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Briquettes fuel production from sugarcane bagasse for sustainable community energy solutions

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Abstract

The objective of this study is to determine optimum conditions for producing briquettes fuel from biomass, examine the properties of the resulting briquette fuel and transfer the technology to target communities. The production process entails implementing a screw-type briquette press equipped with controlled temperatures through a molded pipe clamp electric heater for shaping the briquettes. This is an innovative approach that allows briquettes to be produced and ready for use in a single step, while other processes require the briquettes to be dried first. The production capacity was estimated to be 12 kg/hr. Bagasse, a byproduct of sugarcane processing, was the biomass used in the current research. For this study, four distinct temperatures were chosen for experimentation, 100, 110, 120, and 130°C. The proportions of bagasse, cassava flour, and water were investigated for briquette production utilizing two formulae: 1 kg bagasse to 0.1 kg cassava flour and 0.5 liters water, and 1 kg bagasse to 0.3 kg cassava flour and 0.5 liters water. The findings indicated that bagasse briquettes could be effectively manufactured at 120°C. The ideal proportion of bagasse particles, cassava starch, and water was 1 kg : 0.3 kg : 0.5 liters, respectively. The moisture content, volatile matter, ash, and fixed carbon were respectively 8.04, 70.20, 13.05, and 16.11 wt.% on a dry basis, based on the physical and chemical property tests of the briquette fuel. The material has a density of approximately 856.70 kg/m^3, a compressive strength of 89.34 kg/cm^2, and a higher heat value (HHV) of 24.05 MJ/kg, with a longer burning time than regular charcoal. The research emphasizes using bagasse for innovative renewable energy production technologies and disseminating this technology in target communities in Thailand.

Keywords: Briquette fuel, Sugarcane bagasse, Biomass, Community, Renewable energy

1. Introduction

Biomass is an organic substance that is obtained from both plant and animal origins [1]. It comprises raw materials derived from plants, including sugarcane, rice straw, corn, and wood, as well as animal products and byproducts, including manure, as well as food and agricultural industry waste (e.g., food scraps, sludge), and special raw materials, including bagasse residual from the sugarcane juicer step and sawdust generated during wood processing [2, 3]. Typically, biomass contains a high carbon content, which serves as an energy source that can be utilized via fuel processing, chemical reactions, and thermal processes [4]. Biomass has the potential to replace fossil fuels as a renewable energy source [5, 6]. Dependence on petroleum, natural gas, and coal is diminishing [7]. Since the carbon released is a part of the natural carbon cycle, using biomass lowers greenhouse gas emissions [8-10]. Various technologies are available for conversion of biomass into energy. Commonly used technologies include combustion, which refers to the process of burning biomass in the presence of air, resulting in the generation of heat that can be utilized to produce electricity or directly supply heat [11, 12]. It is the oldest and simplest method of converting biomass into energy. Gasification is a process that involves heating biomass under a limited amount of oxygen to produce a synthetic gas referred to as "syngas" [13, 14]. The synthetic gas, consisting of methane, hydrogen, and carbon monoxide, can be used as a fuel in various energy production processes. Co-gasification process of the engine system is one suitable technology for alternative power generation. Co-gasification of the engine system using coal and biomass reduces the magnitude of CO engine emissions compared to single-feedstock coal gasification [15]. Pyrolysis is a thermal decomposition process that converts biomass into a liquid fuel known as "bio-oil" by subjecting biomass particles to high temperatures ranging from 400-500°C [16, 17], depending on the specific type of biomass, under oxygen limited conditions at a high heating rate [18-20]. Anaerobic digestion is a method applied in treating animal waste and other organic waste in an oxygen-free environment to produce biogas, a fuel composed of methane and carbon dioxide. Alternatively, electricity can be generated through the process of alcohol fermentation [20], which converts sugar or starch-containing biomass into ethanol. This ethanol can be utilized as a standalone fuel or blended with gasoline to create a mixed fuel suitable for engine use. The conversion of raw materials such as corn or sugarcane into energy is typically employed in this process [21].

Sugarcane is an important cash crop known for its high yield in terms of dry weight per annual harvest and land area used. According to the FAO [22], the most significant regions for sugarcane production are Brazil, India, China, Pakistan, and Thailand. Most byproducts will be utilized for sugar production, while a portion will be used to produce ethanol, which serves as a renewable energy resource. In 2023, Thailand produced approximately 105.86 Million Tonnes per year, which consisted of biomass or agricultural

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waste from sugarcane. This waste included sugarcane leaves, tops, and bagasse, amounting to approximately 62.77 Million Tonnes per year. The conversion factors for sugarcane leaves and tops were 0.291, while for bagasse it was 0.302 [23]. Generally, bagasse is employed as a fuel in sugar factories, whereas sugarcane leaves and tops are used to produce fertilizer, animal feed, or are simply burned. A significant portion of this biomass remains largely untapped in terms of energy utilization. Methods to convert bagasse into briquette fuel, a potential alternative for community heating fuels that could replace reliance on liquefied petroleum gas, are needed.

