

Original Research Paper

# Characterization and Evaluation of Charcoal Briquettes Using Banana Peel and Banana Bunch Waste for Household Heating

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**Abstract:** The charcoal briquettes from banana peel and banana bunch wastes from dried banana industry for household heating were characterized and evaluated. A 200 L pyrolyzer was used for charcoal and wood vinegar production at 350°C pyrolysis temperature. The percent yield of charcoal and wood vinegar were determined. The effects of clay binder (0-15% w/w) on the properties of charcoal briquettes such as ash content, hardness, combustion calorific value, emissions data, burn time and combustion efficiency were evaluated. It was found that the percent yields of charcoal and wood vinegar from pyrolysis of banana peel and banana bunch are 57%, 7.53% and 58.6%, 6.76%, respectively. The banana bunch charcoal retained some functional groups to a higher degree than the banana peel charcoal. These include -OH, C = O, C = C, C-H and C-C groups. The porous shapes of banana peel charcoal and banana bunch charcoal are honeycomb and tube structure, respectively. The calorific value of both charcoal briquettes decreased with increasing ratios of clay and ash content. The values range from 5,115.51 to 6,396.66 cal g<sup>-1</sup>. The hardness obtained with 5% clay binder is 23.31 kg and 25.90 kg for banana peel charcoal briquette and banana bunch charcoal briquette, respectively. Both charcoal briquettes containing 5% clay are smokeless during combustion and result in red-brown ash after combustion. The dust and total CO emissions of banana peel charcoal briquette and banana bunch charcoal briquette during combustion are 15.38 µg m<sup>-3</sup> and 3463 ppm and 11.97 µg m<sup>-3</sup> and 1568 ppm, respectively. The maximum temperatures of water are 88 and 84°C and times needed to reach the maximum temperatures were 36 and 48 min for banana peel charcoal briquette and banana bunch charcoal briquette combustion, respectively. The maximum burning times and combustion efficiencies are 114 min and 9.10% and 92 min and 8.38% for banana peel charcoal briquette and banana bunch charcoal briquette, respectively.

**Keywords:** Charcoal Briquette, Wood Vinegar, Banana Peel, Banana Bunch, Households

## Introduction

Charcoal and firewood are among the primary cooking fuels used in many developing countries, even though they both pose a number of environmental, social and economic challenges. Including the ecological impacts of indoor air pollution produced by cooking with solid fuels (Gladstone *et al.*, 2014). Charcoal is an

impure form of graphitic carbon obtained as a residue when carbonaceous material is partially burned with limited access of air. This process rapidly decomposes organic material through anaerobic heating by smoldering agricultural waste (i.e., covering burning biomass with soil) in pits or trenches (Claxton, 2014). The process of fuel combustion involves: (1) Water evaporation required to evaporate the moisture in fuel;

(2) distillation and combustion of volatile organic matter with oxygen producing heat; and (3) combustion of the fixed carbon at a high temperature (Claxton, 2014). However, oxidation of fuel is not always complete and small amounts of carbon monoxide, hydrocarbons and other gases, such as nitrogen/sulfur oxides and fumes are also released. Some of these are harmful to health, some to the environment and some to the atmosphere. Pollutants such as carbon monoxide, sulfur dioxide, nitrogen dioxide and particulate matter are of significance because of the effect they have on the environment and human health (Yazdani *et al.*, 2012). The factors that affect the amount and composition of pollutants released during fuel combustion include burn rate, fuel type, the type of combustion appliance and moisture content of the fuel (Claxton, 2014).

