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Research article

Recycling industrial ethanol waste to solid alcohol and improvement of its physical, chemical and fuel properties

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Abstract

Importance of the work: Ethanol waste from the herbal industry has potential as a raw material for recycling to solid alcohol production.

Objectives: To appraise the physical, chemical and fuel properties of solid alcohol using a water boiling test and heating values.

Materials & Methods: Testing involved solid alcohol produced from curing agents of cellulose, hydroxyethyl cellulose and hydroxypropyl methylcellulose (HPMC) with and without charcoals—bamboo charcoal (BC), cassava rhizome charcoal (CC) or activated carbon from cassava rhizome (AcC)—during 6 mth of storage.

Results: The analysis of the charcoals and activated carbon showed that BC had better chemical properties than CC and AcC, respectively, due to its lower moisture content, volatile matter and ash content; however, it had higher fixed carbon. The solid alcohol produced from HPMCBC had the best fuel properties based on the solid alcohol weight (21.7 g) and the highest total burning time (617–775 s) compared to the control without any curing agents or additives (18.4 g and 539–624 s, respectively). Adding AcC into the solid alcohol decreased its weight, increased the ash residue content, caused shrinkage and was unable to pass the boiling water test. Thus, mixing charcoal (but not activated carbon) into the solid fuel might be an option to study further.

Main finding: The control solid alcohol had calorific values in the range 4,750–4,990 kcal/kg that were considered adequate. This research proposed using HPMCBC and improving the chemical reaction and fuel properties for solid alcohol production and usage.

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Introduction

In recent years, the health food and pharmaceutical industries have developed interesting products to help consumers take care of their health, with manufacturing and scaling up of bioactive compounds from herbal plants producing a large amount of alcohol waste as solvent or co-solvent (Hassim et al., 2021). Nowadays, in Thailand, the manufacture of herbal extracts by emerging industries has used ethanol as a solvent, such as extracts from bastard oleaster, black ginger and tamarind in food and pharmaceutical industries, with ethanol produced as a by-product from the herbal extract production process (Expert Center of Innovative Herbal Products, 2017; Expert Center of Innovative Health Food, 2018). The ethanol is generated mainly during the evaporation and drying of herbal extracts; some herbal companies produce approximately 30 t of fine wastes biomass of the herbs annually (Sienkiewicz et al., 2020). The oily, solid wastes from the herbal industry are currently used in biogas, pellet or briquette production or for bioconversion into vermicompost and food waste composting (Sienkiewicz et al., 2020), whereas the liquid ethanol waste may be converted into solid alcohol for use as solid fuel, with the liquid alcohol being solidified using additives (Kulwattanaporn, 2000). Solid alcohol is a portable flammable fuel that is safe and convenient and provides a stable fire temperature and low deviation in heat value (Du et al., 2013). In general, solid alcohol is used in the food services and tourism industries and in field work (Du et al., 2013). Currently available forms of solid alcohol have low storage stability and can turn soft and leak after a period of storage (Du et al., 2013; Khampha et al., 2020). Most solid alcohol production uses nitrocellulose as a curing agent; however, according to Thai Industrial Standard (2004), nitrocellulose must not be detectable in solid alcohol fuel. Hydroxyethyl cellulose (HEC) is a possible curing agent (Knight and Morgan, 2019). Adding agricultural residues could improve the fuel properties via a reduction in the weight loss of the solid alcohol during storage (Khampha et al., 2020).

In Thailand, the annual production of cassava residues ranks third behind residues from sugarcane and rice (Jusakulvijit et al., 2021). Cassava is a crop grown largely in the northeastern, central and eastern areas of the country (Jusakulvijit et al., 2021). The large amount of biomass available as cassava residue and its potential energy of 1,312 kcal/kg (Department of Alternative Energy Development and Efficiency, 2012) suggest it could be a readily available and cost-effective material for conversion to solid fuel. Bamboo is a fast-growing plant that can be harvested after 3–4 yr without expensive production and maintenance requirements (Subyakto et al., 2012). Bamboo coal has inherent energy (4,398–7,904 kcal/kg) depending on the bamboo species and the carbonization temperature (Park et al., 2020). In addition, the physical properties, inorganic contents and fuel properties of the coal could be improved by increasing the carbonization temperature during the charcoal production process (Subyakto et al., 2012; Park et al., 2020).

Charcoal and solid alcohol properties can be evaluated based on their properties, thermal efficiency and shelf-life by conducting proximate analysis and determining their calorific values (lower and higher heating values) and energy density or thermal efficiency (Ibitoye et al., 2021). The chemical, thermal and fuel properties during 6 mth of storage should be determined to ensure they meet the standard requirements (Thai Industrial Standard Institute, 2004). Thus, the methodology of the current study involved two-step clarification. First, solid alcohol using ethanol waste was produced from the bastard oleaster extract industry with varying curing agents (hydroxyethyl cellulose (HEC), hydroxypropyl methylcellulose (HPMC) and cellulose) and/or charcoal (bamboo coal, cassava coal and activated cassava coal). Second, the aim of the study was to evaluate the physical, chemical and fuel properties of the solid alcohol produced.

Materials and Methods

Ethanol waste from industrial extraction of Elaeagnus latifolia (bastard oleaster)

The ethanol was sourced from waste from the industrial extraction of bastard oleaster at the Thailand Institute of Scientific and Technological Research, Pathum Thani, Thailand. The extraction process used 20% ethanol in the ratio of 1:20 (bastard oleaster powder-to-ethanol) at 50 ± 2 °C, for 2 h. The extract was stirred every 15 min and the bastard oleaster residue was filtered from the aqueous solution with total dissolved solids of 2ºBrix under low pressure (0–200 millibars) at 45±5 °C until the extract had total dissolved solids of 10ºBrix. The used ethanol solvent after extraction was removed by evaporation and the concentration was determined. Ethanol with a concentration above 95% was used for solid alcohol production (Niwaspragit and Noichumpae, 2016).

Preparation of charcoal and activated carbon from bamboo and cassava

Due to their good thermal properties and abundant availability, the stems of *Bambusa beechyana* Munro (bamboo stems) and the rhizomes of *Manihot esculenta* Crantz (cassava rhizomes) from a local area in Chonburi province, Thailand were used to produce charcoal. The bamboo stems were collected and carbonized in a 200 L container at approximately 300–600 °C for 6 h. The charcoal produced from the bamboo was ground and passed through a 212 µm sieve and used as the solid component in solid alcohol production and was designated as bamboo coal (BC). The cassava rhizome was collected from the field 1 mth after harvesting the cassava tubers and carbonized in a 200 L container at approximately 300–600 °C for 6 h. After carbonization, the cassava charcoal was divided into two portions (charcoal and activated carbon). The charcoal was ground and passed through a 212 µm sieve and designated as cassava coal (CC). The second portion was carbonized a second time at 700 °C in a furnace with chemical activation using 85% H_3PO_4 in the ratio of 1:1 for 12 h. Then, the activated carbon (AcC) was dried at 60 °C for 24 h before being subjected to pyrolysis at 800 °C in the furnace, after which it was washed with 5N HCl, 22 N HF and water until the pH of the washing solution was neutral (Thammee et al., 2012). Proximate analysis of the BC, CC and AcC was used to determine their ash residue and moisture contents and their amounts of volatile matter and fixed carbon, following the American Society for Testing and Materials Standard (ASTM D7582, 2015; ASTM D5373, 2016), while the thermal properties (higher and lower heating values) were analyzed using a bomb calorimeter (PARR 6300; USA) according to ASTM D5865 (2013).