Prior studies examined the conversion of bagasse into energy through different methods. For instance, Abdu Karifa et al. [24] investigated enhancement of the quality of raw sugarcane bagasse through torrefaction, focusing on temperatures ranging from 220 to 280°C. The duration of the experimental process was varied between 30 and 120 min. The study revealed that increased torrefaction temperature resulted in a higher carbon content, accompanied by decreased hydrogen and oxygen contents, as well as a decrease in moisture and volatile substances. Additionally, the heat value exhibited a notable increase. Marx et al. [25] investigated application of hydrochar blended with coal or byproducts of sugarcane bagasse hydrothermal liquefaction. The study was conducted using three different ratios: 3:1, 1:1, and 1:3, to produce green coal pellets. The study discovered that a significant amount of hydrochar resulted in greener pellets. Chen et al. [26] investigated the effects of process parameters and raw material characteristics on the physical and mechanical quality of sugarcane bagasse pellets. They did this by considering the impact of three process temperature levels (100, 140 and 180°C), three moisture contents (6, 9, and 12%), three biomass particle sizes (0.5, 1.0 and 1.4 mm) and three pelletizing times (2, 3 and 4 minutes). The study revealed that higher temperature (180°C), moderate moisture content, smaller biomass particle sizes and medium pelletizing time resulted in denser pellets with a glossy surface and no cracks. Suttibak and Loengbudnark [27] developed a procedure for manufacturing charcoal briquettes from sugarcane bagasse for community use. This was done using charcoal particles generated by burning bagasse in a stove with a limited air supply to produce briquettes. The study revealed that the charcoal briquettes had a calorific value of approximately 26.67 MJ/kg, burned more effectively than regular wood charcoal, and could serve as an alternative energy source in communities. Karunanithy et al. [28] developed a briquetting system consisting of a 40 hp motor, feed hopper, and die section, with a capacity of 150-200 kg/h. Raj and Tirkey [29] utilized briquettes derived from bagasse to produce fuel gas using a downdraft gasifier, which was then used in a dual fuel engine. They found that the briquettes were financially viable and profitable over the long term. Repsa et al. [30] tested briquettes made from ground common reed (Phragmites australis) or a common reed and peat mixture, using a manually operated experimental briquetting press, which has a low production rate insufficient for community use. However, their adoption was limited due to the complex transformation process and the lack of cost-effectiveness in community applications. Previous research has shown a lack of investigation into utilization of bagasse as a community energy resource for heating, as an alternative for liquefied petroleum gas. While commonly used in large industries for heating boilers to generate electricity, the practical application of pellet fuel is minimal due to the expense of the technology required for production, making it cost-prohibitive and unsuitable for community use.

Hence, the current study aims to investigate production of briquette fuel derived from bagasse with the purpose of utilizing it as a renewable energy resource in communities. A briquette machine was developed, providing simultaneous heating during the briquetting process, integrating both steps into a single operation. This is a new technology that is suitable for the community. The main objective of this study is to identify the optimal conditions (i.e., temperature and proportion of casava starch) to produce briquette fuel from bagasse as well as analyze the properties of the resulting products (i.e., density, HHV, extinguishing time, proximate analysis, ultimate analysis, and compressive strength). The findings of this study will be utilized to disseminate technology to target communities, aiming to minimize costs in the processing of sugarcane syrup by farmers. Implementation of the Bio Circular Green (BCG) economic model will encourage sustainability within communities and stimulate development of a grassroots economy.

2. Experimental methods

2.1 Biomass sample

The raw bagasse used in the study is a by-product derived from sugarcane juice extraction, which is further processed into sugarcane syrup products by a community enterprise located at Tat Thong Subdistrict, Si That District, Udon Thani Province, Thailand. The sugarcane bagasse to be examined is finely ground using a high-efficiency grinder, with particle sizes ranging from 2 to10 mm, as illustrated in Figure 1.

Figure 1 Characteristics of sugarcane bagasse after being finely ground.

2.2 Sugarcane bagasse analysis

Samples of finely ground sugarcane bagasse are subjected to physical and chemical property analysis, which includes proximate and ultimate analyses, as well as heating value and bulk density determinations, thermogravimetric analysis, and Fourier-transform infrared spectroscopy.

2.2.1 Proximate analysis

Proximate analysis involves determining moisture content, volatile matter, ash, and fixed carbon of a specimen. The moisture, volatile matter, and ash contents are analyzed following ASTM E1756-01, E872-82, and E1755-01 standards, respectively, as described by Eqs. (1), (2), and (3) [31]. The fixed carbon content will be calculated based on the difference as indicated in Eq. (4) [31]. These analyses were conducted in the Mechanical Engineering Laboratory at Udon Thani Rajabhat University, Thailand, and each experiment was replicated three times.

$$MC = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

where, MC is moisture content (wt.%)
m_1 is the initial biomass sample mass (g)
m_2 is the biomass sample mass after drying at 105°C for 24 hours (g)

$$VM = \frac{m_2 - m_3}{m_1} \times 100\% \quad (2)$$

where, VM is volatile matter content (wt.%)
m_3 is mass of biomass sample after burning at 970°C, 7 minutes (g)

$$A = \frac{m_4}{m_1} \times 100\% \quad (3)$$

where, A is ash content (wt.%)
m_4 is the mass of a biomass sample after burning at 575°C for 24 h (g)

$$FC = 100 - MC - VM - A \quad (4)$$

where, FC is fixed carbon content (wt.%)

2.2.2 Ultimate analysis

Ultimate analysis refers to the examination of the fundamental mineral elements present in a specimen, including carbon, hydrogen, sulfur, and oxygen. The oxygen content is calculated using the difference in values obtained by employing a measuring device (C, H, N, S Analyzer, Model Carbon 628, 628S). The analysis was conducted at the Centre for Scientific and Technological Equipment, Suranaree University of Technology, Thailand. Each specimen was analyzed using three replicates.

