJ kg$^{-1}$) and BS sample (19.57 MJ kg$^{-1}$) and the lowest observed result was achieved by SB (18.54 MJ kg$^{-1}$). However, all the results achieved

**Table 4**

Fuel parameters of investigated feedstock materials on average.

| Feedstock materials | wet basis | | | | dry basis | | | dry ash-free state | |
|---|---|---|---|---|---|---|---|---|---|
| | Mc | Ac | GCV | NCV | Ac | GCV | NCV | GCV | NCV |
| | (%) | (%) | (MJ•kg$^{-1}$) | (MJ•kg$^{-1}$) | (%) | (MJ•kg$^{-1}$) | (MJ•kg$^{-1}$) | (MJ•kg$^{-1}$) | (MJ•kg$^{-1}$) |
| CF | 5.22 | 2.96 | 18.78 | 17.52 | 3.12 | 19.83 | 18.62 | 20.47 | 19.22 |
| BS | 4.95 | 1.23 | 18.61 | 17.27 | 1.29 | 19.57 | 18.30 | 19.83 | 18.54 |
| PL | 7.86 | 6.18 | 18.78 | 17.46 | 6.71 | 20.40 | 19.15 | 21.86 | 20.53 |
| SB | 6.03 | 1.23 | 17.44 | 16.09 | 1.31 | 18.54 | 17.28 | 18.79 | 17.51 |

*Mc* - moisture content, *Ac* - ash content, *GCV* - gross calorific value, *NCV* - net calorific value, CF - coconut mesocarp fiber, BS - bamboo skin, PL - pineapple leaves, SB - sugarcane bagasse.

represented a high level of *GCV* (MJ•kg$^{-1}$) and proved a high energy potential of the investigated samples. The comparison of the results of the obtained calorific values of *GCV* (MJ•kg$^{-1}$) result values with results of other authors can be found in Table 6.

*3.1.1.1. Elementary composition.* The elementary composition of investigated feedstock materials influences their calorific values *CV* (MJ•kg$^{-1}$) and behaviour of subsequently produced bio-briquette fuel during combustion. The results values of specific parameters of the elementary composition of the investigated waste materials are clearly visible in Table 5. Especially, a high level of Oxygen *O* (%) (>40%) influences the air consumption during combustion and the amount of produced flue gas. Therefore, it is important to determine such parameters in an attempt to ensure the combustion process. Previously published articles reported that level of Oxygen *O* (%) in ideal case (feedstock material suitable for direct combustion) should range around 15–20% (Malaták et al., 2020).

For observed results comparison with other various biomass types, Table 6 was created. As visible, level of *Ac* (%) differs significantly due to the diversity of biomass type, while *GCV* (MJ•kg$^{-1}$) occurs at a similar level, except few outstanding cases (very low or very high). Nevertheless, after comparison, it can be concluded that investigated samples from current research (CF, BS, PL, SB) represent biomass types with suitable *Ac* (%) level and high *GCV* (MJ•kg$^{-1}$) level.

Due to the interdisciplinarity of performed research (thematic intersection of recycle practice, clean energy production, chemical analyses, engineering technology) it is necessary to state the safety and suitability of represented feedstock materials for combustion processes; thus, chemical analyses have to be performed to prove that investigated feedstock material can be even considered for further utilisation as a feedstock for bio-briquette production.

The comparison of primary and secondary data from Tables 4–6 proved that investigated feedstock materials occur at satisfactory level of ash content *Ac* (%) in compare with other commonly produced waste biomass materials noted in Table 4. Obtained and compared results of calorific values *GCV* (MJ•kg$^{-1}$) indicate high level of such indicator within the amount of produced heat during combustion, thus, suitability of investigated feedstock materials for energy production via direct combustion.