Agro-industrial biomass comprised of lignocellulosic waste is an inexpensive, renewable, abundant source of fuel material, which provides a unique natural resource for large-scale and cost-effective bio-energy collection. Lignocellulosic materials including agricultural wastes, forestry residues, grasses and woody materials have great potential for bio-fuel production. All plant materials are mostly composed of about 10-25% lignin, 20-30% hemicellulose and 40-50% cellulose (Anwar *et al.*, 2014). However, low density of biomass results in handling problems. Therefore, the aim of densification methods is to increase biomass density and in turn its calorific per unit of volume (Kusumaningrum and Munawar, 2014). Bio-pellet is an alternative energy that can substitute low grade coal using biomass sources. Bio-pellet from biomass sources has environmental advantages over coal. Several aspects such as moisture content, particle size and chemical compound, particularly lignin, content can influence bio-pellet properties. The advantages of bio-pellet include uniformity, high compressive strength and higher calorific value than its raw materials (Kusumaningrum and Munawar, 2014). Charcoals have been also transformed into briquettes for ease of handling and to reduce the dust problem and increase the energy density (Sjlie, 2012). Briquette charcoal is a solid fuel from organic matter containing carbon, which has a high calorific value and can be lit for a long time (Nuriana *et al.*, 2014). There are clear advantages of charcoal briquettes that include price, burn time, environmental sustainability and potential for product standardization (Mwampamba *et al.*, 2013). Wood charcoal briquettes have also been produced for their global warming reduction potential (Rousset *et al.*, 2011) and are also financially and economically viable (Onaji and Siemons, 1993).

Nonindustrial charcoal production generates large emissions of greenhouse gases in the form of CO<sub>2</sub> from forest degradation and methane from oxidation in

traditional kilns, which are used by more than half of the households with very incomplete combustion and typically offering about 15% efficiency (Sjlie, 2012). More than 90% of CO<sub>2</sub> emissions are due to biomass conversion to charcoal. Roughly 3.9660 Kg of CO<sub>2</sub> emitted per 1 kg of charcoal produced. CO<sub>2</sub> emissions throughout the charcoal production process are totally compensated for the environmental quality of the raw materials used (Rousset *et al.*, 2011). Lignocellulosic materials (i.e., hazelnut shells) have been converted to charcoal, liquid and gaseous products (Demirbaş, 1999). This process can reduce gas emissions by converted them into liquid smoke or wood vinegar. Wood vinegar is produced when smoke from charcoal production is cooled by outside air while passing through a chimney. The cooling effect causes condensation of pyrolytic liquor, particularly when the temperature of smoke produced by carbonization ranges between 80 and 180°C. This temperature is reached at the carbonization stage of exothermic decomposition and is indicated by the production of yellowish, acrid smoke (Burnette, 2010). Wood vinegar mainly consists of phenolic compounds and acetic acid. Wood vinegar can be used for many purposes. For instance, phenolic components, such as phenol, guaiacol and cresol can act as biocidal agents with antifungal properties. The acetic acid functions as termiticidal agent. The 2-propanone and 1-hydroxy-derivatives is value-added product for the synthesis of pharmaceuticals (Oramahi and Diba, 2013).

Banana peel is another type of agricultural, waste which originates from industrial banana production. Banana is one of the most popular tropical fruits consumed worldwide. In Thailand, 200 tons of banana peel is produced daily and the amount is constantly increasing. A small fraction of the peel is used for animal feed and the remainder becomes rotted garbage. Banana peel is carbohydrate rich and could, potentially, be converted into bioenergy (Nathoa *et al.*, 2014). Banana waste contains 14% lignin, 14.8% hemicellulose and 13.2% cellulose (Anwar *et al.*, 2014). It has the potential for industrial charcoal production for domestic use.

Cassava flour (Teixeira *et al.*, 2010), low density polyethylene (Massaro *et al.*, 2014), pyrolytic oil and tar (Demirbaş, 1999) have been used as binders for the production of charcoal briquettes. These binders can increase the density, mechanical resistance, calorific value, flowability, durability, hardness and moisture resistance of charcoal briquettes (Jeżerska *et al.*, 2014). However, these compounds also generate smoke while burning due to the highly volatile matter contained in them. Clay is kaolinite type material. It has high chemical stability, low expansion coefficient, high hardness and strong layers (Mopoung *et al.*, 2014). It is expected to be suitable as a binder for the production of smokeless charcoal briquettes.

This research focuses on charcoal briquette production from banana peel and banana bunch wastes that may be an economically and ecologically viable substitute for other fuel types in domestic use. The raw materials were converted to charcoal and wood vinegar by a pyrolysis process. The aim of this process is to reduce the gas and smoke emissions into the environment. The charcoal and wood vinegar production by a 200-liter-vertical-oil-drum kiln were studied for percent yield. The charcoal was characterized by SEM, FTIR and approximate analysis. Clay was used as a binder, as it is abundant in nature and inexpensive, for the reduction of the emissions (CO, dust and smoke) and to increase hardness and burn time of the briquettes. The charcoal briquettes were analysed for thermal and mechanical properties using standard techniques including hardness testing, bomb calorimetry and combustion testing to improve environmental conditions of communities using traditional heating sources.