Solid alcohol production

A sample (1 L) of ethanol was warmed at a controlled internal solution temperature of approximately 60 °C and then 56 g of stearic acid was dissolved into the warmed ethanol (Du et al., 2013). The curing agents used in this study were HEC, cellulose and HPMC and the charcoals and the activated carbon used were BC, CC and AcC, as mentioned above. Mixes of 30 g or 60 g of the sole curing agent (HEC, cellulose or HPMC; commercial grade) and the sole charcoal/activated carbon (BC, CC or AcC) were added into the stearic acid-ethanol solution before adding 16.7% w/v NaOH (120 mL) into the mixture. Before the fuel solidified, the solution was poured into a container and enclosed using polyethylene film and kept in a closed container. The solid alcohol was kept for 6 mth and sampled for property testing at 0 mth, 1 mth, 2 mth, 3 mth, 4 mth and 6 mth (Khampha et al., 2020). The experimental sets of solid alcohol are shown in Table 1.

Table 1 Experimental sets of solid fuel alcohol samples

Formula	Curing agent	Charcoal/activated carbon
Control	-	-
HEC	HEC	-
Cellulose	Cellulose	-
HPMC	HPMC	-
Bamboo coal (BC)	-	Bamboo coal (BC)
HECBC	HEC	Bamboo coal (BC)
CelluloseBC	Cellulose	Bamboo coal (BC)
HPMCBC	HPMC	Bamboo coal (BC)
Cassava coal (CC)	-	Cassava coal (CC)
HECCC	HEC	Cassava coal (CC)
CelluloseCC	Cellulose	Cassava coal (CC)
HPMCCC	HPMC	Cassava coal (CC)
Activated cassava (AcC)	-	Activated cassava (AcC)
HECAcC	HEC	Activated cassava (AcC)
CelluloseAcC	Cellulose	Activated cassava (AcC)
HPMCAcC	HPMC	Activated cassava (AcC)

HEC = hydroxyethyl cellulose; HPMC = hydroxypropyl methylcellulose.

Property testing of solid alcohol

Physical, chemical and thermal properties

The physical properties of the different solid alcohol samples were analyzed for solid alcohol weight, ash residue content and burning rate. The thermal properties of the solid alcohol (based on the higher heating value) were analyzed using a bomb calorimeter (PARR 6300, USA) according to ASTM D5865 (2013).

Fuel properties: Water boiling test

Distilled water (100 mL) was used in this test in a 250 mL beaker. The boiling test of the solid alcohol was used to determine the boiling time, rolling boil time and total burning time (Du et al., 2013; Khampha et al., 2020). The heating value and the water boiling tests were carried out after storage periods of 0 mth, 1 mth, 2 mth, 3 mth, 4 mth and 6 mth.

Statistical analysis

All experiments were done in triplicate and the analyses were performed using the SPSS program (SPSS Inc.; USA). Data were subjected to analysis of variance with differences determined based on Tukey's honestly significant difference. All tests were considered significant at $p < 0.05$.

Results

Proximate analysis and thermal properties of bamboo coal, cassava coal and activated cassava coal

Proximate analysis was conducted to determine the contents of moisture, volatile matter, fixed carbon and ash of the charcoal and activated carbon prepared from the bamboo coal, cassava coal and activated cassava coal. The bamboo and cassava coals had significantly lower moisture contents (8.67% and 8.80%, respectively, Table 2) than the activated cassava coal (13.33%). The bamboo coal had a significantly lower content of volatile matter (15.72%) than the cassava coal and activated cassava coal (20.48% and 20.80%, respectively) with a significantly higher content of fixed carbon (69.16%) and a significantly lower content of ash (6.44%). Lower contents of moisture, volatile matter and ash but a higher content of fixed carbon in the charcoal could be indicators of good performance by a solid fuel (Chen et al., 2009). Thus, the bamboo coal had improved solid fuel characteristics compared to the cassava coal and activated cassava coal, respectively.

The lower (net) and higher (gross) heating values of the coal and activated carbon are shown in Fig. 1. The higher heating value is based on the lower heating value with the addition of the heat of vaporization of the water content in the fuel. Bamboo coal had significantly greater lower and higher heating values (6,610 kcal/kg and 6,765, respectively, Fig. 1) than those of the cassava coal (5,750 kcal/kg and 5,922 kcal/kg, respectively) and activated cassava (5,223 kcal/kg and 5,341 kcal/kg, respectively). These results showed that the bamboo charcoal had high heating values of over 6,000 kcal/kg; thus, it had potential as a solid fuel for cooking purposes (Ministry of Industry, 2004a). Bamboo coal may have greater potential than cassava coal and activated cassava coal due to its higher lower heating value.

Physical appearance of solid alcohol

The solid alcohol samples produced with and without curing agent appeared homogeneously white in color, while those with charcoal or activated carbon were homogeneously black (Fig. 2). During storage for 6 mth, some formulas gradually changed in color (from black to brown) and in appearance (shrinking), which might have been related to other properties, such as the solid alcohol weight, ash residue content and burning rate (Tables 4–6).

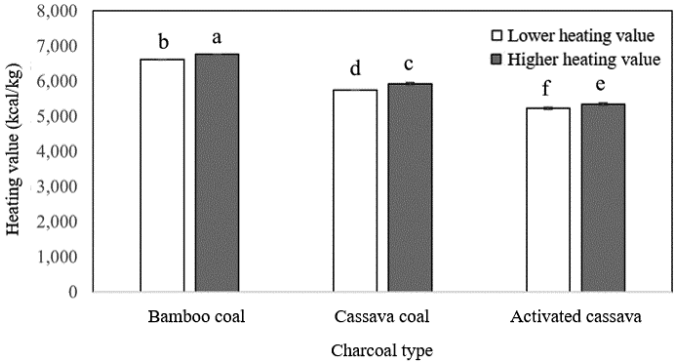

Fig. 1 Lower heating value and Higher heating values of Bamboo coal, Cassava coal and Activated cassava coal, where error bars indicate ± SD and different lowercase letters above bars indicate significantly ($p < 0.05$) different