2.2.3 Heating value

The heating value of a substance is calculated using data derived from the ultimate analysis. These calculations are performed on a dry basis. The higher heating value (HHV) is determined using the formula presented by Sheng and Azevedo [32], as indicated in Eq. (5). The lower heating value (LHV) is calculated using the HHV and the hydrogen content (H), as specified in Eq. (6). Biomass samples are analyzed for their heating value using a bomb calorimeter, adhering to the ASTMD 240 standard. The results are reported in units of cal/g and subsequently converted to MJ/kg for comparison with calculated values. Analyses were conducted at the Mechanical Engineering Laboratory of Udon Thani Rajabhat University, Thailand, with each experiment done in triplicate.

$$HHV\left(\frac{MJ}{kg}\right) = -1.3675 + 0.3137C + 0.7009H + 0.0318O^{*} \quad (5)$$

where, C and H are the percentages of carbon and hydrogen, respectively (on a dry basis).

The term O* = 100 – C – H – Ash.

$$LHV\left(\frac{MJ}{kg}\right) = HHV - 2.442 \times 8.936\left(\frac{H}{100}\right) \quad (6)$$

2.2.4 Bulk density

Bulk density will use particles of bagasse for analysis in a 50 ml graduated glass cylinder. Determined according to ASTM D7481-09 standard [33]. Weight is measured in units of g/ml and then converted to kg/m3, calculated according to Eq. (7).

$$\rho = \frac{m}{V} \quad (7)$$

where, ρ is the bulk density of the biomass sample (g/ml)
m is the mass of the biomass sample (g)
V is the volume of the biomass sample (ml)

2.2.5 Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) is used to study thermal degradation and combustion characteristics. Fundamental tests of the sugarcane bagasse sample were conducted using TGA and differential thermal analysis (DTA) techniques. Experiments were performed on a simultaneous TGA/DSC (SDT 2960 (V3.0F), TA Instruments). Approximately 9 mg of each sample was heated under a nitrogen atmosphere from room temperature to 1,000°C at a heating rate of 10°C/min. These experiments were carried out at the Center of Scientific and Technological Equipment (CSTE), Suranaree University of Technology, Nakhon Ratchasima, Thailand.

2.2.6 Fourier-transform infrared spectroscopy (FTIR)

Analysis of biomass samples also used an infrared absorption technique, Fourier-transform infrared spectroscopy (FTIR). These measurements can be used to determine the molecular structure and chemical composition of biomass samples. FTIR employs infrared radiation of varying wavelengths to interact with samples. Molecules within the sample absorb infrared waves at specific wavelengths. This absorption is caused by the vibration of chemical bonds (such as C H, N-H, O-H bonds) within a molecule. Infrared light is transmitted through the biomass sample, and part of this light is absorbed by the biomass sample. The light transmitted through the biomass sample is evaluated by instruments known as interferometers. The transmitted light is subsequently captured and recorded as a Fourier transform infrared (FTIR) spectrum, which displays the intensity of light absorption at different wavelengths. The spectrum displays areas of specific absorption that correspond to the chemical bonds present in the biomass sample, enabling identification of chemical functional groups, molecular structures, and chemical changes. A Bruker TENSOR 27 Fourier Transform Infrared spectrometer (FT-IR) was employed using in ATR mode, measurement range MIR 4000-400 cm^{-1} for this analysis at the Center for Scientific and Technological Equipment, Suranaree University of Technology, Thailand. Each measurement was repeated three times.

2.3 Briquette production unit

Briquettes fuel derived from bagasse are produced through utilization of a temperature-controlled screw press with a molded pipe clamp electric heater for shaping the briquettes. A schematic diagram of this equipment is presented in Figure 2. The conceptual framework of the briquette fuel production unit prioritizes the attributes of the ultimate product, which include its user-friendliness and the accessibility of technology to the community. Hence, the fuel produced will take the form of cylindrical rods similar to charcoal briquettes that can be immediately utilized. The fuel pellet production machine employed in the study utilizes a screw to compress the mixture into a cylindrical shape. Additionally, it employs an electric heater to heat the mixture within a cylindrical mold. The machine has a 5 HP electric motor operating at 220 V, along with a tank containing the necessary ingredients for pellet fuel. This mixture consists of bagasse particles, tapioca starch, and water, which is blended using a horizontal mixer. The mixture will be conveyed through an exit port that can be adjusted to control the outlet. The mixture is directed towards a tray and then transferred to the pressing chamber. Internally, there is a screw thread designed to convey and compress the fuel mixture utilizing a mold pipe with an inner diameter of 45 mm. The outer surface of the tube is equipped with a 500-W sheath-type electric heater that warms the mold tube as the fuel mixture is conveyed and compressed through it. Temperature is regulated by an electrical control unit located within the control box. The pellets are severed using electro-pneumatic blades. The length of the fuel briquette can be customized based on the sensor installation distance requirements.

