Asia-Pacific Journal of Science and Technology: Volume: 29. Issue: 04. Article ID.: APST-29-04-07. Research Article

Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by the Research and Graduate Studies Division,
Khon Kaen University, Thailand

Development of charcoal briquettes from rubber seed shells mixed with food waste binder as an alternative energy source

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Received 20 June 2023
Revised 16 October 2023
Accepted 17 October 2023

Abstract

Rubber seed shells (RSS) are an abundant biomass in Thailand that can be used as a source of charcoal briquettes for alternative energy. Food waste from the domestic sector also has the potential to be used as an effective binder in the production of charcoal briquettes. This research aimed to develop charcoal briquettes from RSS using food waste as an alternative binder material. The ratio of RSS charcoal to food waste binder was varied at 2:1, 5:1, and 10:1 (v/v). Cassava starch, a popular and conventional binder, was used as a binder to compare with food waste. Cylindrical charcoal briquettes, 40 mm in diameter and 40 mm long, were formed by a hydraulic press with a pressing force of 1 ton. The results show that the variation in the charcoal:binder (C:B) ratio affected the bulk density, moisture, ash, volatile matter content, heating value, and compressive strength. RSS charcoal briquettes at a C:B ratio of 1:1 was considered suitable because they had the highest heating value and a relatively high compressive strength of 6,219 ± 229 cal/g and 53.29 ± 2.91 N/cm^2, respectively. The moisture content and heating value of this RSS charcoal briquette are within the range set by the Thai Industrial Standard Institute (TISI) standard. The heating value of RSS charcoal briquettes made from food waste binder at a suitable C:B ratio (10:1) was not significantly different from those made from cassava starch binder at the same C:B ratio, but the compressive strength was significantly lower.

Keywords: Alternative energy, Charcoal briquette, Food waste, Rubber seed shells

1. Introduction

The current global energy crisis is caused by the constant increase in energy consumption due to the increasing world population, while fossil fuels are limited and may run out in the near future. Solar, wind, hydro energy, and biomass are needed as alternatives to our fossil energy resources due to their being clean and renewable energy sources [1]. Biomass is organic matter that is a natural energy storage source such as trees, agricultural waste, and industrial waste such as rice husk, bagasse, sawdust, animal manure, household waste, etc. Thailand is an agricultural country with a large amount of biomass available as an energy source. Therefore, biomass energy is one of the alternatives that the government prioritizes in developing potential and ensuring that the public sees the importance of using renewable energy from domestic energy sources in order to reduce the use of fossil fuels. Most biomass waste is used as fuel for cooking and process heating in a residential setting by direct combustion, due to its simplicity, convenience, and low cost. Unfortunately, biomass in its raw form has a low density, low heating value, high moisture content, and high ash content. Carbonization is one of the most effective methods to solve this. It permits the conversion of biomass into carbon via pyrolysis. Carbonization of biomass residues nearly doubles the energy value per unit of weight. When burned, charcoal can generate PM2.5 and emit less carbon dioxide than raw biomass [2]. In addition, if used to make charcoal briquettes, a small amount of smoke is produced compared to traditional charcoal [1]. Thus, the conversion of biomass into highly efficient fuels such as charcoal briquettes is becoming more attractive.

Charcoal briquettes are produced from charcoal powder and binder, mixed and compacted into the desired shape by mechanical moulding [3]. Charcoal briquettes have an economic advantage due to their simple production process, high heating value, and readily available raw materials. They have numerous applications, ranging from domestic use for cooking and heating to use by small industries.

Thailand is one of the world's largest natural rubber producers, with 35,769 square kilometres or 3,576,862 hectares (ha) under rubber plantation in 2020 [4]. This number increases annually. Each hectare can yield approximately 150 kg of seeds. Therefore, Thailand can produce up to 0.536 million tons of rubber seeds per year [5]. Rubber seeds are inedible and abundant in the country. Some of them are planted as rubber seeds, while much of the remainder is left to rot in the rubber plantations. Thus, the use of rubber seeds could be of great interest. Rubber seeds contain a shell and a kernel. The kernel has been investigated for biodiesel production from rubber seed oil [6]. Seed shells have been used as a raw material for the production of activated carbon [7] and charcoal briquettes [8]. These applications could increase the value of Thailand's rubber trees.