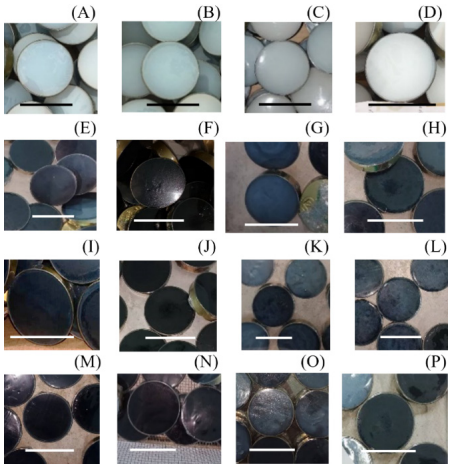

Fig. 2 Optical appearance of solid alcohol at month 0 of production: (A) control; (B) HEC; (C) HPMC; (D) cellulose; (E) HECBC; (F) HPMCBC; (G) celluloseBC; (H) BC; (I) HECCC; (J) HPMCCC; (K) celluloseCC; (L) CC; (M) HECAcC; (N) HPMCAcC; (O) celluloseAcC; (P) AcC, where scale bars = 5 cm; see Table 1 for formulas of different samples

Table 2 Proximate analysis (mean ± SD) of bamboo coal, cassava coal and activated cassava coal

Charcoal	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)
Bamboo coal	8.67±0.07^{b}	15.72±0.18^{b}	69.16±0.23^{a}	6.44±0.15^{b}
Cassava coal	8.80±0.09^{b}	20.48±0.16^{a}	57.57±0.45^{b}	13.16±0.44^{a}
Activated cassava	13.33±0.27^{a}	20.80±0.45^{a}	52.64±0.19^{c}	13.23±0.30^{a}

Mean±SD in the same column superscripted with different lowercase letters are significantly ($p < 0.05$) different (a > b > c).

Thermal properties of solid alcohol

The thermal properties of the solid alcohol are shown in Table 3. The higher heating values of all sets of solid alcohol kept for 0 and 6 mth were not significantly decreased, except for the HPMC, HPMCBC, and HPMCAcC solid alcohol samples. After storage for 6 mth, only the higher heating value of the HPMCAcC solid alcohol sample (5,234 kcal/kg, Table 3) was significantly lower than that of the control solid alcohol sample (5,584 kcal/kg, Table 3). The high levels of all heating values showed that the solid alcohol had good thermal properties. Furthermore, the control samples of solid alcohol without any curing agent or additive had lower heating values at the high level, based on the solid fuel alcohol standard of 4,800 kcal/kg (Thai Industrial Standards Institute, 2004). The lowest heating values of the control solid alcohol kept for 1 mth, 2 mth, 4 mth and 6 mth were 4,990 kcal/kg, 4,850 kcal/kg, 4,750 kcal/kg and 4,960 kcal/kg, respectively (data not shown). Thus, the alcohol waste from the herb and food industry has potential for recycling and the production of solid alcohol.

Table 3 Higher heating values (meanSD) of solid alcohol samples (kilocalories per kilogram)

Formula	Storage (mth)				
	0	1	2	4	6
Control	5,553.93±6.38^{abcA}	5,501.35±40.85^{abAB}	5,473.89±14.38^{abAB}	5,381.71±16.61^{defB}	5,583.59±41.87^{aA}
HEC	5,574.01±30.13^{abcA}	5,421.17±16.55^{bcdC}	5,489.58±21.37^{aB}	5,490.75±21.71^{aB}	5,527.33±11.15^{aAB}
Cellulose	5,583.72±20.77^{abA}	5,527.87±49.25^{aA}	5,418.72±7.70^{abcdA}	5,443.04±214.18^{abcdA}	5,409.26±28.17^{abA}
HPMC	5,616.38±22.69^{aA}	5,238.79±76.70^{eD}	5,482.04±20.47^{aB}	5,345.20±10.70^{efCD}	5,432.23±8.36^{abBC}
BambooCoal	5,542.55±26.74^{abcdA}	5,475.92±10.56^{abcAB}	5,467.13±30.01^{abAB}	5,415.47±67.84^{abcdeB}	5,488.11±32.20^{abAB}
HECBC	5,516.46±34.80^{bcdefA}	5,487.56±22.56^{abcB}	5,378.12±25.47^{cdefgA}	5,482.23±2.40^{aA}	5,493.61±17.11^{aA}
CelluloseBC	5,499.58±20.09^{cdefA}	5,410.39±6.07^{bcdBC}	5,400.10±27.13^{bdefC}	5,468.85±40.10^{abAB}	5,496.49±33.53^{aA}
HPMCBC	5,534.45±43.36^{abcdeA}	5,459.17±27.28^{abcdAB}	5,432.96±23.73^{abcAB}	5,463.42±176.21^{abcAB}	5,336.02±4.82^{abB}
CassavaCoal	5,461.87±8.81^{defAB}	5,388.60±54.38^{cdAB}	5,387.22±17.14^{cdefAB}	5,381.87±12.52^{defB}	5,463.25±20.71^{abA}
HECCC	5,504.35±48.89^{bcdefA}	5,513.19±9.54^{abA}	5,351.04±21.33^{defgB}	5,402.17±20.43^{bcdeB}	5,541.78±11.79^{aA}
CelluloseCC	5,553.85±20.26^{abcA}	5,453.11±45.41^{abcdAB}	5,312.49±51.75^{fgC}	5,405.40±40.70^{bcdeBC}	5,550.41±6.75^{aA}
HPMCCC	5,501.58±29.88^{bcdefA}	5,482.51±21.17^{abcA}	5,377.73±28.22^{cdefgB}	5,455.63±0.74^{abcdA}	5,470.29±35.27^{abA}
ActivatedCassava	5,435.25±20.03^{fA}	5,421.15±14.12^{bcdA}	5,326.81±20.96^{efgB}	5,181.88±14.98^{gC}	5,462.02±28.53^{abA}
HECAcC	5,441.85±25.00^{fB}	5,422.58±13.38^{bcdB}	5,420.17±13.44^{abcdB}	5,387.77±26.57^{cdefB}	5,557.48±43.19^{aA}
CelluloseAcC	5,452.58±20.79^{efA}	5,371.08±12.75^{dB}	5,350.43±16.24^{defgB}	5,218.12±8.43^{gC}	5,509.00±43.49^{aA}
HPMCAcC	5,442.80±25.08^{fA}	5,507.56±31.39^{abA}	5,302.87±28.36^{gBC}	5,320.77±25.58^{fB}	5,234.41±21.19^{bC}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