**Table 6**

Fuel parameters of various waste biomass types (Özyuğuran and Yaman, 2017).

| Biomass | Ash content | Gross calorific value |
|---|---|---|
| | (%) | (MJ•kg$^{-1}$) |
| Peanut husk | 0.15 | 19.16 |
| Coconut shell | 1.02 | 20.24 |
| Almond shell | 3.48 | 19.53 |
| Chickpea husk | 3.98 | 18.26 |
| Cacao husk | 4.41 | 17.85 |
| Red lentil hull | 5.24 | 18.27 |
| Soybean residue | 6.45 | 19.26 |
| Cornstalk | 7.19 | 16.55 |
| Thyme | 8.96 | 18.16 |
| Green bean stem and husk | 9.60 | 16.86 |
| Sunflower stem | 11.10 | 16.18 |
| Tobacco waste | 15.36 | 14.51 |

### *3.1.2. External binder impact on feedstock mixtures*

Practical experimental measurements and observed results indicated that the need of binder use within the low-pressure briquetting technology is indispensable; thus, it is necessary to use external binding agents while using low-pressure presses for agglomeration of feedstock materials. The ratio of feedstock material and external binding agent is an important factor that influences the final efficiency of such a densification process (Pilusa et al., 2012; Ngusale et al., 2014; Yank et al., 2016). Although the diversity offers a great opportunity to combine technical specifications in an attempt to manufacture the most suitable manual low-pressure briquetting press with respect to specifications of local requirements, it also causes ambiguities in the press type selection. The complex evaluation of which type of feedstock materials (biomass) is suitable for the specific type of manual low-pressure briquetting press has not yet been specified, and overall monitoring of this issue is lacking. Therefore, it is important to investigate and examine those relations, as such determination could contribute to a simpler decision and selection of a manual low-pressure briquetting press suitable for specific feedstock materials and local conditions. Thus, for such technology would be suitable (or necessary) to use mixed feedstock materials. Such mixed feedstock materials (mixed waste biomass) work with the properties of all mixed feedstock materials and uses them to improve the final quality of the mixture. The ratio of mixed feedstock materials indicates if it is mixed waste biomass or pure waste biomass kind with additive

**Table 5**

Elementary composition of investigated feedstock materials on average.

| Feedstock materials | wet basis | | | | | dry basis | | | | | dry ash-free state | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | H | N | S | O | C | H | N | S | O | C | H | N | S | O |
| | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) | (%) |
| CF | 48.19 | 5.27 | 0.31 | 0.04 | 38.03 | 50.82 | 5.57 | 0.33 | 0.04 | 40.13 | 52.45 | 5.75 | 0.34 | 0.04 | 41.42 |
| BS | 47.45 | 5.56 | 0.25 | – | 40.55 | 49.94 | 5.85 | 0.26 | – | 42.66 | 50.59 | 5.92 | 0.27 | – | 43.22 |
| PL | 43.89 | 5.24 | 1.33 | 0.17 | 35.35 | 47.61 | 5.69 | 1.44 | 0.18 | 38.37 | 51.03 | 6.10 | 1.54 | 0.19 | 41.13 |
| SB | 44.81 | 5.44 | 0.41 | – | 42.05 | 47.72 | 5.79 | 0.43 | – | 44.75 | 48.35 | 5.86 | 0.44 | – | 45.34 |

*C* - Carbon, *H* - Hydrogen, *N* - Nitrogen, *S* - Sulphur, *O* - Oxygen, CF - coconut mesocarp fiber, BS - bamboo skin, PL - pineapple leaves, SB - sugarcane bagasse.

(KratzeisenStarcevic et al., 2010). The type or amount of additives is not generally defined, and both are carefully chosen according to specific chemical (lignin content) or mechanical (particle size) properties to achieve the highest improvement of briquette quality (Kaliyan and Morey, 2010). Lignin is extracted from cell structures during pressing and acts as a glue to bind different components of material into the form of a briquette. This implies that suitable additives can be found between materials with a high lignin content (Karunanithy et al., 2012).