Many studies have been conducted on the production of charcoal briquettes from various agricultural waste, including bagasse [3,9], madan wood waste, coconut shell [1], rubber seed [10], sawdust [11], corncob bagasse, rice husk and bran [12], water hyacinth [13], palm kernel shell [14], and orange bagasse [15]. Furthermore, many studies have been conducted on the binders used for charcoal briquette production, including cassava starch [1,14], molasses [13], clay [9], and corn starch [15]. To date, no studies have reported the use of household waste, specifically food waste, as a binder for charcoal briquettes. Food waste disposal is one of the world's major crises because about 1.3 billion tons of food waste is generated worldwide. In Thailand, a population of 66 million generates 145 kg of food waste per person per year [16]. Thus, choosing food waste as a binder is advantageous because it is readily available. Starch-containing waste with a glue-like substance and residues from household sources are not only economical but also environmentally benign. School canteens are important places that generate a lot of food waste from people eating all the time, especially during lunchtime. A large school canteen in Thailand can generate approximately 1,800 kilograms of food waste per day [17]. A small canteen in Udon Thani Rajabhat University generates approximately 300 kilograms of food waste per day, as recorded by the housekeeping group. As a result, a lot of food waste accumulates in canteens throughout the country.

Therefore, the objective of this study was the development and characterisation of charcoal briquettes from rubber seed shells (RSS) using food waste as a binder, varying the charcoal to binder ratio (C:B) at 2:1, 5:1, and 10:1 (v/v), compared to using a conventional binder like cassava starch.

2. Materials and methods

2.1 RSS charcoal preparation

Rubber seeds were collected from rubber plantations in Na-Yoong district, Udon Thani Province, Thailand. The RSS was separated from its kernel by hand (Figure 1A) then placed in the sun to dry for 3 days. All dried RSS, with diameters ranging from 1 to 4 cm, were conventionally pyrolysed at around 500°C in a 200 L incinerator. This was done until smokeless and RSS charcoals were properly obtained. Charcoal from RSS was ground in a stone mortar and sieved through a 3 mm sieve to get charcoal powder.

2.2 Binder preparation

Food waste and cassava starch were used as binders in this study. Cassava starch binder was prepared by dissolving 250 g of cassava starch in 0.5 L of hot water to form a paste. After obtaining the paste, another 0.5 L of water was added and boiled. The paste was stirred gently until a smooth homogeneous gelatinized starch solution was obtained. The solution was allowed to cool down before it was used. The food waste used as a binder was collected from a school canteen because it is readily available and numerous types of food are commonly found. The impurities, such as plastic, paper, and bone were separated from the food waste. Then, 2 kg of food waste was mixed with 500 mL of water before being blended with a blender until homogeneous.

2.3 Charcoal briquettes preparation

The charcoal powder was mixed with a binder (food waste or cassava starch) at C:B ratios of 2:1, 5:1, and 10:1 by volume using a measuring cylinder. The proportions used in this study have undergone preliminary mixing trials. The mixture was pressed in a cylindrical mould by a hydraulic press at 1 ton of pressure. The cylindrical mold used has an inner diameter of 40 mm and a length of 60 mm without a centre hole. After the briquette process, cylindrical charcoal briquettes, 40 mm in diameter and 40 mm long, were obtained from the

RSS (Figure 1B). The briquettes were dried by sunlight for 3 days until the moisture content was less than 8%. Charcoal briquettes made with water instead of binder were used as a control.

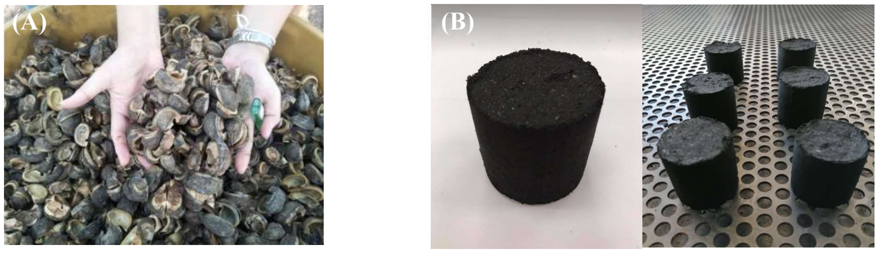

Figure 1 Rubber seed shells (A), and charcoal briquettes made from rubber seed shells (B).