Table 4 Solid alcohol weights (mean ± SD in grams) of samples

Formula	Storage (mth)				
	0	1	2	3	6
Control	18.36±0.08^{bA}	18.64±0.62^{aA}	18.09±0.30^{aA}	16.84±0.70^{cdeA}	16.80±2.52^{bcA}
HEC	19.86±0.15^{abA}	19.58±0.70^{aAB}	17.40±0.69^{aC}	18.10±0.48^{abcdBC}	17.89±0.86^{abC}
Cellulose	20.15±0.31^{abA}	19.10±0.86^{aA}	19.00±0.75^{aAB}	17.29±0.65^{abcdeB}	18.46±0.58^{abAB}
HPMC	19.61±0.32^{abA}	19.35±0.14^{aA}	19.67±1.25^{aA}	19.53±0.75^{aA}	18.56±0.99^{abA}
BambooCoal	20.47±0.74^{abA}	19.21±1.52^{aA}	18.30±1.79^{aA}	19.55±0.79^{aA}	16.64±1.99^{bcdA}
HECBC	19.44±1.52^{abA}	18.88±1.17^{aA}	18.87±0.51^{aA}	18.25±0.40^{abcdA}	17.33±0.89^{abcA}
CelluloseBC	19.46±0.29^{abA}	18.75±0.30^{aAB}	18.61±0.35^{aAB}	18.12±0.48^{abcdBC}	17.03±0.84^{abcC}
HPMCBC	21.71±0.46^{aA}	19.38±0.96^{aAB}	18.92±0.95^{aB}	18.67±1.27^{abcB}	18.28±0.77^{abB}
CassavaCoal	20.50±0.35^{abA}	19.06±0.74^{aA}	18.85±0.20^{aA}	19.06±0.55^{abcA}	15.43±1.45^{bcdB}
HECCC	20.75±0.10^{abA}	19.42±1.03^{aAB}	18.64±1.03^{aB}	18.72±0.53^{abcB}	18.04±0.19^{abB}
CelluloseCC	19.29±0.77^{abA}	18.98±0.89^{aA}	18.48±1.80^{aAB}	17.01±0.27^{bcdeAB}	15.57±1.10^{bcdB}
HPMCCC	20.81±0.89^{abAB}	18.98±1.07^{aB}	19.58±0.63^{aB}	19.31±1.38^{abB}	23.19±1.20^{aA}
ActivatedCassava	19.77±1.20^{abA}	18.49±0.68^{aA}	17.42±1.07^{aA}	17.84±1.08^{abcdA}	8.26±4.07^{eB}
HECAcC	19.94±0.58^{abA}	19.18±1.67^{aA}	17.69±0.68^{aAB}	19.02±0.90^{abcA}	15.11±1.12^{bcdB}
CelluloseAcC	19.37±1.53^{abA}	17.58±0.32^{aA}	17.14±0.23^{aA}	15.90±0.54^{deA}	11.19±2.64^{cdeB}
HPMCAcC	20.65±1.82^{abA}	18.31±1.39^{aA}	18.18±0.62^{aA}	15.21±1.18^{eAB}	10.34±5.12^{deB}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples

Table 5 Ash residue contents (mean ± SD in grams) of solid alcohol samples

Formula	Storage (mth)				
	0	1	2	3	6
Control	1.72±0.04^{cA}	1.92±0.05^{efA}	2.00±0.13^{cdA}	1.92±0.19^{fA}	1.84±0.31^{aA}
HEC	2.28±0.15^{abcA}	2.12±0.17^{defA}	2.00±0.19^{cdA}	2.04±0.07^{fA}	2.24±0.15^{aA}
Cellulose	2.12±0.19^{abcA}	2.31±0.24^{cdefA}	2.55±0.31^{abcdA}	2.40±0.11^{defA}	2.49±0.17^{aA}
HPMC	1.77±0.03^{cA}	1.75±0.10^{fA}	1.76±0.11^{dA}	1.90±0.08^{fA}	1.91±0.07^{aA}
BambooCoal	2.74±0.07^{aA}	2.72±0.24^{abcdA}	2.67±0.24^{abcA}	3.08±0.22^{abcdA}	2.68±0.13^{aA}
HECBC	2.15±0.30^{abcA}	2.39±0.26^{cdefA}	2.58±0.38^{abcdA}	2.83±0.41^{abcdeA}	2.95±0.41^{aA}
CelluloseBC	2.36±0.02^{abcA}	2.42±0.09^{cdeAB}	2.90±0.12^{abB}	2.91±0.09^{abcdeB}	2.73±0.38^{aAB}
HPMCBC	2.33±0.11^{abcA}	2.36±0.12^{cdefA}	2.83±0.37^{abcA}	2.60±0.10^{bcdefA}	2.69±0.43^{aA}
CassavaCoal	2.22±0.05^{abcA}	2.90±0.18^{abcB}	3.12±0.37^{abB}	3.13±0.11^{abcB}	2.77±0.22^{aAB}
HECCC	2.21±0.02^{abcA}	2.35±0.15^{cdefAB}	3.05±0.18^{abC}	3.41±0.12^{aD}	2.68±0.12^{aB}
CelluloseCC	1.98±0.09^{bcA}	2.48±0.27^{abcdeB}	2.59±0.04^{abcdB}	2.93±0.22^{abcdeB}	2.57±0.13^{aB}
HPMCCC	2.42±0.18^{abA}	2.24±0.06^{defA}	2.31±0.05^{bcdA}	2.55±0.25^{cdefA}	2.46±0.10^{aA}
ActivatedCassava	2.61±0.32^{abA}	3.11±0.24^{aA}	2.89±0.22^{abA}	2.76±0.23^{abcdeA}	3.51±1.55^{aA}
HECAcC	2.30±0.33^{abcA}	2.45±0.26^{bcdeA}	2.27±0.12^{bcdA}	2.57±0.23^{bcdefA}	2.22±0.18^{aA}
CelluloseAcC	2.59±0.45^{abA}	3.09±0.12^{abA}	3.30±0.61^{aA}	3.27±0.58^{abA}	2.88±0.47^{aA}
HPMCAcC	2.42±0.36^{abA}	2.50±0.49^{abcdeA}	2.71±0.37^{abcA}	2.34±0.06^{efA}	3.68±1.70^{aA}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