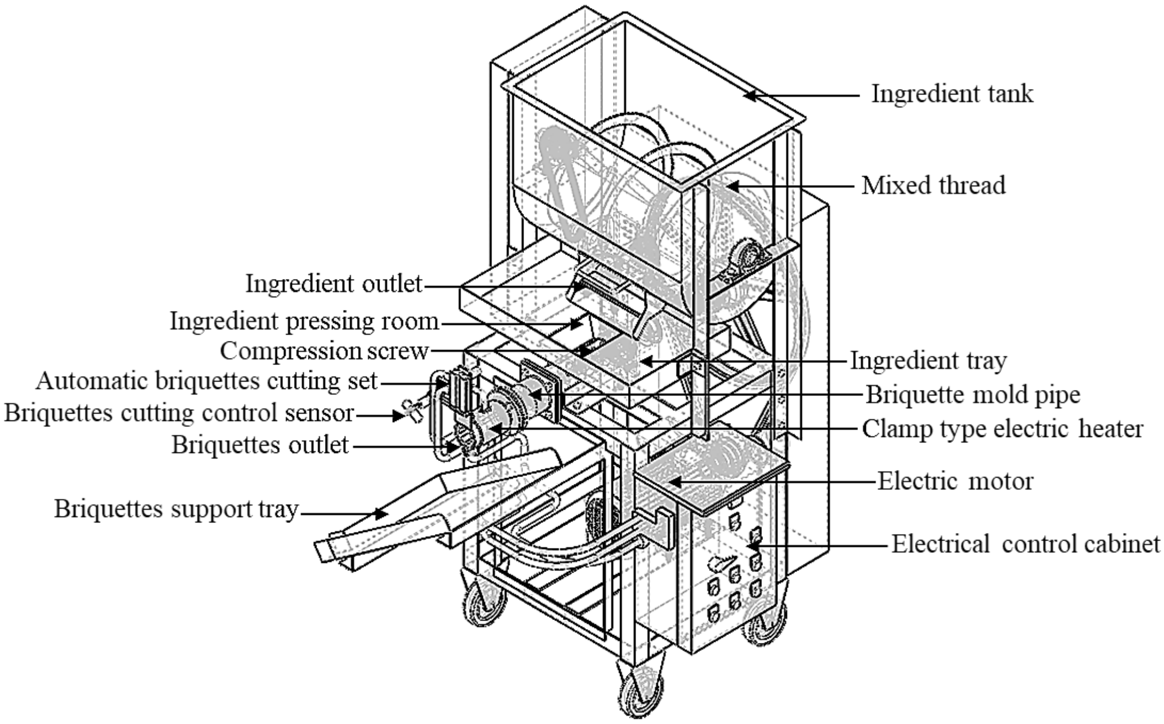

Figure 2 Accessories of a briquette production unit with a screw press and temperature control operating with a sheath-type electric heater.

2.4 Experimental conditions

Table 1 shows the experimental parameters for producing briquettes fuel from bagasse to find the appropriate conditions. In this study, two ratios of bagasse particles, cassava starch and water was studied 1 kg : 0.1 kg : 0.5 L and 1 kg : 0.3 kg : 0.5 L, respectively.

The difference between these two formulas was the amount of tapioca starch, which acts as a binder. Four temperatures were selected for the experiments, 100, 110, 120 and 130°C. The temperature was controlled by measuring it at the clamp electric heater and sending the signal to the PID controller inside the control box. Bagasse particle sizes used in the study were in the range of 2 - 10 mm. Each experimental run required one hour.

Table 1 Conditions for briquette fuel production from sugarcane bagasse.

Parameter	**Proportion of ingredients (bagasse particle (kg) : cassava flour (kg) : water (liters))**	
	1 : 0.1 : 0.5	**1 : 0.3 : 0.5**
Temperatures (°C)	100, 110, 120, 130	100, 110, 120, 130
Particle size ranges (mm)	2-10	2-10

2.5 Analysis of briquette fuel products

Analysis of bagasse briquette fuel involved selecting samples obtained under optimal conditions for various tests. Proximate analysis, elemental composition analysis, heating value, density, compressive strength, and extinguishing time testing were done. Each experiment was done in triplicate.

2.5.1 Proximate analysis

Proximate analyses of the briquette fuel samples derived from bagasse were conducted in a similar manner to the biomass sample analysis described in Section 2.2.1.

2.5.2 Elemental composition

Carbon, hydrogen, nitrogen, and oxygen contents were determined using the same technique as those applied for the ultimate analysis of biomass, described in Section 2.2.2. The H/C and O/C molar ratios were calculated according to the formulae presented in Eqs. (8) and (9) [34, 35].

$$H/_C = \frac{\%H/_{1/N}}{\%C/_{12/N}} \quad (8)$$

$$O/_C = \frac{\%O/_{16/N}}{\%C/_{12/N}} \quad (9)$$

where, N is Avogadro's number with the value of 6.02×10^{23} (atoms/mol).