2.4 Characterization of RSS charcoal briquettes

The characteristics of the RSS charcoal briquettes - bulk density, moisture content, volatile matter content, ash content, fixed carbon content, heating value, and compressive strength - were examined. The bulk density of the briquettes was determined by the ratio of their mass to their volume. The moisture content of charcoal briquettes was determined by ASTM D3173. The volatile matter (%V) and ash contents (%Ash) were determined by ASTM D3175 and ASTM D3174, respectively. After determining the volatile matter and ash content, the formula was used to calculate the fixed carbon content (%FC).

$$\%FC = 100 - \%V - \%Ash \tag{1}$$

The heating value of charcoal was analyzed according to ASTM D5865 using a bomb calorimeter. This technique measures the heat emitted by determining the difference in temperature before and after the complete combustion of a given amount of sample (1 g) introduced into the bomb. The heating value was calculated using Equation (2), where Q is the heating value of the sample (MJ/g), W is the water equivalent of a calorimeter (MJ/°C), Δt is temperature change (°C), and g is the mass of the sample (g).

$$Q = \frac{W\Delta t}{g} \tag{2}$$

The compressive strength of charcoal briquettes was determined by analysis of their resistance to compression using a universal testing machine (model TM113). In this test, briquettes were subjected to progressive and constant pressure until they broke. All tests were performed in triplicate.

Comparison of means was done using one-way ANOVA with the Duncan test as a post hoc test. A t-test for independent samples was utilized to compare the mean difference between two samples. The statistical analyses were conducted with a level of confidence of 95% ($\alpha = 0.05$) using the SPSS statistics program (Version 17.0 by IBM corporation).

3. Results and discussion

Charcoal briquettes were fabricated in this study from RSS using food waste and cassava starch as binders at different C:B ratios (2:1, 5:1, 10:1 v/v). The characterization test results for RSS charcoal briquettes are shown in Table 1. These results were compared to the Thai Community Product Standards (TCPS) for charcoal bars (ICPS No. 238/2547) governed by the Thai Industrial Standard Institute (TISI) [18] which determines that charcoal briquettes should have a moisture content of less than 8% and heating value over 5,000 cal/g. The moisture content of all briquettes tested was in the range of 4.87-6.96% by weight, which is within the limit set by the TISI standard.

3.1 Bulk density of RSS charcoal briquettes

Bulk density is commonly measured as the mass-to-volume ratio of briquettes, and it is a crucial metric for evaluating their combustion properties, ignition behavior, transportation, and storage efficiency. Charcoal briquettes with a high density are difficult to ignite, whereas those with a density that is not too high will be simpler to ignite [13]. The bulk density of RSS charcoal briquettes obtained in this study is shown in Table 1. The results demonstrate that RSS charcoal briquettes made from cassava starch binder exhibited a significantly higher bulk density (0.653 ± 0.013-0.706 ± 0.012 g/cm^3) compared to those made from food waste binder (0.609 ± 0.017-0.649 ± 0.010 g/cm^3) at the same C:B ratio. This result may be due to cassava starch adhering to charcoal particles with a greater force than food waste. This causes the charcoal particles to be more compacted and have a greater mass. In addition, the type of binder may cause the expansion or shrinkage of briquettes, resulting in different bulk densities [19]. However, when compared to the result for the control briquettes (0.607 ± 0.015 g/cm^3), RSS charcoal briquettes made from food waste binder at C:B ratios of 5:1 and 10:1 (v/v) showed significantly higher bulk densities, which indicates that food waste can be used as a binder to improve the density of charcoal briquettes. In the control test, water was used instead of binder, which does not help the adhesion of charcoal particles, resulting in a low bulk density.

Table 1 Characteristics of RSS charcoal briquettes made with food waste and cassava starch binder at different ratios compared to control.