Table 6 Burning rates (mean ± SD in seconds per gram) of solid alcohol

Formula	Storage (mth)				
	0	1	2	3	6
Control	32.82±0.52^{bcA}	33.46±0.96^{abA}	32.83±0.59^{abA}	32.31±1.45^{bcdeA}	32.22±1.53^{bcA}
HEC	39.22±0.85^{abA}	36.31±0.26^{aAB}	34.98±1.87^{abBC}	34.76±2.24^{abcdBC}	32.48±0.72^{bcC}
Cellulose	30.39±0.65^{cB}	30.93±0.32b^{AB}	31.42±0.88^{abAB}	32.61±1.14^{abcdeA}	31.92±0.37^{cAB}
HPMC	33.99±2.59^{bcA}	34.29±2.66^{abA}	33.19±0.90^{abA}	33.46±1.66^{abcdeA}	32.81±0.65^{bcA}
BambooCoal	31.07±0.96^{cB}	33.68±1.53^{abAB}	33.64±0.19^{abAB}	34.03±1.37^{abcdeA}	35.20±0.72^{bcA}
HECBC	33.18±0.85^{bcAB}	33.78±0.84^{abAB}	35.13±1.07^{abA}	32.78±0.86^{abcdeB}	34.59±0.61^{bcAB}
CelluloseBC	30.91±0.82^{cB}	32.75±0.41^{abAB}	34.75±0.54^{abA}	35.74±2.18^{abcA}	33.51±1.51^{bcAB}
HPMCBC	35.71±2.57^{abcA}	31.87±0.80^{bA}	35.01±3.44^{abA}	36.89±1.45^{abA}	34.80±2.09^{bcA}
CassavaCoal	31.30±1.43^{cA}	32.66±1.22^{abA}	31.54±1.58^{abA}	32.87±1.78^{abcdeA}	32.74±1.04^{bcA}
HECCC	34.66±0.54^{abcAB}	33.84±0.35^{abAB}	33.17±0.43^{abB}	33.61±0.93^{abcdeAB}	35.67±1.42^{bA}
CelluloseCC	31.90±0.79^{cA}	31.62±2.29^{bA}	30.77±1.02^{bAB}	29.62±1.81^{eAB}	26.33±2.06^{dB}
HPMCCC	41.16±5.56^{aA}	33.24±0.79^{abBC}	35.97±0.99^{aAB}	37.16±1.32^{aAB}	27.20±0.18^{dC}
ActivatedCassava	32.66±1.79^{cA}	33.46±2.42^{abA}	32.58±0.91^{abA}	34.63±0.94^{abcdA}	33.48±0.00^{bcA}
HECAcC	36.26±2.69^{abcA}	34.96±0.90^{abA}	35.26±0.96^{abA}	35.19±1.12^{abcdA}	34.65±0.74^{bcA}
CelluloseAcC	31.12±1.03^{cA}	33.01±1.59^{abA}	32.22±2.15^{abA}	30.86±2.10^{deA}	34.13±0.62^{bcA}
HPMCAcC	32.77±3.44^{bcB}	34.01±1.48^{abB}	35.79±3.24^{aAB}	31.94±0.97^{cdeB}	42.39±0.15^{aA}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

Chemical properties of solid alcohol

The chemical properties of the solid alcohol were determined in terms of weight, ash residue content and burning rate (Tables 4–6). The solid alcohol weight in most of the formulas significantly decreased after 1 mth of storage (from 19.3–20.8 g in the month of production to 8.3 –18.0 g in month 6, Table 4). The control, cellulose, HPMC, BC, HECBC and HPMCCC solid alcohol samples did not significantly decrease in their weights after storage for 6 mth. Thus, the curing agents (cellulose and HPMC) and the charcoals (BC and CC) might have potential for improving the solid

alcohol weight and other properties. The control and most of the solid alcohol formulas did not significantly increase the ash residue contents after 2 mth of storage (1.7–2.7 g in month 0 and 1.8–3.3 g in month 2, Table 5). However, the ash residue contents of celluloseCC and HECCC significantly increased after 1 mth and 2 mth of storage (2.5 g and 3.1 g, respectively) compared to the month of production (2.0 g and 2.2 g, respectively, Table 5). Most of the solid alcohol formulas were not significantly different in burning rates throughout their 6 mth storage periods, except for the HEC, celluloseCC and HPMCCC solid alcohols (31.9–41.2 s/g in month 0 and 26.3–32.5 s/g at month 6, Table 6). This might have been affected by the total burning time and lost weight during storage. Thus, using CC as an additive in solid alcohol might not increase the inflammable solid fuel property during 6 mth of storage.

Notably, the different solid alcohol formulas had significantly different weights, ash residue contents and burning rates (Tables 4–6). The control solid alcohol was significantly lower in weight compared to the HPMCBC solid alcohol formulas in the month of production (Table 4). Although the weight of HPMCBC reduced during storage for 6 mth, the weights of the control and HPMCBC solid alcohol samples were not significantly different. The net weight should always be above the minimum weight specified by Thai Industrial Standards Institute (2004). The solid alcohol formation by chemical reaction might be involved in weight loss during storage (Equations 1–2). Because the byproduct of the reaction is H_2O, this might disappear during storage. Although cellulose $(C_6H_{10}O_5)_n$, HEC $(C_{29}H_{52}O_{21})$ and HPMC $(C_{56}H_{108}O_{30})$ have different molecular weights and densities, the formulas with different additives might have influenced similar weight losses.

$$\underset{\text{Steric acid + Ethanol}}{CH_3\text{-}(CH_2)16\text{-}COOH + C_2H_5OH} \xrightarrow{NaOH} \underset{\text{Solid alcohol + Water}}{CH_3\text{-}(CH_2)_{16}\text{-}COO\text{-}C_2H_5 + H_2O} \quad (1)$$

$$\underset{\text{Steric acid + Ethanol + HPMC}}{CH_3\text{-}(CH_2)_{16}\text{-}COOH + C_2H_5OH + C_{56}H_{108}O_{30}} \xrightarrow{NaOH} \underset{\text{Solid alcohol—HPMC as curing agent + Water}}{CH_3\text{-}(CH_2)_{16}\text{-}COO\text{-}C_2H_5\text{---}\ C_{56}H_{108}O_{30} + H_2O} \quad (2)$$

The control and HPMC solid alcohol samples had the significantly lowest ash residue contents compared to the solid alcohol samples containing charcoal in the month of production (month 0; BC and AcC, Table 5). Adding charcoal may have increased the ash residue contents after burning the fuel. The AcC solid alcohol sample and those mixed with HEC, cellulose and HPMC had significantly increased ash residue contents in the month of production compared to the control. This might have been due to the AcC interacting with the HEC, cellulose, HPMC or solid alcohol itself and forming material that raised the fire-point temperature in the burning reaction that could not be burnt and consequently remained as residue. Although the ash residue contents of all solid alcohol samples were in the range 9–13% of their weights in the month of production, the AcC sample shrank after 6 mth of storage and retained a high ash residue content with residue (42%; 3.51 g, Table 5) that did not burn; thus, AcC might not be suitable as an ingredient for solid alcohol production.

There was a significant difference in the burning rates of the control solid alcohol sample compared to the HPMCCC solid alcohol (month 0, Table 6). Adding HPMC and charcoal CC significantly increased the burning rate (41 s/g) of the solid alcohol compared with the control (39 s/g), while the other formulas (cellulose, BC, celluloseBC, CC, celluloseCC, ArC and celluloseAcC) had significantly lower burning rates. The cellulose or sole charcoal and activated carbon samples did not perform well as curing agent and additives for solid alcohol production. Notably HPMC mixed with activated carbon (AcC) could enhance solid alcohol storage at 6 mth, with a significantly higher burning rate of 42 s/g. The activated carbon property might be involved in HPMC curing characteristics.

Fuel property of solid alcohol

A shorter water boiling time indicates a better fuel property for producing heat energy when burning solid alcohol. There was an increase in the boiling time with increased storage (Table 7). The boiling times of the solid alcohol samples were in the range 205–307 s in the month of production, whereas after 6 mth of storage, the boiling times were in a higher range (270–352 s). Most of the solid alcohol formulas, including the control, significantly increased the boiling times, except for the BC, HECBC, CC, HECCC and HPMCCC solid alcohol samples that maintained this property. Thus, adding a curing agent (HEC or HPMC) or charcoal (BC or CC) or both might improve the boiling time of the solid alcohol. The comparable boiling times of the control with most of the solid alcohol formulas in the month of production were not significantly different, while the HPMCCC samples had a significantly higher boiling time (307.4 g, Table 7) compared with the control (221.9 s, Table 7). Mixing CC with HPMC increased the ash residue (month 0, Table 5) and increased the burning rate (month 0, Table 6) but did not improve the boiling time compared to the control (month 0, Table 7). In addition, the AcC solid alcohol samples could not boil water after being kept for 6 mth, confirming that it was not appropriate for use as an ingredient in solid alcohol (Table 5 and 7).