## Materials and Methods

### Materials

Materials used in this study are the banana peel and banana bunch wastes, which were obtained from Kong Krailat district, Sukhothai province, Thailand. These materials contain  $88.2 \pm 0.1\%$  moisture,  $1.8 \pm 0.1\%$  ash,  $9.8 \pm 0.1\%$  volatile matter and  $1.9 \pm 0.0$  fixed carbon for banana peel and  $92.9 \pm 0.5\%$  moisture,  $0.8 \pm 0.1\%$  ash,  $5.1 \pm 0.0\%$  volatile matter and  $1.4 \pm 0.1$  fixed carbon for banana bunch (Mopoung, 2005). Clay is a binder agent. It is composed of a tetrahedral  $\text{SiO}_4$  sheet and an octahedral sheet containing  $\text{Al}^{3+}$  ions (Rao *et al.*, 2011).

### Pyrolyzer

A 200-liter-vertical-oil-drum kiln (Fig. 1) was used for pyrolysis of banana peel and banana bunch. It consists of a door (22.5×22.5 cm) located towards the bottom to allow the controlled inflow of the primary air that allows the fire to ignite and grow. The pyrolyzer contains three chimneys (6 cm in diameter and 75 cm of height) with cooling attached at the bottom of the pyrolyzer. The cooling is located at the bottom of the chimneys to condense the cracked gases, which then flow down through the chamber to form wood vinegar. A fourth chimney (6 cm in diameter and 18 cm of height, fixed on lid) is located at the top of the pyrolyzer and it provides an outlet for initial white smoke and is closed after yellowish and acrid smoke appears.

### The Production of Charcoal and Wood Vinegar

The banana peel and banana bunch were air dried. The dried banana peel and banana bunch were

carbonized at 350°C in a 200-liter-vertical-oil-drum kiln for 1 day. The temperature was measured by thermocouple (Hioki 3441-02 K Type Thermocouple Temperature HiTester) located in the combustion zone. The charcoal and wood vinegar were collected and the percent yield was calculated.

After installation 15-20 kg of banana peel or banana bunch was loaded in the pyrolyzer and was pre-heated to drive the cool air in the pyrolyzer out and to dehydrate the raw material until the smoke turned white (Fig. 1a). Then, the material was allowed to burn further until the temperature increased up to 350°C.

During pyrolyzer operation, the bottom door is propped open until the fire is self-sustaining, at which point it is closed and all possible cracks are blocked with clay to restrict the levels of oxygen inside so as to create environment favorable for the pyrolysis. It is also necessary to cover the kiln completely by placing a lid at the top chimney (Fig. 1b). During pyrolysis, charcoal, as well as liquids and gasses are produced. The smoke was condensed to wood vinegar by flow through the three cooling chimneys. The production of raw wood vinegar is finished when the droplets turn black, indicating that tar had formed (Burnette, 2010).

After the carbonization process, the pyrolyzer was allowed to cool to atmosphere temperature for 1 day. Then, charcoal and wood vinegar were collected and measured to calculate the percent yield.

### Characterization of Charcoal

Charcoals were characterized by FTIR (GX, Perkin Elmer) and SEM (LEO 1455 VP). The proximate analysis was also used for ash content (ASTM, 1996a), volatile matter (ASTM, 1996b) and fixed carbon (ASTM, 1994) determination in dried weight.

### Charcoal Briquettes Production

After carbonization for 1 day, the kiln is then left to cool until it is safe to touch the exterior. After the kiln has cooled, the charcoal can be harvested and ground to fine powder. Various ratios of banana peel charcoal, or banana bunch charcoal, to clay (100:0, 95:5, 90:10 and 85:15) were used. The mixtures were wetted and blended with water. Moisture, in specific amounts, was reintroduced to the charcoal/clay mixture before pressing in order to increase briquette strength through capillary binding effects. The charcoal/clay mixture was then briquetted using a male/female roller configuration in a roller press briquetter with 7.5 horsepower motor, three-phase power, capacity of three tons per day (Fig. 2a). The charcoal briquette is cylindrical in shape (4 cm in external diameter, 0.8 cm in internal diameter and 10 cm in length) (Fig. 2b). The briquettes were then dried in the sun for 7 days.