Binder	C:B ratio (v/v)	Moisture (%)	Bulk density (g/cm^3)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Heating value (cal/g)	Compressive strength (N/cm^2)
Food waste	2:1	6.67 ± 0.10^{d}	0.609 ± 0.017^{a}	9.48 ± 0.16^{e}	40.13 ± 2.64^{d}	43.72 ± 2.86^{a}	$5{,}312 \pm 205^{a}$	20.60 ± 1.85^{b}
	5:1	6.35 ± 0.10^{c}	0.649 ± 0.010^{b}	8.47 ± 0.21^{d}	32.92 ± 2.83^{bc}	52.27 ± 2.67^{bc}	$5{,}778 \pm 239^{bc}$	57.62 ± 1.90^{c}
	10:1	4.87 ± 0.21^{a}	0.644 ± 0.014^{b}	8.32 ± 0.15^{d}	28.37 ± 2.41^{a}	58.44 ± 2.61^{d}	6219 ± 229^{d}	53.29 ± 2.91^{c}
Cassava	2:1	6.96 ± 0.16^{e}	0.653 ± 0.013^{b}	7.09 ± 0.16^{a}	34.54 ± 1.07^{c}	51.41 ± 1.09^{b}	$5{,}703 \pm 134^{b}$	147.79 ± 8.46^{e}
starch	5:1	6.13 ± 0.14^{c}	0.701 ± 0.018^{c}	7.26 ± 0.14^{a}	30.61 ± 0.84^{ab}	56.00 ± 0.89^{cd}	$5{,}873 \pm 122^{bcd}$	132.89 ± 5.52^{d}
	10:1	6.29 ± 0.17^{c}	0.706 ± 0.012^{c}	7.99 ± 0.21^{c}	28.09 ± 2.03^{a}	57.63 ± 2.29^{d}	$6{,}164 \pm 243^{cd}$	125.45 ± 7.15^{d}
Control		5.78 ± 0.11^{b}	0.607 ± 0.015^{a}	7.64 ± 0.15^{b}	28.62 ± 1.90^{a}	57.97 ± 1.92^{d}	5901 ± 253^{bcd}	1.59 ± 0.08^{a}

Alphabets with the same letter show that there is no significant difference, Alphabets with different letter show that there is significant difference. Values with the same superscript letter are not significantly different; different superscript letters indicate significant difference.

For the food waste binder test, RSS charcoal briquettes at a C:B ratio of 5:1 (v/v) showed the highest bulk density (0.649 ± 0.010 g/cm^3), while the lowest value was found at a C:B ratio of 2:1 (v/v) (0.609 ± 0.017 g/cm^3). The bulk density of RSS charcoal briquettes at a C:B ratio of 10:1 (v/v) (0.644 ± 0.014 g/cm^3) was slightly less than that at a C:B ratio of 5:1 but not significantly different. In the case of cassava starch binder, the bulk density of RSS charcoal briquettes at a C:B ratio of 2:1 (v/v) was significantly lower than that at C:B ratios of 5:1 and 10:1 (v/v). This result may be due to the different densities of the binder and the charcoal powder itself. At a C:B ratio of 2:1 (v/v), the amount of binder was enough to affect the bulk density of the charcoal briquettes. These results resemble those from Zanella et al.'s study [15]. They developed charcoal briquettes from orange bagasse using corn starch as a binder at different binder concentrations. The results show that the density decreased somewhat with increased binder content but was not significantly different.

This result demonstrates that the type and content of the binder affect the bulk density of charcoal briquettes. In addition, the bulk density of briquettes depends on process variables, such as moisture content, particle size, and compaction pressure [15,20].

3.2 Ash content of RSS charcoal briquettes

Ash is the non-combustible component that remains after something burns. The ash content of a charcoal briquette can affect its calorific value; a higher ash content results in a lower calorific value [20]. Therefore, the ideal charcoal briquette has a low ash content. The ash content of RSS charcoal briquettes made from both binders at different C:B ratios is illustrated in Table 1. RSS charcoal briquettes made from cassava starch binder had a significantly lower ash content (7.09 ± 0.16%-7.99 ± 0.21%) than those made from food waste binder (8.32 ± 0.15%-9.48 ± 0.16%) at all C:B ratios. This result may be due to the fact that food waste is combustible and contains a higher inorganic content than cassava starch paste, resulting in a higher ash content. This result aligns with the findings of Ngamlert et al. [21] who examined charcoal briquettes made from eucalyptus bark using five different kinds of binder, molasses, rice stick, clay, water hyacinth, and cassava starch. The use of cassava starch as a binder resulted in the lowest ash content compared to the other binders. In addition, when comparing the ash content of briquettes made from food waste binder to that of the control, the ash content of briquettes made from food waste binder was significantly higher at all C:B ratios (8.32 ± 0.15%-9.48 ± 0.16%) than that of the control (7.64 ± 0.15%). This indicates that food waste has a high ash content, which may affect the ash content of RSS charcoal briquettes.