The selection of appropriate additives and their ratio in feedstock was scientifically investigated in many previous studies. It is important to realise that every specific feedstock material is adapted to different additives added in a certain ratio, which forms a unique mixture, leading to improved final bio-briquette fuel quality. Consequently, bio-briquette fuel produced from a unique mixed feedstock must be subjected to tests to define overall appropriateness of external binders and its suitable ratio in feedstock mixture. The positive influence of cassava starch (as an external binder) on the final quality of bio-briquette fuel produced from tropical hardwood sawdust was proved in the previous study (Emerhi, 2011). Other paper by Saptoadi (2008) analysed lignite and denatured rice husk as a sustainable external binder for various waste biomass feedstock materials. Utilisation of dry cow dung as an external binder was proven in case of bio-briquette fuel produced from raw mango and acacia leaves and sawdust. The best level of mechanical durability DU (%) of monitored bio-briquette samples was achieved by samples produced from feedstock material containing 10% of dry cow dung (Birwatkar et al., 2014). The research results mentioned reflect the wide scope and importance of the use of external binders in the production of bio-briquettes in an attempt to improve the mechanical quality of final products in various industry sectors.

## 3.2. Low-pressure bio-briquette samples

The first observed findings related to the production of bio-briquette samples by using a manual low-pressure briquetting press were the specifications and requirements on feedstock materials, their preparation, mixing with external binder, and the form in which they were used. All those steps differed from commonly used processes within high-pressure briquetting technology. Primarily, feedstock materials had to be mixed with wastepaper (external binding agent) and water (surrounding medium). Secondary, the ratio of feedstock materials and external binding agent represented an important factor influencing the final efficiency of the densification process. By using those two facts, the feedstock mixtures were properly prepared for low-pressure briquetting. Bio-briquette samples were produced by using the investigated wooden manual low-pressure briquetting press equipped with the square-shaped pressing chamber with the inner side of 80 mm; thus, they occurred in the form of square blocks with a side of 80 mm. As described in the methodology chapter, eight types of bio-briquette samples were produced (expressed in Fig. 8).

Briquettes are commonly produced in the shape of a square or rectangle, but it can be produced in the form of lumps or other moulded shapes (Alexander, 2012). A variety of standardised briquette shapes are shown in Fig. 9, which implies that the bio-briquette samples produced occurred in the form and shape corresponding to a related standard. A hole in the middle of produced bio-briquette samples was the result of the drainage system of investigated low-pressure briquetting press; in practice, it helps with briquette samples combustion properties due to better Oxygen flow during burning.

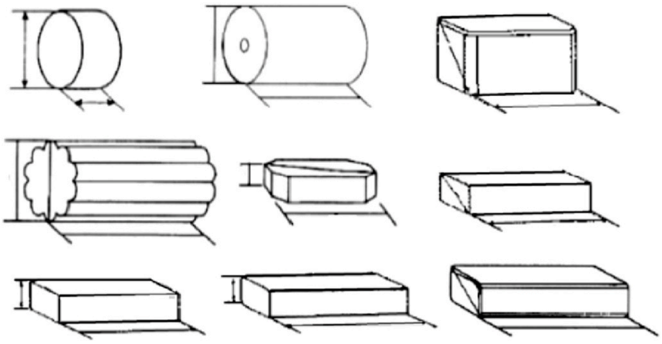

**Fig. 9.** Variety of normalized bio-briquette fuel shapes (ISO 17225-1, 2015).

### 3.2.1. Bio-briquette samples mechanical parameters

Volume density $\rho$ (kg•m$^{-3}$) together with initial moisture content *Mc* (%) represented mechanical quality indicators of produced bio-briquette samples. The results of initial moisture content *Mc* (%) (Table 7) proved undesirable high values; however, such results were expected because the wet feedstock materials were used within the low-pressure briquetting technology.

Such observation indicates that subsequent drying process (before low-pressure bio-briquette fuel combustion) is necessary in case of low-pressure briquetting technology. Within that, the suitability of the drainage system was also demonstrated; a hole in the middle of the final product helps to dry the bio-briquette samples and improves their porosity. However, the subsequent drying process represents an additional amount of consumed energy in compare with bio-briquette fuel produced by high-pressure briquetting technology, which uses dried feedstock materials. It can be stated that the subsequent drying process (electrical or solar energy) is an integral part of the process of low-pressure briquetting technology. However, the investigated low pressure briquetting technology was designed for use in developing countries, which commonly have great potential in sun-drying; thus, for the utilisation of solar energy (Opoku et al., 2020). Within the sustainability of investigated low-pressure briquetting press and energy security, the solar energy might be the answer for the additional subsequent drying process.