Table 7 Boiling times (mean ± SD in seconds) of solid alcohol samples

Formula	Storage (mth)				
	0	1	2	3	6
Control	221.92±11.16^{bA}	253.72±15.45^{abAB}	252.75±10.99^{abcAB}	264.51±14.15^{bcdB}	279.52±14.38^{aB}
HEC	206.76±12.87^{bA}	242.07±15.26^{bAB}	255.99±12.45^{abcB}	234.29±5.21^{dAB}	272.05±22.18^{aB}
Cellulose	210.46±2.80^{bA}	279.24±28.29^{abBC}	247.83±12.29^{bcAB}	255.00±10.13^{cdB}	308.94±15.89^{aC}
HPMC	204.78±6.28^{bA}	254.40±13.27^{abBC}	237.74±7.81^{cB}	260.72±5.25^{bcdBC}	270.25±19.18^{aC}
BambooCoal	242.52±17.80^{abA}	289.88±12.48^{aA}	273.04±8.53^{abcA}	267.94±9.77^{bcdA}	273.99±34.98^{aA}
HECBC	238.68±18.19^{abA}	279.28±19.96^{abA}	273.90±12.96^{abcA}	265.51±16.88^{bcdA}	291.88±52.45^{aA}
CelluloseBC	232.96±3.70^{bA}	270.58±10.23^{abB}	261.66±8.23^{abcAB}	271.33±14.35^{abcdBC}	308.17±24.11^{aC}
HPMCBC	242.54±24.50^{abA}	245.21±2.92^{abA}	263.11±12.62^{abcAB}	277.12±2.11^{abcAB}	324.78±50.15^{aB}
CassavaCoal	243.35±4.42^{abA}	265.82±9.01^{abA}	267.62±7.51^{abcA}	256.67±4.86^{bcdA}	276.67±30.68^{aA}
HECCC	245.39±8.47^{abA}	262.47±20.17^{abA}	263.37±7.25^{abcA}	272.75±16.91^{abcA}	280.75±9.33^{aA}
CelluloseCC	240.35±13.29^{abA}	262.28±2.32^{abAB}	287.67±23.09^{aBC}	253.38±7.61^{cdAB}	318.70±17.54^{aC}
HPMCCC	307.39±75.23^{aA}	256.73±3.56^{abA}	265.00±5.77^{abcA}	254.62±8.60^{cdA}	307.37±7.88^{aA}
ActivatedCassava	247.81±6.40^{abA}	277.94±28.96^{abA}	265.97±10.06^{abcA}	290.90±22.04^{abcA}	0.00±0.00^{bB}
HECAcC	253.38±14.18^{abA}	272.42±5.02^{abAB}	280.44±19.32^{abAB}	294.76±5.54^{abB}	325.25±2.61^{aC}
CelluloseAcC	247.69±12.85^{abA}	274.74±13.27^{abAB}	287.36±9.83^{aABC}	307.86±24.12^{aBC}	331.06±15.70^{aC}
HPMCAcC	245.53±32.43^{abA}	247.09±6.52^{abA}	250.40±22.33^{abcA}	277.15±9.51^{abcA}	351.51±0.00^{aB}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

In contrast to the boiling time, a longer rolling boil time indicates a better solid alcohol fuel in producing heat energy. Table 8 shows that increasing the storage of the solid alcohol decreased the rolling boil time compared to the month of production (month 0). The rolling boil times in the month of production were in the range 325–454 s and those after 6 mth of storage were in the range 61–308 s. The control solid alcohol did not have a significantly different rolling boil time compared to the other solid alcohol formulas in the month of production. The AcC solid alcohol samples could not boil water after being kept for 6 mth (Table 8).

Table 8 Rolling boil times (mean ± SD in seconds) of solid alcohol samples

Formula	Storage (mth)				
	0	1	2	3	6
Control	334.85±17.44^{abA}	298.89±13.95^{bcAB}	282.57±8.20^{abAB}	237.34±29.13^{cdeB}	236.34±60.82^{abB}
HEC	426.32±19.00^{abA}	394.24±23.83^{aAB}	315.52±23.58^{abCD}	351.37±42.52^{abBC}	274.17±11.74^{abD}
Cellulose	389.34±25.51^{abA}	290.91±37.26^{cBC}	336.17±27.37^{abAB}	282.81±16.60^{abcBC}	238.59±8.63^{abC}
HPMC	443.03±36.94^{abA}	384.88±25.72^{abAB}	398.57±46.11^{aAB}	370.49±44.93^{aAB}	307.88±34.26^{aB}
BambooCoal	356.64±11.67^{abA}	268.28±34.18^{cAB}	287.12±48.11^{abAB}	322.56±25.40^{abcAB}	220.94±78.98^{abB}
HECBC	353.52±57.61^{abA}	304.90±52.46^{abcAB}	299.70±14.97^{abAB}	286.97±10.36^{abcAB}	217.00±19.59^{abB}
CelluloseBC	342.32±8.02^{abA}	285.83±34.50^{cA}	302.91±16.34^{abA}	284.79±31.27^{abcA}	194.40±12.65^{abcB}
HPMCBC	454.47±55.25^{aA}	267.46±16.54^{cB}	276.40±16.66^{abB}	278.80±7.94^{abcB}	215.33±48.58^{abB}
CassavaCoal	385.66±7.91^{abA}	282.48±28.63^{cBC}	281.06±23.77^{abBC}	308.42±27.94^{abcAB}	187.28±64.57^{abcC}
HECCC	424.50±30.26^{abA}	321.99±24.93^{abcAB}	351.95±129.45^{abAB}	263.02±32.42^{bcdAB}	252.64±18.34^{abB}
CelluloseCC	351.82±12.77^{abA}	309.99±19.66^{abcA}	282.30±55.84^{abA}	266.28±32.17^{bcdA}	152.84±59.63^{bcB}
HPMCCC	425.22±39.49^{abA}	316.16±28.25^{abcA}	316.13±27.61^{abA}	335.77±53.06^{abcA}	192.33±48.32^{abcB}
ActivatedCassava	343.68±44.08^{abA}	291.37±39.60^{cA}	260.04±37.66^{abA}	267.90±11.06^{bcdA}	0.00±0.00^{dB}
HECAcC	421.90±48.94^{abA}	296.75±27.07^{bcB}	321.86±21.40^{abAB}	310.36±48.61^{abcB}	170.26±32.90^{bcC}
CelluloseAcC	324.56±63.16^{bA}	257.54±8.85^{cAB}	223.24±35.53^{bAB}	160.78±35.56^{eBC}	60.56±20.79^{cdC}
HPMCAcC	372.38±83.27^{abA}	329.46±45.34a^{bcAB}	293.73±60.05^{abAB}	178.16±29.27^{deB}	245.85±0.00^{abAB}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