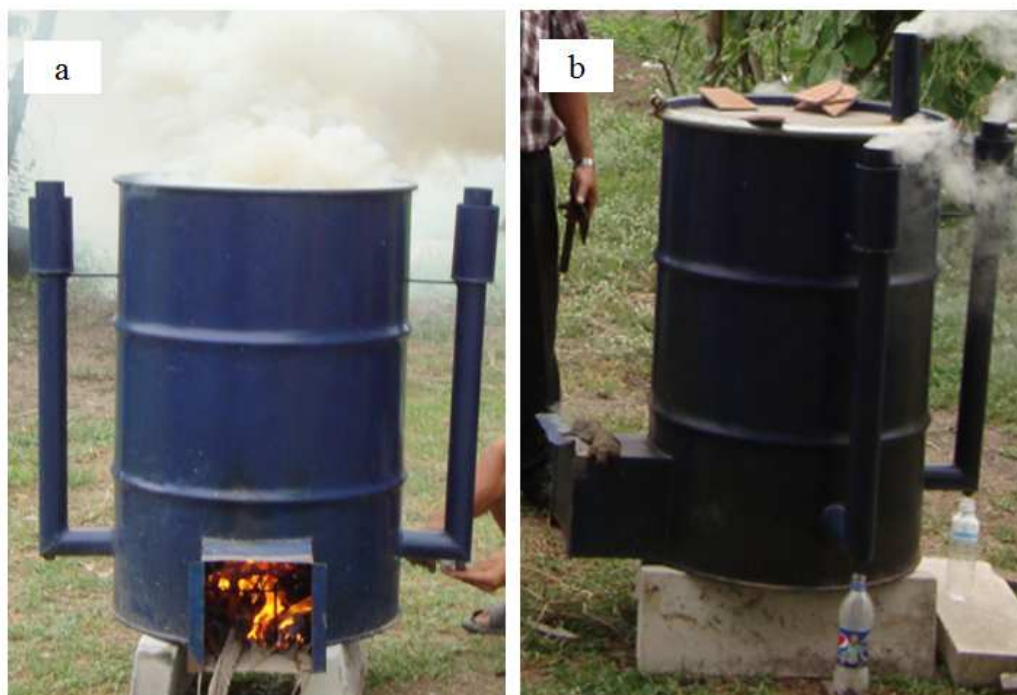


Fig. 1. The 200 L pyrolyzer during (a) ignition and (b) carbonization



Fig. 2. The charcoal briquettes from a roller press briquetter with motor (a) briquetter (b) extruded charcoal

### *Characterization of Charcoal Briquettes*

The ash content, calorific value, hardness, combustion calorific value, emissions data, burning time and combustion efficiency of charcoal briquettes were evaluated.

#### *The Calorific Value Determination*

For the determination of the calorific value the higher heating value was measured by an automatic bomb calorimeter (1108 Oxygen Combustion Bomb Parr).

### *Hardness Measurement*

Hardness of the charcoal briquettes was determined by a tensile tester (Shimadzu Autograph, model AG-25TB). Tensile tester works by gradually increasing the pressure on the charcoal briquettes. The pressure is increased until the charcoal briquettes have been crashed, struck, or deformed. Press is simulated by the string principle. String has one end created by the tip, which is pressing on the charcoal briquettes. The resulting value is deduced from the pressure when charcoal briquettes have been crashed.

### *Emission, Burning time and Combustion Efficiency Analyses*

The Thai-bucket stove, which is used extensively throughout Thailand for cooking, was used for the testing of emissions, burning time and combustion efficiency. This stove is based on traditional ceramic designs. The stove has two main components, a galvanized iron bucket and an inner ceramic firebox. The stove is also insulated with cement plaster. The bucket is approximately 300 mm wide and 270 mm deep. It has an opening of 100×50 mm cut into its side from the bottom, the inner ceramic firebox is 190 mm in diameter, holes of 20 mm in diameter are cut into the grates. Charcoal can be burnt on the grate. The fuels are normally ignited with kindling. Refueling is done by lifting the pot. The stove weighs about 10 kg (Bhattacharya *et al.*, 2002).