The mechanical parameters of investigated bio-briquette samples differed in the case of samples after production (wet form) and after

**Table 7**
Moisture content *Mc* (%) of bio-briquette samples after production.

| Ratio | CF | BS | PL | SB |
|---|---|---|---|---|
| 1:1 | 69.19 ± 1.03 | 67.14 ± 0.64 | 71.42 ± 0.68 | 71.58 ± 0.62 |
| 2:1 | 65.82 ± 1.33 | 68.73 ± 1.14 | 71.32 ± 2.71 | 75.29 ± 1.84 |

CF - coconut mesocarp fiber, BS - bamboo skin, PL - pineapple leaves, SB - sugarcane bagasse, ± - standard deviation.

**Fig. 8.** Bio-briquette samples produced from various feedstock mixtures: a) CF (1:1), b) BS (1:1), c) PL (1:1), d) SB (1:1).

post-production processing (dry form) within the change of their dimensions. Thus, the direct influence of moisture content *Mc* (%) was observed. Bio-briquette samples mass *m* (g) and volume density $\rho$ (kg•m$^{-3}$) decreased, while their height *h* (mm) increased during the drying process. Final result values of dried samples volume density $\rho$ (kg•m$^{-3}$) are noted in Table 8.

In general, the achieved level of volume density $\rho$ (kg•m$^{-3}$) prevalently ranged between 200 and 220 kg m$^{-3}$ with the exception of samples CF (1:1) and SB (2:1), which achieved lower level. The technical standard related to the bio-briquette fuel volume density $\rho$ (kg•m$^{-3}$) ISO 13061-2 (2014), titled: “Physical and mechanical properties of wood. Test methods for small clear wood specimens. Determination of density for physical and mechanical tests”, states required level of volume density $\rho > 1{,}000$ kg m$^{-3}$. Such requirement is mandatory only for wood bio-briquette fuel produced commercially by using of high-pressure briquetting press. Thus, the requirements stated by mentioned standard were not decisive in evaluating the produced bio-briquette samples.

Table 9 provides a comparison of observed results with other bio-briquettes produced by low-pressure briquetting press. As visible, bio-briquette samples investigated by other researchers achieved a higher level of volume density $\rho$ (kg•m$^{-3}$), but as reported in Table 9, used low pressure briquetting presses that worked with a higher operating pressure *P* (MPa). The investigated manual low-pressure briquetting press worked with operational pressure *P* (MPa) equal to approximately 0.5 MPa, which can be evaluated as a low level compared to the data noted in Table 9 and should be increased. However, changing the dimensions of the press (mainly extension of the lever length) can positively influence the final volume density $\rho$ (kg•m$^{-3}$) of the bio-briquette samples produced. Designed dissolvability and easy dismantling of developed press components allow such changes, which represents the advantage of such equipment.

The comparison expressed in Table 9 must be understood as an indicative because all reported values although comes from low-pressure briquetting presses, but as was mentioned previously, low-pressure briquetting technology differs in accordance to target local conditions and requirements. Prevalently it differs in pressing units (piston, screw), a number of samples produced at one time, components materials (wood, metal), construction (single lever, double lever) and others. Table 9 was also created to summarise the relations between operational pressure *P* (MPa) and bio-briquette fuel volume density $\rho$ (kg•m$^{-3}$); thus, the efficiency of the low-pressure briquetting technology. As can be seen in Table 9, the level of bio-briquette fuel volume density $\rho$ (kg•m$^{-3}$) is not always higher if a higher pressure is used. Clearly, there are several more factors that influence the final mechanical quality of a produced bio-briquette fuel, such as the type of external binding agent and feedstock material used, their ratio, bio-briquette shape, press unit, and overall press construction (Pilusa et al., 2012; Ngusale et al., 2014; Yank et al., 2016). Although the achieved operation pressure *P* (MPa) occurred at a relatively low level, compared to other published results (Table 9), the equipment was able to produce full-fledged bio-briquette fuel and therefore its viability was demonstrated.