The ash content of RSS charcoal briquettes made from cassava starch binder gradually increased with a decrease in binder content, while the ash content of those made from food waste binder decreased with a decrease in binder content. The results indicate that the difference in ash content of all briquettes produced was due to the amount and type of binder added [22,23]. Depending on the ash content of the binder, the ash content of briquettes may vary.

3.3 Volatile matter content of RSS charcoal briquettes

Volatile matter is a mixture of long- and short-chain hydrocarbons, including combustible and incombustible gases that are emitted during combustion. These gases influence the combustion behavior of charcoal briquettes. A charcoal briquette with a high volatile matter content has a high combustion rate and produces more fumes during the burning process. This means that ideal charcoal briquettes should have a minimal volatile matter content. The ideal briquette may be difficult to ignite, but it will burn smoothly and emit less smoke. RSS charcoal briquettes made from food waste binder had a higher volatile matter content (28.37 ± 2.41%-40.13 ± 2.64%) than those made from cassava starch binder (28.09 ± 2.03%-34.54 ± 1.07%) at the same C:B ratio (Table 1). However, it was only at the C:B ratio of 2:1 (v/v) that the volatile matter values were significantly different. This result indicates a higher level of volatile matter in food waste than in cassava starch. The volatile matter content of the briquettes made from both binders had the same trend of the results, that is, the volatile matter content increased with increasing binder content. The volatile matter of RSS charcoal briquettes made from cassava starch at a C:B ratio of 2:1 (v/v) was significantly higher than that at C:B ratios of 5:1 and 10:1 (v/v) but the volatile matter content of briquettes at C:B ratios of 5:1 and 10:1 (v/v) was not significantly different. In the case of food waste binder, the volatile matter content of RSS charcoal briquettes at a C:B ratio of 2:1 (v/v) was significantly higher than that at C:B ratios of 5:1 and 10:1 (v/v), respectively. This implies that an increase in binder content can increase the volatile matter content of charcoal briquettes due to the effect of the volatile matter content in the binder itself. This result is consistent with the findings of Zanella et al. [15] and Abdulganiyu et al. [24], who produced charcoal briquettes from orange bagasse and raphia palm seeds using corn starch and cassava starch as binders, respectively, at various binder concentrations. They discovered that the volatile matter content increased with the amount of binder in the briquettes.

However, the volatile matter content of charcoal briquettes depends not only on the type and content of the binder but also on the compaction pressure, charcoal particles, raw material, carbonization conditions and temperature, and measurement methods [9,11,20].

3.4 Fixed carbon content of RSS charcoal briquettes

Fixed carbon indicates the proportion of carbon available for char combustion after all volatile matter has been extracted from biomass. This does not equal the total quantity of carbon in the fuel, as a significant amount is also released as hydrocarbons from volatile matter. Carbons will react with oxygen to produce heat. The proportion of fixed carbon in charcoal briquettes is a significant factor in determining their calorific value [25]. A high-quality fuel briquette will have a low volatile matter and ash content and a high fixed carbon content. The fixed carbon content of RSS charcoal briquettes made from both binders at different C:B ratio is illustrated in Table 1. The fixed carbon value of RSS charcoal briquettes made from cassava starch binder at a C:B ratio of 2:1 (v/v) was significantly lower than that of those at C:B ratios of 5:1 and 10:1 (v/v), but there was no significant difference between that of those at C:B ratios of 5:1 and 10:1 (v/v), while the fixed carbon content of RSS charcoal briquettes made from food waste at a C:B ratio of 2:1 (v/v) was significantly lower than that of those at C:B ratios of 5:1 and 10:1 (v/v), respectively. Generally, a high moisture, ash, and volatile matter content leads to a low fixed carbon content. The moisture, ash, and volatile matter content of RSS charcoal briquettes vary as a result of varying the binder concentration (C:B ratio). However, the quantity of fixed carbon in the raw material is the most important factor in the generation of heat during combustion.