2.5.3 Heating value

The heating value of briquettes fuel derived from sugarcane bagasse will be analyzed in a manner similar to that used for biomass samples, as described in Section 2.2.3.

2.5.4 Bulk density

The obtained briquettes fuel, characterized by a cylindrical shape with an external diameter of approximately 45 mm, an internal diameter of around 12 mm, and length of approximately 60 mm, exhibit high density. These characteristics will be analyzed according to the ASTM D7481-2009 standard [33, 34]. The calculation for determining the overall density of the briquette samples was done according to Eq. (7).

2.5.5 Compressive strength

Compressive strength of the briquettes fuel samples, with an external diameter of 45 mm, an internal diameter of 12 mm, and a length of 60 mm, was tested using a compression testing machine (STYE-2000). The analysis was performed in the Mechanical Engineering Laboratory at Udon Thani Rajabhat University, Thailand.

2.5.6 Extinguishing time testing

Extinguishing time testing involves evaluating the combustion duration of briquettes fuel in a heating stove, comparing it with the combustion duration of common charcoal, hardwood or eucalyptus wood, and dried sugarcane bagasse, which is a waste material from the community's sugarcane syrup production process. In this study, each experimental sample weighed approximately 3 kg.

2.6 Technology disseminated to target communities

The technology for producing briquettes fuel from sugarcane bagasse will be transferred to target communities, specifically to the agricultural enterprises involved in processing sugarcane products in Tat Thong Subdistrict, Sri That District, Udon Thani Province, Thailand. This initiative aims to use these briquettes as an alternative energy resource, reducing the cost of petroleum gas needed for heating in the sugarcane syrup production process and also mitigating environmental issues caused by burning sugarcane bagasse.

3. Results and discussion

3.1 Characterization of sugarcane bagasse

Table 2 shows the characteristics of the bagasse samples analyzed in the study. The results indicate that bagasse has a volatile content of approximately 78.41 wt.% on a dry basis, a carbon content of approximately 45.47 wt.% on a dry basis, and a higher heating value (HHV) of about 17.25 MJ/kg (4,119.33 Cal/g) determined using a bomb calorimeter. These findings agree with the research conducted by Wang et al. [36], which reported similar values. Upon comparison with the findings of Allende et al. [37], it was observed that there was a significant increase in the heating value, particularly in terms of calorific value. This can be attributed to the higher carbon content and lower oxygen content of the specimens, which contribute to a greater calorific value compared to wood biomass. The study by Gurtner et al. [38] revealed a decreased concentration of volatile substances (82.70 wt.%) and a reduced heat value (19.30 MJ/kg). Biomass typically has an H/C ratio ranging from 1.4 to 1.75 and an O/C ratio ranging from 0.65 to 0.9. Sugarcane bagasse falls within these ranges, with an H/C ratio of 1.73 and an O/C ratio of 0.65. According to a van Krevelen diagram [39], lower O/C and H/C ratios are preferred. If the O/C ratio is high, a heating value will be lower because some of the energy is required to break the oxygen bonds. Moreover, excessive oxygen can cause the fuel to undergo self-oxidation, leading to degradation during storage before use. Additionally, a high H/C ratio increases the likelihood of incomplete combustion.

Table 2 Characteristics of sugarcane bagasse.

Analysis	Sugarcane bagasse	Sugarcane bagasse[a]	Sugarcane bagasse[b]
Proximate analysis (wt.%, dry basis)			
Moisture (wet basis)	7.02±0.10	N/A	9.90
Volatile matter	78.41±0.52	79.20±0.70	76.00
Fixed carbon*	13.71±0.46	17.30±0.30	10.00
Ash	7.39±0.67	3.50±0.20	4.00
Ultimate analysis (wt.%, dry basis)			
Carbon	45.74±0.14	47.57±0.11	41.93
Hydrogen	6.59±0.05	5.64±0.07	5.47
Nitrogen	0.41±0.02	0.16±0.01	0.21
Sulfur	0.22±0.02	-	-
Oxygen*	40.24±0.80	46.62±0.09	53.39
H/C molar ratio	1.73±0.02	N/A	N/A
O/C molar ratio	0.65±0.02	N/A	N/A
Molecular formula	$CH_{1.73}O_{0.65}$	N/A	N/A
Heating value by bomb calorimeter (MJ/kg, dry basis)			
HHV	17.25±0.03	16.80±0.40	N/A
Heating value by calculation (MJ/kg, dry basis)			
HHV	18.88±0.02	N/A	17.32
LHV	17.44±0.02	N/A	13.86
Bulk density (kg/m^3)	189.71±5.83	N/A	N/A

*Calculated by difference
[a]Wang et al. [36].
[b]Allende et al. [37].