The selection of the investigated feedstock materials was found to be successful in combination with wastepaper shredded into strips. Hence, their mixtures created a fixed bond between particles. As a consequence, the utilisation of herbaceous biomass is recommended for low-pressure briquetting technology. Comparison of different pressing units of low-pressure briquetting technology, a piston press vs screw press, proved that the screw press led to better results (volume density $\rho = 695.75$ kg m$^{-3}$) even when a lower level of operational pressure ($P = 0.9$–$1.8$ MPa) was used (Pilusa et al., 2012).

**Table 8**

Volume density $\rho$ (kg•m$^{-3}$) of produced bio-briquette samples after drying process.

| Ratio | CF | BS | PL | SB |
|---|---|---|---|---|
| 1:1 | 181.15 ± 7.73 | 215.19 ± 17.05 | 221.83 ± 13.88 | 199.04 ± 9.41 |
| 2:1 | 222.32 ± 14.36 | 201.67 ± 10.42 | 211.97 ± 16.60 | 161.29 ± 18.92 |

CF - coconut mesocarp fiber, BS - bamboo skin, PL - pineapple leaves, SB - sugarcane bagasse, ± - standard deviation.

**Table 9**

Comparison of low-pressure briquetting presses and bio-briquette fuels.

| Feedstock material | *P* (MPa) | $\rho$ (kg•m$^{-3}$) | Reference |
|---|---|---|---|
| Rice husk + bran | 4.2 | 426.85 | (Yank et al., 2016) |
| Tannery solid wastes | 3.9 | 661.67 | Onukak et al. (2017) |
| Mixed biomass[a] | 0.9 - 1.8 | 695.75 | Pilusa et al. (2012) |
| Sawdust | 1.1 | 310.00 | Sotannde et al. (2010) |
| Rice straw | 0.2 - 1.0 | 207.48 | Agyeman and Oldham (1986) |
| Banana leaves | | 179.69 | |
| Teak leaves | | 227.53 | |
| Coconut mesocarp | 0.5 | 201,74 | Author’s data |
| Bamboo skin | | 208,43 | |
| Pineapple leaves | | 216,90 | |
| Sugarcane bagasse | | 180,17 | |

*P* - operation pressure (MPa), $\rho$ - bio-briquette volume density (kg•m$^{-3}$).

[a] 32% spent coffee grounds, 23% coal fines, 11% sawdust, 18% mielie husks, 10% wastepaper, 6% paper pulp.

The comparison of investigated ratios of biomass and external binder (wastepaper) proved better results in case of ratio 1:1 for BS, PL and SB bio-briquette samples. In general, the presence of binders positively influences the final mechanical quality of bio-briquette fuel (Kaliyan and Morey, 2010). Better results within the ratio 2:1 was observed in the case of CF bio-briquette samples; the volume density $\rho$ (kg•m$^{-3}$) increased with increasing of the biomass portion in feedstock mixture. Such a result indicates the advantage of fibrous materials within the low-pressure briquetting because fibrous materials can create solid, strong bonds. Comparison of used biomass:binder ratios (1:1, 2:1) and final bio-briquette samples volume density $\rho$ (kg•m$^{-3}$) is expressed in Fig. 10.

### 3.2.2. *Statistical evaluation*

The ANOVA results for the volume density as the dependent variable along with effect of material, ratio and interaction of both of them are presented in Table 10. As can be seen from the p-values, there is a significant effect of material on bio-briquette volume density, as well as interaction of material and ratio effects on bio-briquette volume density ($p < 0.05$). The effect of ratio on the bio-briquette volume density was not found to be significant ($p < 0.05$).