3.5 Heating value of RSS charcoal briquettes

The heating value (or calorific value) of a fuel is the standard measurement of its energy content. It is the quantity of heat released when a unit of fuel is completely burned. High-heating-value charcoal briquettes are ideal for high-quality fuel. A high heating value corresponds to high heat production, which expedites the heating process. The heating value of RSS charcoal briquettes made from both binders at different C:B ratios is shown in Table 1. TISI stipulates that the calorific value should exceed 5,000 cal/g, and all of the RSS charcoal briquettes in this study met the standard (TPCS). When the heating values of RSS charcoal briquettes made from cassava starch and food waste binder were compared, only those at a C:B ratio of 2:1 (v/v) were significantly different, while the values of the briquettes at C:B ratios of 5:1 and 10:1 (v/v) were not significantly different. The briquettes made from food waste binder at a C:B ratio of 2:1 (v/v) (5,312 ± 205 cal/g) had a significantly lower heating value than those made from cassava starch (5,703 ± 134 cal/g) and the control (5,901 ± 253 cal/g). The result implies that a certain amount of food waste can reduce the heating value of RSS charcoal briquettes. This result may be due to the high volatile matter and ash content of the briquettes at this ratio, resulting in a low fixed carbon content and consequently low heating value.

For the effect of C:B ratio or binder content on the heating value of RSS charcoal briquettes, the results show that the heating value of briquettes made from both binders increased with decreasing binder content. This result indicates that a low binder content can improve the heating value of charcoal briquettes. The maximum calorific value of RSS charcoal briquettes was 6,219 ± 229 cal/g when using food waste as binder at C:B ratio of 10:1, which was significantly different from that at the other C:B ratios. The highest heating value may be due to the lowest moisture content and low volatile matter at this tested ratio. This is a result of the low volatile matter content in the food waste. This trend in the results agrees with that in the study of Zanella et al. [15], who found that the heating value of charcoal briquettes from orange bagasse increased with decreasing binder content due to the lower calorific value of the binder itself.

3.6 Compressive strength of RSS charcoal briquettes

Rajkumar and Venkatachalam [26] define compressive strength as the utmost crushing load a briquette can withstand before cracking or breaking. It can be approximated based on the maximum force applied to the briquette's face. Briquettes produced with a low compressive strength tend to crumble more quickly during combustion and break readily during transport. Therefore, a briquette with high compressive strength is the ideal for good-quality charcoal briquettes. The compressive strength of RSS charcoal briquettes made from both binders with different C:B ratios is presented in Table 1. The compressive strength of the control briquette was 1.59 ± 0.08 N/cm^2 which is lower than the values obtained for briquettes with binders. This result demonstrates that the addition of binder to densify briquettes can improve their compressive strength. The binder allows agglomeration between the charcoal particles and makes the briquette strong. Five possible mechanisms for binding between particles were reported by Rumpf [27]: attraction forces, interfacial forces and capillary pressure, adhesion and cohesion forces, solid bridges, and mechanical interlocking. The binding mechanism of the binders in this study may involve just some mechanisms or all of them.

The compressive strength of RSS charcoal briquettes made from cassava starch binder was higher than that of those made from food waste binder at all C:B ratios. This result implies that the cassava starch has a stronger adhesive property. In the phase of paste formation, the application of heat and water to cassava starch disrupts the granular structure of the starch molecules via separation and sufficiently uncoils their structure so they can catch onto other particles with their powerful adhesive properties. This result agrees with those of Aransiola et al. [23], who studied charcoal briquettes made from corncobs with three types of binder, cassava starch, corn starch, and gelatin. They found that making briquettes from cassava binder could increase the compressive strength more than using corn starch and gelatin as binders, respectively.

Although RSS charcoal briquettes made from food waste binder had lower compressive strengths than those made from cassava starch binder, the maximum value (57.62 ± 1.90 N/cm^2) was still 36 times higher than that of the control. This result indicates the ability of food waste to be used as a binder for making charcoal briquettes. Generally, the components of food waste are carbohydrate, protein, fat, and fiber. Although a starch-based food waste material can be a good binder, and the adhesive properties of protein and starch have long been recognized, they need to be modified by thermal or chemical modification to obtain adhesives [28]. Maybe in future studies, if food waste goes through these processes, the compressive strength of briquettes can be increased.