The total burning times of the solid alcohol samples are shown in Table 9. The longer the total burning time, the better the solid fuel. The total burning times of the HEC, CC, HECCC, HPMCCC, ArC, HECArC and celluloseArC samples in the month of production (604–855 s) were significantly higher than those after storage for 6 mth (381–643 s), whereas those of the control and other formulas were not significantly different (Table 9). The HEC, HPMCBC and HPMCCC solid alcohol samples had significantly higher total burning times (779, 775 and 855 s, respectively) than the control (602 s, Table 9). The HEC and HPMCCC solid alcohol samples had significantly decreased total burning times after storage for 6 mth, whereas the HPMCBC sample could maintain its total boiling time throughout storage for 6 mth (617–775 s, Table 9). This suggested adding HPMC and BC could improve solid alcohol properties, such as weight and total boiling time (Tables 4 and 9, respectively).

Discussion

The charcoal and activated carbon samples of BC, CC and AcC were examined for heating values and proximate analysis. The results showed that bamboo coal was the best solid fuel due to its highest heating value (6,610 kcal/kg) and fixed carbon content (69.2%), with the lowest contents of moisture (8.7%), volatile matter (15.7%) and ash (6.4%) compared to CC and AcC, respectively. Its qualities make it suitable as wood charcoal for cooking due to its low moisture content (< 10%), high heating value (> 6,000 kcal/kg), low ash residue content (< 8%) and low volatile matter (< 25%), based on the standards of the Ministry of Industry (2004a). The improvement of carbonization of bamboo charcoal may produce even better results regarding these chemical contents (Park et al., 2020), while also improving its suitability for grilling use, with very low volatile matter (< 8%) and moisture content (< 8%) and a low ash residue content (< 3%), based on the standards of the Ministry of Industry (2004b). The current study showed that bamboo charcoal was outstanding for conversion into solid fuel due to its high calorific value (6,610 kcal/kg, Fig. 1) and ready availability. Bamboo occupies 3.2% of the world's forest area, with approximately 65% of all bamboo being grown in Asia (Park et al., 2019). Most bamboo species are distributed in the tropical and temperate zones; in Southeast Asia, there are 311 bamboo species, with 80–100 species distributed throughout Thailand (Sungkaew et al., 2014). The bamboo used in the current study was Beechey or Silk-ball bamboo (*Bambusa beechyana* Munro) and its charcoal with added HPMC had significantly increased fuel properties in terms of the total burning time of the solid alcohol samples compared to the control solid alcohol.

The solid alcohol samples in the current study could maintain relatively high calorific values (5,182–5,616 kcal/kg). However, their lower weights and increased ash residue

Table 9 Total burning times (mean ± SD in seconds) of solid alcohol

Formula	Storage (mth)				
	0	1	2	3	6
Control	602.75±11.65^{cA}	623.83±29.42^{abA}	593.70±3.81^{abA}	544.57±44.61^{deA}	539.09±58.39^{abcA}
HEC	779.05±12.30^{abA}	710.91±20.21^{aAB}	607.77±18.45^{abC}	629.61±53.54^{abcdBC}	581.66±40.49^{abC}
Cellulose	612.38±21.72^{bcA}	590.58±22.90^{bA}	596.47±9.52^{abA}	563.81±24.80^{cdeA}	589.08±16.19^{abA}
HPMC	666.86±57.38^{bcA}	663.27±47.17^{abA}	652.68±42.36^{abA}	653.77±51.89^{abcdA}	609.06±38.65^{aA}
BambooCoal	635.83±22.38^{bcA}	645.99±40.39^{abA}	615.64±58.34^{abA}	665.41±36.22^{abcA}	585.66±69.02^{abA}
HECBC	644.76±43.34^{bcA}	638.13±47.85^{abA}	662.42±10.25^{abA}	598.08±5.93^{bcdeA}	599.78±38.79^{abA}
CelluloseBC	601.63±14.50^{cAB}	614.03±11.10^{abAB}	647.02±21.81^{abA}	647.22±34.38^{abcdA}	569.98±5.45^{abB}
HPMCBC	774.97±51.86^{abA}	617.36±22.85^{abA}	664.37±97.34^{abA}	688.64±49.29^{abA}	636.92±59.25^{aA}
CassavaCoal	641.24±18.46^{bcA}	622.08±2.15^{abA}	594.52±30.97^{abA}	626.05±27.70^{abcdA}	504.10±33.66^{abcB}
HECCC	719.25±12.54^{abcA}	657.31±35.23^{abB}	617.96±26.37^{abB}	629.00±0.57^{abcdB}	643.45±21.07^{aB}
CelluloseCC	615.57±39.87^{bcAB}	646.14±41.43^{abA}	629.90±32.83^{abA}	584.98±27.10^{bcdeAB}	530.06±16.60^{abcB}
HPMCCC	855.40±109.33^{aA}	630.53±27.75^{abB}	704.38±37.95^{aAB}	717.51±52.11^{aAB}	630.89±36.80^{aB}
ActivatedCassava	644.32±10.40^{bcA}	619.10±57.15^{abA}	567.53±38.60^{bA}	618.15±47.19^{abcdA}	431.89±0.00^{bcB}
HECAcC	723.95±75.08^{abcA}	669.71±43.12^{abA}	623.38±7.25^{abAB}	669.87±53.28^{abcA}	523.55±39.59^{abcB}
CelluloseAcC	603.65±66.39^{cA}	580.83±38.13^{bA}	552.31±37.10^{bA}	489.95±19.95^{eAB}	380.85±84.03^{cB}
HPMCAcC	680.41±128.73^{bcA}	623.84±71.19^{abA}	649.20±36.39^{abA}	485.28±31.88^{eA}	539.28±179.08^{abcA}

Different lowercase or uppercase superscripts denote significant ($p < 0.05$) difference among means in the same column or the same row, respectively. See Table 1 for formulas of different samples.

contents after 2 mth of storage (HPMCBC and HECCC, Table 4; and HECCC and celluloseCC, Table 5) indicated degraded physical and chemical properties. Furthermore, the fuel property of boiling time increased, while the rolling boil time and total burning time decreased after 1 mth of storage (HPMC, Table 7; HPMCBC, CC, Table 8; HECCC, Table 9). The solid alcohol could have formed a chemical reaction between stearic acid and sodium hydroxide ($C_{17}H_{35}COOH + NaOH = C_{17}H_{35}COONa + H_2O$) that produced sodium stearate, which is a polar, long-chain carbon molecule that when heated, produces a three-dimensional net structure in the alcohol that after cooling for a while, would result in a solid structure based on the alcohol and sodium stearate molecules, which in turn could be used as solid alcohol (Du et al., 2013). There has been reported use of curing agents to extend storage, such as methylcellulose or ethylcellulose, which are cellulose derivatives that fix solid alcohol, (Knight and Morgan, 2019). Curing agents, including cellulose, are suitable for forming solid alcohol (Kulwattanaporn, 2000). The current results showed that HPMC could significantly increase fuel properties in terms of the rolling boil time of solid alcohol compared to the control, cellulose and HEC solid alcohol. The control solid alcohol in the current study was produced from ethanol waste from bastard oleaster extraction and its thermal qualities were good compared to the solid alcohol produced from the commercial ethanol waste from black ginger and tamarind seed extracts (Khampha et al., 2020). Based on storage for 6 mth, the current study indicated that the samples based on the bastard oleander extraction could maintain good heating values and burning rates (Tables 3 and 6).