To investigate more into the differences among all groups, Tukey’s HSD Test was performed (see Table 11). The significant differences ($p < 0.05$) between each group is indicated in bold. From the table we can see, that e.g. material SB with ratio 2:1 is significantly different from the other groups, except for CF with 1:1 ratio. Furthermore, it is worth mentioning that the post-hoc analysis revealed that the SB briquettes prepared with the 1:1 ratio were not significantly different ($p > 0.05$) from the other materials, except for the SB material with the 2:1 ratio.

As it is explained in the text, the data analysed in Table 10 indicates that the type of material used significantly influences the volume density of the briquettes. Additionally, there is a significant interaction between the material and the ratio in their effects on the bio-briquette volume density ($p < 0.05$). However, the ratio itself does not have a significant impact on the volume density of the briquettes ($p > 0.05$). Table 11 explains where the differences among the tested groups can be found.

## 3.3. *Comparison of briquetting technologies*

After manual low-pressure briquetting press manufacture, use and

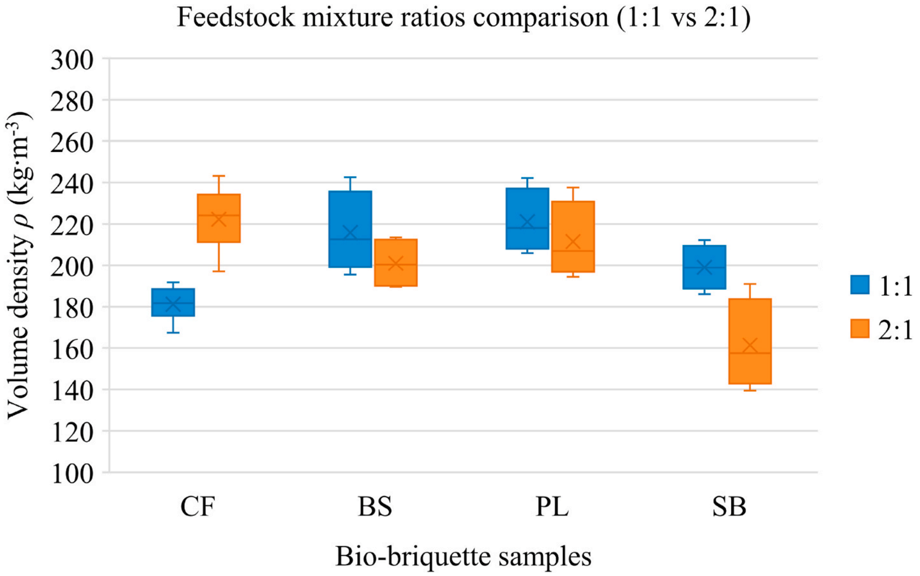

**Fig. 10.** Comparison of biomass:binder ratios (1:1 vs 2:1) in final bio-briquette samples volume density $\rho$ (kg•m$^{-3}$).

**Table 10**
ANOVA results of the volume density (dependent variable) in relation to material and ratio effect.

| | SS | DF | MS | F-value | p- value |
|---|---|---|---|---|---|
| Intercept | 1561570 | 1 | 1561570 | 7735.626 | $<$0.05 |
| Material | 5778 | 3 | 1926 | 9.541 | $<$0.05 |
| Ratio | 264 | 1 | 264 | 1.306 | $>$0.05 |
| Material*Ratio | 12384 | 3 | 4128 | 20.449 | $<$0.05 |
| Error | 8075 | 40 | 202 | | |

SS - sum of squares, DF - degree of freedom, MS - mean square.
$p > 0.05$ – non-significant.
$p < 0.05$ – significant.

verification, the obtained data were used for comparison of with high-pressure briquetting press (which is described in the methodology section). The comparison described in Table 12 was made in terms of differences between the mentioned equipment, while identical feedstock materials were used for the production of bio-briquette samples and subsequent testing. A particular emphasis has been placed on the suitability of specific equipment for different production conditions and availability (focus on rural developing areas) and on user-friendliness. Data noted in Table 12 are specific parameters of those two monitored briquetting presses. The parameters of different equipment available on the market (for example, price) or developed within certain development activity (for example, construction) might differ.