The compressive strength of RSS charcoal briquettes made from cassava starch increased with an increase in binder quantity. This may be due to the glue-like substance of gelatinised cassava starch, which, in this study, increased the binding strength between charcoal particles. The compressive strength of RSS charcoal briquettes made from cassava starch at a C:B ratio of 2:1 (v/v) was significantly higher than that at C:B ratios of 5:1 and 10:1 (v/v), but the results were not significantly different between C:B ratios of 5:1 and 10:1 (v/v). On the other hand, the compressive strength of RSS charcoal briquettes made from food waste decreased somewhat with increasing binder content. The RSS charcoal briquettes made from food waste at a C:B ratio of 5:1 (v/v) had the maximum compressive strength (57.62 ± 1.90 N/cm^2) but it was not significantly different from that at a C:B ratio of 10:1 (v/v) (53.29 ± 2.91 N/cm^2). The lowest compressive strength of 20.60 ± 1.85 N/cm^2 was found at a C:B ratio of 2:1 (v/v), which was significantly different from that at C:B ratios of 5:1 and 10:1 (v/v). The low compressive strength at a high binder (food waste) content shown in these results may be due to excess food waste making the adhesion between charcoal particles loose and weak. This result implies that the type and content of binder can affect the compressive strength of charcoal briquettes.

3.7 Comparison of RSS charcoal briquette characteristics to those in the literature

Table 2 shows the characteristics of the charcoal briquettes developed in this study compared to those made from different materials by other researchers. Many types of biomass have been used for charcoal briquette production, such as raphia palm seed, rice stalk, peanut shell, palm kernel shell, cassava rhizome, madan wood, corn cob, orange bagasse, bagasse, and water hyacinth as well as RSS. This research is to develop charcoal briquettes from RSS using food waste as an alternative binder material. From our results, the C:B ratio of 10:1 (v/v) is suitable because it has a relatively high heating value and high compressive strength; the optimal C:B ratio of 10:1 (v/v) was therefore selected and used for comparison with other studies.

Table 2 Comparison of charcoal briquettes made from different raw materials and binders.

Raw material	Binder	Binder content	Bulk density (g/cm^3)	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Heating value (cal/g)	Compressive strength (N/cm^2)	References
Rubber seed shell	Food waste	10:1 v/v	0.644	4.87	8.32	28.37	58.44	6,219	53.29	This study
	Cassava starch	(9%v/v)	0.701	6.13	7.26	30.61	56.00	5873	132.89	
Raphia palm seed	Cassava starch	20% w/w	-	12.86	11.85	64.30	10.91	3,056	-	[24]
Rice stalk	Cassava starch	30% w/w	0.642	25	23	44.8	32.20	3,313*	82*	[29]
Rubber seed shell	Cassava starch	8% (-)	-	7.4	3.55	13.14	75.92	7,106	-	[8]
Peanut shell			-	7.14	6.28	12.34	74.24	7,047	-	
Palm kernel shell	Cassava starch	135:20 (w/w)	-	1.08	0.06	71.8	27.07	4,474*	-	[14]
Cassava rhizome	Cassava starch	7:3 (w/w)	0.79	7.23a	13.48a	46.39a	32.90a	5,718*	111.4*	[30]
Madan wood	Cassava starch	14:1 (w/w)	0.68	7.8	3.9	20.3	68.0	6,622	-	[1]
Corn cob	Cassava starch	30% w/w	0.986	5.34	-	-	-	-	832*	[23]
	Gelatin starch		0.886	7.13					505*	
Wood	Native and modified starch	8% w/w	0.7	< 6	5–10	25–30	60–68	6,334*	2,450*	[22]
Orange bagasse	Corn starch	10% w/w	0.594	2.563	7.973	63.091	28.936	6,419*	140.6*	[15]
Maize cob	Sago flour	6:1 (w/w)	-	7.22	16.21	21.33	32.33	5,570	-	[20]
Bagasse	Clay:molasses	40:1:1 (w/w)	-	4.1	36.4	27.2	36.4	4,390	-	[9]
Water hyacinth	Molasses	70:30 (w/w)	0.84	-	-	-	-	3,967*	187.3*	[13]

*Calculation from the literature data or converted units.
[a]Charcoal powder.