3.2 Thermogravimetric analysis

Figure 3 presents thermogravimetric analysis (TGA) and differential thermal analysis (DTA) graphs that compare the degradation of bagasse particles in the absence of oxygen using a heating rate of 10°C/min and the principle of slow pyrolysis. The pyrolysis process of the lignocellulosic biomass can be divided into four main regions: moisture, hemicellulose, cellulose, lignin. The findings of the research indicate that the weight loss of bagasse samples in the initial period, at temperatures approximately <120 °C, is primarily due to water evaporation. Decomposition of hemicellulose occurred at temperatures ranging 220-315°C, while a clear decrease in weight occurred at temperatures around 315–400°C, which corresponds to cellulose decomposition. Subsequently, at approximately > 450°C, the weight gradually decreased due to the decomposition of lignin [40]. The DTA graph of bagasse demonstrates that the greatest a peak degradation rate is observed at a temperature of around 350°C, which aligns with the findings of Teixeira et al. [41] and Somasundaram et al. [42], who conducted TGA experiments on bagasse. Following the step below 400°C, a shoulder between 400 and 1,000°C was observed. In general, lignin pyrolysis occurs above 400°C. Therefore, the shoulder between 400 and 1,000°C should be associated with the decomposition of lignin and proteins. The post-decomposition residual matter, approximately 13.00 wt.%, consists predominantly of fixed carbon, which aligns with the proximate analysis results given in Table 1.

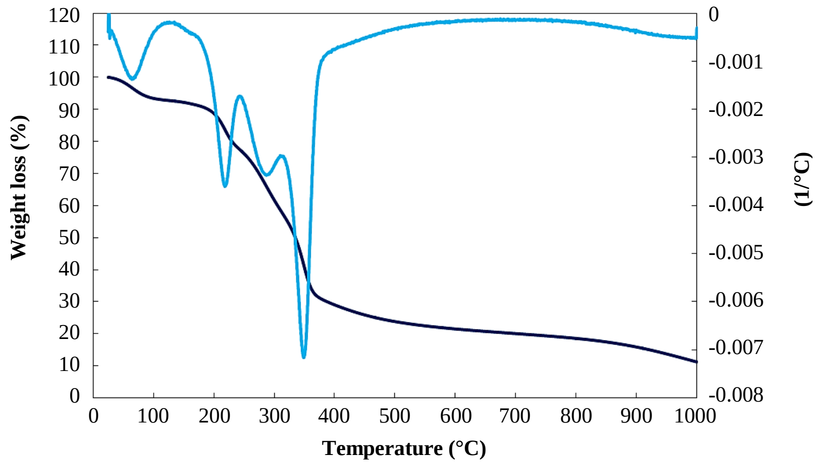

Figure 3 TGA and DTA curves of sugarcane bagasse.

3.3 Fourier-transform infrared spectroscopy (FTIR)

Figure 4 illustrates Fourier-transform infrared spectroscopy (FT-IR) spectral curves of sugarcane bagasse. FTIR spectroscopic analysis was employed to investigate the structural changes of pretreated lignocellulosic sugarcane bagasse hydrolyzed with enzymes and suspended in water. The relative transmittance of the sample spectra demonstrated significant changes. The spectra showed areas of lower and higher transmittance which represents the difference between the most degraded sample (enzyme-treated) and the less degraded samples. FT-IR spectra show a clear peak at 888 cm^{-1}, which is attributed to the β-glycosidic bonds between the sugar units, revealing substrate breakdown by the enzyme complex. The peaks at 1,242 cm^{-1} and 1,513 to 1,805 cm^{-1}, indicate that to maximize the hydrolysis, it is necessary to apply specific enzymes to degrade lignin. After hydrolysis, the residual solid was more recalcitrant to attack by cellulase and xylanase, due to the presence of aromatic groups of the lignin structure [43]. The substrate suspended in distilled water presents differences from enzymatically hydrolyzed samples with lower peak intensity indicating less structural breakdown [44]. The result is consistent with the result reported by Manatura [45] and Oyibo et al. [46]

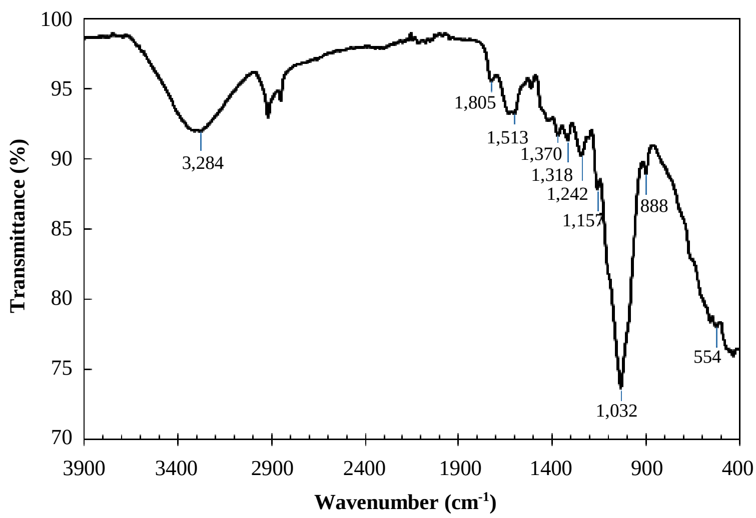

Figure 4 FT-IR spectral curves of sugarcane bagasse.