When considering all the information obtained, differences were found in almost every monitored parameter of the selected technologies. However, such differences did not indicate overall unsuitability or disadvantageous of specific briquetting technology. The observed differences indicated that each briquetting technology is suitable and advantageous for different conditions and environment. Thus, the efficiency of a specific briquetting press depends on the precise requirements of its production conditions. Between the main monitored parameters contained the question of the target area (developing vs developed countries), the level of desired press development and sophistication (commercial vs individual production), requirements on fuels' mechanical quality (need of fuel storage vs. direct utilisation), combustion possibilities (mechanised industrial furnaces vs. open fireplace for cooking), financial investment issues, or availability of properly trained operators. The most visible difference between such technologies was observed during visual inspection, as well as parameters such as the price and size of the presses. Furthermore, the need for electricity for press work, the feedstock material requirements and the quality of the biofuel produced represented by the volume density $\rho$ (kg•m$^{-3}$) were considered as the main parameter defining the technologies investigated. Thus, the possible user or owner of such equipment must firstly define their own possibilities, such as expectations regarding the press' efficiency and the ability to ensure the requirements of the press. When all such issues are clarified, the chosen type of briquetting technology will fit into the conditions and satisfy those expectations.

Table 12 was created to illustrate the fact that each sustainable technology must be questioned prior to its implementation regarding its suitability and effectiveness for the target location. All properties and characteristics must be taken into the consideration. As visible in Table 12, high pressure briquetting technology is not suitable for rural areas of SE Asia, despite the fact that there is a high potential to produce bio-briquette fuel from waste biomass. This idea directly implies that

**Table 11**
Tukey's HSD Test – multiple comparison of p-values of bio-briquette volume density.

| M | R | CF 1:1181.15 | CF 2:1222.32 | BS 1:1215.84 | BS 2:1201.02 | PL 1:1221.08 | PL 2:1211.52 | SB 1:1199.04 | SB 2:1161.29 |
|---|---|---|---|---|---|---|---|---|---|
| CF | 1:1 | | **0.000** | **0.003** | 0.259 | **0.001** | **0.014** | 0.385 | 0.259 |
| CF | 2:1 | **0.000** | | 0.993 | 0.187 | 1.000 | 0.887 | 0.114 | **0.000** |
| BS | 1:1 | **0.003** | 0.993 | | 0.816 | 1.000 | 1.000 | 0.704 | **0.000** |
| BS | 2:1 | 0.259 | 0.187 | 0.816 | | 0.497 | 0.964 | 1.000 | **0.007** |
| PL | 1:1 | **0.001** | 1.000 | 1.000 | 0.497 | | 0.979 | 0.377 | **0.000** |
| PL | 2:1 | **0.014** | 0.887 | 1.000 | 0.964 | 0.979 | | 0.914 | **0.000** |
| SB | 1:1 | 0.385 | 0.114 | 0.704 | 1.000 | 0.377 | 0.914 | | **0.012** |
| SB | 2:1 | 0.259 | **0.000** | **0.000** | **0.007** | **0.000** | **0.000** | **0.012** | |

M: Material, R: Ratio, Tests Error: Between MS = 201,87, df = 40,000.

**Table 12**
Comparison of used low-pressure and high-pressure briquetting technologies.

| | Properties | Press type | |
|---|---|---|---|
| | | High-pressure press | Low-pressure press |
| Machine properties | Operation pressure | 80–100 MPa | <5 MPa |
| | Pressing chamber | Cylindrical | Square |
| | Pressing unit | Piston | Piston |
| | Power | Electricity | Man |
| | Power consumption | 4.4 kW | – |
| | Size | 2.91 $m^3$ | 0.07 $m^3$ |
| | Weight | ±800 kg | ±10 kg |
| | Purchase price | ±30,000 USD | ±20 USD[a] |
| | Productivity | 30 kg $h^{-1}$ | <5 kg $h^{-1}$ |
| Bio-briquette properties | Shape | Cylindrical | Block |
| | Diameter | 40 mm; 50 mm | 80 mm |
| | Weight | 116.64 g | 49.10 g |
| | Height | 56.67 mm | 42.72 mm |
| | Moisture content | 9.11% | 67.50% |
| | Density | 1094.64 kg $m^{-3}$ | 201.38 kg $m^{-3}$ |
| | Post-production treatment | None | Drying |
| | Storage | Yes | Hermetically sealed |
| Feedstock requirements | Moisture content | 7–15% | >50% |
| | Particle size | <10 mm | <50 mm |
| | Need of binder | No | Yes |