A very high bulk density of 0.986 g/cm^3 was observed in charcoal briquettes produced from corn cobs by Aransiola et al. [23] while a very low density of 0.594 g/cm^3 was observed for bagasse charcoal briquettes in the study of Zanella et al. [15]. The bulk density of RSS charcoal briquettes made from food waste binder in this study (0.644 g/cm^3) was moderate compared to previous reports. Moisture content, ash content, volatile matter content, and fixed carbon content from the literature vary from 2.563% to 12.86%, 0.06% to 36.4%, 12.34% to 71.8%, and 10.91% to 75.92%, respectively. The values obtained in this study are within the range of these reports in the literature.

The heating value varies from type to type of raw materials used in charcoal briquette production. The highest heating value of 7,106 cal/g was observed for RSS charcoal briquettes produced by Murni and Setyoningrum [8] using the same type of material as in our study. The lower ash and volatile matter contents and high fixed carbon content in those studies would lead to higher heating values, since the calorific value of briquettes depends not only on the type of raw material but also on the source of raw materials, binder type and concentration, carbonization condition and temperature, charcoal particle size, compaction pressure, and measurement instrument and method used. The lowest heating value of 3,056 cal/g was observed for raphia palm kernel charcoal briquettes in the study of Abdulganiyu et al. [24]. This low heating value is a result of a low fixed carbon content (10.97%). The heating value of RSS charcoal briquettes with food waste binder from this study is close to that of wood charcoal briquettes reported by Borowski et al. [22]. The heating value of charcoal briquettes made from RSS observed in this study was higher than that of those made from raphia palm seeds, rice straw, palm kernel shells, maize cob, bagasse, and water hyacinth. This indicates that RSS and food waste binder are efficient materials for producing high calorific value charcoal briquettes.

The compressive strength from the literature ranges from 82 to 2,450 N/cm^2, the value from the work of Borowski et al. [22] being the highest and quite different from the others. If the value from their work is excluded, the compressive strength is in a narrower range of 82-832 N/cm^2. The compressive strength of RSS charcoal briquettes with food waste binder in this study, 53.29 N/cm^2, had a lower value than those in the literature. As previously described, the food waste binder could improve the compressive strength of charcoal briquettes when compared to the control. In addition, food wastes can be modified to increase their binding properties [28]. Therefore, there is a way to improve the compressive strength of RSS charcoal briquettes made from food waste binder. The difference in compressive strength of each charcoal briquette is caused not only by the type of raw materials itself but also by the briquette's shape and size, particle size, compaction pressure, binder type and concentration, and also the measurement instrument and methods used [15,23,29,30].

Our RSS charcoal briquettes with food waste binder were characterized as having good properties, especially their heating value which is in the high range compared to other literature and higher than that of the RSS charcoal briquettes made using cassava starch binder. This shows the possibility of using food waste as a binder to produce charcoal briquettes, instead of the currently popular cassava starch. This is because starch sources such as cassava starch are costly and competitive with food resources, while food waste is a completely waste product that is abundant and readily available. Therefore, the use of food waste is feasible, efficient, and beneficial.

4. Conclusion

RSS and food waste have the feasibility to be used as raw materials and binders for charcoal briquette production, respectively. RSS charcoal briquettes with food waste binder at a C:B ratio of 10:1 (v/v) are suitable due to their highest heating value of 6,219 ± 229 cal/g and relatively high compressive strength of 53.29 ± 2.91 N/cm^2. When comparing the characteristics of these suitable briquettes with those of the control, TISI-standard, and the literature, it was found that the results were satisfactory. These briquettes can be applied for domestic use, i.e., cooking and heating. Some parameters, especially compressive strength, need to be improved by modifying food waste with heat or chemicals to increase their adhesive properties. Improving these processes may cause the charcoal particles to stick together more tightly, increasing the compressive strength of the briquettes. This can be achieved with further study.

5. Acknowledgements

The authors appreciate the Division of Biotechnology, Food Technology and Nutrition and Mechanical Engineering, Faculty of Technology, Udon Thani Rajabhat University for supporting this research.

6. References

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