3.4 Optimization of briquette fuel production from sugarcane bagasse

An investigation was conducted to determine optimal conditions for producing briquette fuel from bagasse. This involved examining the ratio of bagasse particles, cassava starch, and water in two different formulae: 1 kg : 0.1 kg : 0.5 L and 1 kg : 0.3 kg : 0.5 L. The experiments involved choosing four temperatures: 100, 110, 120, and 130°C. The bagasse particles utilized in the study had a consistent size ranging from 2–10 mm in all experiments. Based on the experimental results, the experimental results based on visual observation it was concluded that the most effective briquette fuel could be produced by utilizing a ratio of 1 kg of bagasse to 0.3 kg of tapioca starch and 0.5 liters of water and operating the press at a temperature of 120°C. The briquettes fuel have a cylindrical shape that effectively coalesces the ingredients. They have smooth and shiny dark surfaces, are highly dense, and can be easily compressed into briquettes. The production capacity was estimated to be 12 kg /hr with a feed rate of 20-30 kg/hr, which is suitable for community use. Compared to the work of Karunanithy et al. [28] (feed rate of 150-200 kg/hr), this capacity is relatively small. Minimal use of tapioca starch, 0.1 kg, contributes to the formation of briquettes with loose structures and cracks, owing to insufficient compaction of the briquettes fuel. The research outcomes suggest that operating under low-temperature conditions leads to the briquette surfaces displaying lower levels of smoothness and glossiness. Conversely, excessively high temperatures, specifically 130°C, can cause the surface of the briquettes to burn against the surface of the mold pipe, thereby hindering their movement through the mold pipe, as shown in Table 3.

Table 3 Characteristics of briquette fuel under various experimental conditions.

Conditions/Temperatures	**Ratio of sugarcane bagasse : cassava starch : water**	
	1 kg : 0.1 kg : 0.5 L	**1 kg : 0.3 kg : 0.5 L**
100°C	 The mixture does not bond well and does not form proper rods.	 The mixture bonds, but the surface exhibits significant cracking.
110°C	 The mixture begins to bond well, but the fuel rods show extensive cracking.	 The mixture bonds well with only minor surface cracks.
120°C	 The mixture starts to bond effectively, with the surface developing a dark, glossy appearance, but the fuel rods exhibit cracks.	 The mixture bonds effectively, with a dark, glossy surface, and the fuel rods are free of cracks.
130°C	 The mixture begins to bond well, but the surface becomes very dark and burnt, making it difficult to extrude and transport the fuel rods due to burning and extensive adherence to the mold pipes.	 The mixture bonds very well, with the surface darkening and showing signs of burning, but the fuel rods are difficult to transport due to partial burning and adherence to the mold pipes.

3.5 Characterization of briquette fuel products

Table 4 illustrates the characteristics of the briquette fuel products derived from bagasse. The study shows that briquette fuel contains approximately 8.04 wt.% moisture content on a dry basis, which is lower than the acceptable standard criteria of 14 wt.% [47]. The carbon content on a dry basis is approximately 61.18 wt.%, and the higher heating value (HHV) was 24.05 MJ/kg. This value closely aligns with the findings of Tomen et al. [34] in their study on briquette fuel produced from sawdust, which reported an HHV value of 24.72 MJ/kg. Upon comparison with the study of Cardozo and Malmquist [48] regarding sugarcane bagasse pellets as a fuel, it was discovered that the briquettes had greater heating values. This can be attributed to incorporation of cassava flour as a binder during the production process, which consequently generated greater carbon content and increased heating values. Examination of the briquette fuel indicated a density of approximately 856.70 kg/m³. This density surpasses that of bagasse pellets of Cardozo and Malmquist [48]. Furthermore, briquette fuel, originating from bagasse, displayed molar ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) of 1.59 and 0.19, respectively. Their compressive strength was roughly 89.34 kg/m².

3.6 Extinguishing time testing

In Figure 5, a comparative analysis is presented of the combustion duration of bagasse briquettes fuel relative to conventional wood charcoal, eucalyptus wood, byproducts of the community's sugarcane syrup production process and dried sugarcane bagasse. This information can guide potential applications within the community. The experimental outcomes demonstrate a notable superiority of bagasse briquettes fuel in terms of combustion duration, outperforming all other tested fuel samples. Further observations identified that bagasse briquettes fuel not only exhibit high flammability, but also generate comparatively less smoke than both bagasse and eucalyptus wood. This characteristic presents an environmental benefit, significantly enhancing the feasibility of substituting briquettes fuel for household petroleum gas. Figure 6 (a) and (b) show the testing of the combustion of the briquettes fuel in a heating stove.

Table 4 Characteristics of briquette fuel products from sugarcane bagasse.