[a] Price of press manufactured in the Republic of Indonesia (in 2016) and the Socialist Republic of Vietnam (in 2018).

technology must be simplified and 'downgraded' to meet the specific requirements and capacities of rural areas of Southeast Asia and to represent available, interesting, and understandable equipment. Table 12 and related discussion lead to a deeper understanding of all the meanings of the term Sustainable technology.

## 4. Conclusion

In general, reuse of all investigated waste materials is highly recommended with respect to their origin in order to maintain principles of appropriate waste management and follow the 'three R's' of waste management: 'Reduce - Reuse - Recycle'. It can be concluded that the investigated waste materials had a high potential for energy generation (by direct combustion) due to their satisfactory level of calorific values $CV$ (MJ•kg$^{-1}$) and ash content $Ac$ (%). The designed and developed manual low-pressure briquetting press was successful within the entire process of equipment design, manufacturing, operation, and bio-briquette samples production. Limitation was observed in low level of exerted operation pressure $P$ (MPa), resulting in low level of bio-briquette samples volume density $\rho$ (kg•m$^{-3}$). Therefore, changes in the design (lengthening of the lever) of the equipment are recommended in order to increase the operating pressure $P$ (MPa), therefore also bio-briquette samples volume density $\rho$ (kg•m$^{-3}$). The necessity of external binder usage within the low-pressure briquetting technology was determined to be unquestionable because of the impossibility of producing bio-briquette samples from pure feedstock materials. Through a combination of investigated feedstock materials with an external binder (wastepaper) in different ratios (1:1, 2:1) was stated the ideal proportion of external binder in the feedstock mixture was stated. All observed primary data were positively evaluated and proved a wide range of applications of low-pressure briquetting technology for clean and renewable energy generation. The general assessment of the applicability of the equipment investigated in practice indicated the suitability of this technology for energy generation and waste management in rural areas of developing countries due to its simplicity and intelligibility. It is inexpensive and straightforward to operate, and its construction can serve as an improvement of proper waste management practices and be a relevant alternative to the adequate utilisation of biomass waste. In particular, with respect to the insufficient level of waste management in rural areas of developing countries resulting in a significant amount of potential feedstock materials, it has been proven as a very feasible technology.

The importance of the research presented lies in the publication of interesting and unusual data on interdisciplinary topics which can lead to the raising the awareness about the suitability of low-pressure briquetting technology in rural areas in SE Asia, the reuse of waste biomass and the understanding of it as a commodity, the use of renewable sources of energy for energy dependency and clean energy production at the household level, etc. The importance of research is constantly raised due to the worldwide needs for the transition from fossil fuels to renewable sources of energy, the need for proper waste management and reduction of environmental and health risks related to insufficient combustion methods and treatment of waste materials. The content and idea of the article will contribute to the development of clean energy production, while raising awareness of sustainable technologies for proper waste management. Taking into account the idea presented in the article, further research activities can be conducted to adapt already proven sustainable technologies within their effectiveness and accessibility to the needs of specific target areas or groups.

## CRediT authorship contribution statement

**Anna Brunerová:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing, Data curation, Validation, Visualization. **Milan Brožek:** Formal analysis, Investigation. **Dinh Van Dung:** Investigation, Writing – review & editing. **Le Dinh Phung:** Investigation, Writing – review & editing. **Udin Hasanudin:** Investigation, Writing – review & editing. **Dewi Agustina Iryani:** Investigation, Writing – review & editing. **Veronika Chaloupková:** Formal analysis, Writing – review & editing. **Hynek Roubík:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.140624.

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