The potential of cassava rhizome for conversion to heat energy has been supported by the estimate of electricity production in a biomass power plant being as high as 1,272 million kWh/yr or approximately 151.47 MW at 20% efficiency power plant operation for 350 d/yr (Department of Alternative Energy Development and Efficiency, 2012). The average values for residue-to-crop ratios indicate that much more cassava rhizome (0.35) is produced than other residues (0.12–0.28) and substantially more than the residues from sugarcane (0.25–0.31). In addition, its lower moisture content (29.6%) makes it suitable for conversion to biochar rather than other residues (stem, leaves, peel) and bagasse, rice straw, palm leaves and empty fruit bunches (33.9–72.5%, Jusakulvijit et al., 2021). The current study showed that charcoal from cassava rhizome with added HPMC could significantly increase fuel properties in terms of the total burning time of solid alcohol samples compared to the control solid alcohol sample.

Adding activated carbon from cassava rhizomes reduced the solid alcohol weight during storage for 6 mth from 19.8 g to 8.3 g, increased the ash residue content from 2.6 g to 3.5 g, reduced the total burning time from 644.3 s to 431.9 s and was unable to boil water in the water boiling test (Tables 4–5, and 7–9). The chemical activation process in the cassava rhizome might transform the material and change the fuel properties of cassava charcoal by reducing its heating value from 5,750 kcal/kg (cassava charcoal) to 5,223 kcal/kg (activated carbon, Fig. 1), increasing the moisture content from 8.8% (cassava charcoal) to 13.3% (activated carbon) and reducing the fixed carbon from 57.6% (cassava charcoal) to 52.6% (activated carbon, Table 2). The activated carbon from cassava charcoal had a clumped appearance with a high moisture content (> 10%); thus, it should not be used as an additive in solid alcohol. Examination of characteristics, such as the particle surface area, pore size and thermal stability, of cassava charcoal and activated carbon from cassava charcoal may need to be examined to clarify properties suitable for other purposes, such as an adsorbent.

In the current study, the control solid alcohol produced from industrial waste had a good range of heating values (5,381.7–5,583.6 kcal/kg, Table 1) and good fuel properties throughout storage for 6 mth (Tables 7–9). The solid alcohol formulated with HPMC resulted in much improved chemical (ash residue content) and fuel (rolling boil time) properties compared to the control solid fuel samples (Tables 5 and 8). During storage for 6 mth, the HPMC solid alcohol had ranges for the higher heating value of 5,239–5,616 kcal/kg, weight of 18.6–19.7 g, ash residue content of 1.8–1.9 g, burning rate of 32.8–34.3 s/g, boiling time of 204.8–270.3 s, rolling boil time of 307.9–443.0 s and total burning time of 609.1–666.9 s. Adding bamboo charcoal with HPMC increased the weight (18.3–21.7 g) and the total burning time to 617.4–775.0 s (Tables 4 and 9). Thus, the ethanol waste from the herb industry could be recycled to produce solid alcohol. Furthermore, adding HPMC as a curing agent and mixing with bamboo charcoal improved the solid alcohol properties of weight and total burning time. Adding activated carbon (AcC) into the solid fuel was not suitable due to its negative impact on burning properties. The solid alcohol produced in the current study had a high quality based on the industrial standard for solid fuel alcohol. Furthermore, the charcoal products in the current study could be readily produced by local communities and would be highly suitable for use as wood charcoal for cooking. The solid alcohol production in the current study could be easily upscaled to the pilot scale.

In conclusion, this study evaluated using industrial ethanol waste for the production of solid alcohol. The formation of solid alcohol with different curing agents was proposed. The chemical reaction of the solid alcohol with the best performance is shown in Equation 3:

$$\underset{\text{Steric acid + Ethanol + HPMC + BC}}{CH_3\text{-}(CH_2)_{16}\text{-}COOH + C_2H_5OH + C_{56}H_{108}O_{30} + BC} \xrightarrow{NaOH} \underset{\text{Solid alcohol---HPMC + BC+ Water}}{CH_3\text{-}(CH_2)_{16}\text{-}COO\text{-}C_2H_5\text{---}\ C_{56}H_{108}O_{30} + BC + H_2O} \quad (3)$$

The solid alcohol was formed by using steric acid and ethanol as starting materials and adding HPMC as a curing agent. The result showed that ethanol and stearic acid bonded to form ethyl stearate, a fatty acid ester. The hydroxy group of HPMC can have an intermolecular bond with the alkoxy carbonyl group of ethyl stearate (Equation 3), resulting in the possible formation of a long chain network (SandhyaRani et al., 2018). The current results suggests that the obtained solid alcohol had possibly interacted with HPMC via intermolecular forces, such as hydrogen bonding. Thus, it raised the fire-point temperature in the burning reaction of the solid alcohol and allowed a longer time for the gaseous state. Furthermore, HPMC has a more complex structure and a higher molecular weight than the other curing agents used in the current study. Consequently, it is likely to have better attraction to the solid alcohol than the other curing agents and to have better solid alcohol fuel properties, such as increased weight and a longer total burning time, when mixed with bamboo charcoal. Bamboo charcoal in HPMCBC solid alcohol might have micropores in the surface area of the particles that could interact or bind with ethyl stearate-HPMC complexation. Carbonized bamboo charcoal has been reported to have average iodine adsorption of 175 mg/g at 200–1,000 °C carbonization (Park et al., 2020). The surface area and pore-size characteristics of the bamboo charcoal in the current study should be determined to clarify the interaction. In addition, cellulose ether, such as HPMC, could have improved hydration inhibition by coating with an acid or a glyoxylated surface before adding a caustic material for alcohol solidification (Gartner, 1990). Packaging could also protect solid alcohol hydration and deterioration due to light and oxygen (Pristouri et al., 2010). Paraffin has been reported to improve solid alcohol in applications in high altitude anoxia (Zhang et al., 2009). Polyvinylpyrrolidone and ludox have been reported as agents that improve the melting point, while alums and borax have been reported as auxiliary agents that improve the melting point for solid alcohol (Zhang et al., 2009). However, the low-cost, solid alcohol with curing agent used in the current study should be evaluated for use in anoxybiotic conditions or wider regions with greater heights above sea level or in a mountain region environment.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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