Analysis	Briquettes from sugarcane bagasse	Briquettes from sawdust[a]	Pellets from sugarcane bagasse[b]
Proximate analysis (wt.%, dry basis)			
Moisture (wet basis)	8.04±0.45	6.77	6.00±0.05
Volatile matter	70.20±0.55	28.57	N/A
Fixed carbon*	16.11±0.98	66.60	N/A
Ash	13.05±0.48	4.83	N/A
Ultimate analysis (wt.%, dry basis)			
Carbon	61.18±0.55	55.42	48.20±2.90
Hydrogen	8.08±0.11	5.23	6.10±0.50
Nitrogen	1.33±0.12	-	0.30±0.10
Sulfur	0.89±0.07	-	0.03±0.007
Oxygen*	17.61±0.35	33.85	44.30
H/C molar ratio	1.59±0.01	1.132	N/A
O/C molar ratio	0.19±0.01	0.458	N/A
Molecular formula	$CH_{1.59}O_{0.19}$	N/A	N/A
Heating value by bomb calorimeter (MJ/kg, dry basis)			
HHV	21.91±0.01	24.72	N/A
Heating value by calculation (MJ/kg, dry basis)			
HHV	24.05±0.24	N/A	19.30±0.40
LHV	22.28±0.22	N/A	17.90±0.40
Bulk density (kg/m^3)	856.70±9.07	495	590±0.20
Compressive strength (kg/m^2)	89.34±5.67	N/A	N/A

*Calculated by difference.
[a]Tomen et al. [34].
[b]Cardozo and Malmquist. [48].

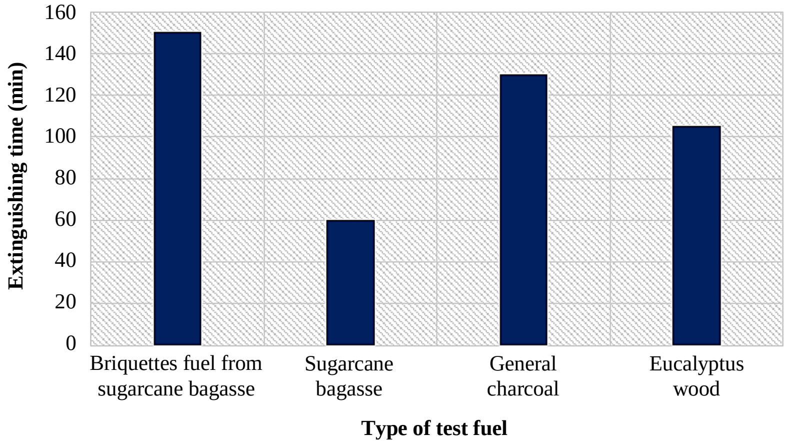

Figure 5 Extinguishing time of briquette fuel from sugarcane bagasse compared with test fuel samples.

(a) Briquettes from sugarcane bagasse (b) Combustion of briquettes fuel in stove

Figure 6 Evaluation of the combustion performance of sugarcane bagasse briquette fuel in a stove.

3.7 Technology disseminated to target communities

The technology and innovation in producing briquettes fuel from sugarcane bagasse derived from this research, have been successfully implemented and transferred to a target community. This is a group of agricultural entrepreneurs at a community enterprise processing sugarcane product in Tat Thong Subdistrict, Si That District, Udon Thani Province, Thailand. The current initiative aims to use briquette fuel as an alternative energy resource, thereby reducing the expenses associated with using petroleum gas for heating in the community's sugarcane syrup processing, as illustrated in Figure 7 (a). The community's syrup product is shown in Figure 7 (b). Adoption of this technology and innovation by the community has led to a significant cost reduction for liquid petroleum gas, approximately 30,000 Thai baht per production cycle. Given that these agricultural processes operate twice a year, the use of sugarcane bagasse briquette fuel as an alternative energy source can reduce annual energy costs of this process by about 60,000 Thai baht. Additionally, this approach substantially diminishes incineration of sugarcane bagasse, which is a waste product from the production process, and promotes a reduction in pollution from dust and smoke caused by burning process waste.

(a) Heating the stove briquettes fuel from sugarcane bagasse (b) Sugarcane syrup products

Figure 7 Utilization of briquettes fuel derived from sugarcane bagasse as an alternative energy source for providing heat to the community's syrup processing stoves.

4. Conclusions

The main aim of this study was to determine the most appropriate conditions to develop briquette fuel using biomass. The characteristics of the produced briquette fuel were analyzed and the technology disseminated to a target community. The study revealed that the optimal temperature for producing briquettes fuel from sugarcane bagasse was 120°C, and the best ratio of bagasse particles, cassava starch, and water was 1 kg of sugarcane bagasse : 0.3 kg of cassava starch : 0.5 L of water. Physical and chemical properties of the briquettes fuel showed moisture, volatile matter, ash, and fixed carbon contents of 8.04, 70.20, 13.05, and 16.11 wt.% on a dry basis, respectively. Their density, compressive strength, and higher heating value (HHV) were approximately 856.70 kg/m^3, 89.34 kg/cm^2, and 24.05 MJ/kg, respectively. The combustion duration was longer than that of typical wood charcoal. This study successfully transferred technology and innovation for producing briquettes fuel from sugarcane bagasse to a target community, offering an alternative energy resource for a syrup production process and reducing annual petroleum gas fuel expenses by approximately 60,000 Thai baht. The technology also mitigates pollution from burning agricultural waste and is easily accessible to the community. Furthermore, it is crucial that communities have easy access to technology, leading to establishment of model communities for sustainable development of grassroots economies. In the future, the composition of volatile substances released during the combustion of briquette fuel will be analyzed to study emissions into the environment.

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