#### *Emission Test*

The Thai-bucket stove to be tested was placed in the center of an indoor laboratory room. The emitted fumes were analyzed by dust detector (TISCH Air Environment Equipment) and CO analyzers (Gas Alert Micro 5). Dust detector and CO analyzers were placed 0.5 m from the stove. The charcoal briquette was ignited and after 5 min measurements of dust and CO were taken every 20 sec for 15 min. The flow rate was 1.17 L s<sup>-1</sup>.

#### *Burning Time and Efficiency Measurement*

The charcoal briquettes were weighted accurately and were tested for burning time and efficiency using the Thai-bucket stove. Efficiency is defined as the ratio of the energy entering the pot to the energy content of the fuel consumed. The distilled water boiling test is used for testing the efficiency of the stoves. A known quantity of distilled water is heated on the stove to achieve simmering. Water is brought to boil during the heating up phase and is maintained within 5°C of boiling point for 30 min. There are problems associated with determining the individual efficiencies of both the heating up and simmering phases. This is because removal of combustibles at the end of the heating up phase is problematic. Thus, only the overall efficiency over the entire test period can be determined. After the amount of water evaporated is calculated, the remaining fuel is separated and weighed and the net amount of energy consumed is determined by the method of Bhattacharya *et al.* (2002). Effectively, this means the latent heat of water is included in the higher heating value. The higher heating value is calculated with water exiting the system in liquid form, while the latent heat value is calculated with the assumption that the water product leaves as vapour (Bhattacharya *et al.*, 2002).

## **Results and Discussion**

### *The Production of Charcoal and Wood Vinegar*

#### *Percent Yield of Charcoal and Wood Vinegar*

The percent yield of charcoals and wood vinegars are shown in Table 1. It can be seen that the percent yield of charcoal from banana bunch is slightly higher than from banana peel. In turn there are lower yields of wood vinegar from banana bunch. Consequently, the content of volatile matter remains higher in banana bunch charcoal. This is because of the volatile matter from banana bunch is converted to wood vinegar during carbonization to a lower extent than from banana peel. Another reason for the lower wood vinegar yield from banana bunch may be due to low initial amounts of volatile compounds in banana bunch in comparison to banana peel. Thus banana bunch yields less wood vinegar. The value of fixed carbon in banana bunch charcoal is also higher than in banana peel charcoal. The ash content in banana peel charcoal tended to be higher than in banana bunch charcoal. This is because of the higher initial ash content in banana peel being higher than in banana bunch.

When comparing the results of this study to the production of wood vinegar from bark of Durio at pyrolysis temperature of 412°C it can be noticed that the published work reports percent yield in the range from 33.87 to 39.23% (Oramahi and Diba, 2013). The reason for the lower wood vinegar yield from both banana peel and banana bunch obtained in the current work may be due to the pyrolysis temperature (350°C), which might be insufficient for complete pyrolysis to take place, thus yielding less wood vinegar product. Alternatively, the pyrolyzer used in this study may have low efficiency for condensation resulting in low yield of wood vinegar.

#### *Characterization of charcoal*

The FTIR spectrum of banana bunch charcoal (Fig. 3d) shows strong peaks of various functional groups, which are present to a lesser degree in the FTIR spectrum of banana peel charcoal (Fig. 3c). This indicates that banana bunch was pyrolysed to a lesser degree than banana peel. This assumption is further supported by the lower yield of wood vinegar from banana bunch than banana peel. The broad band at about 3400 cm<sup>-1</sup> of both raw materials (Fig. 3a and b) corresponds to -OH stretching; this band is related to specific intramolecular hydrogen bonds of cellulose (Tibolla *et al.*, 2014). It represents the hydrophilicity of banana peel and banana bunch (Fig. 3a and b). However, the band at about 3400 cm<sup>-1</sup> of both charcoals (Fig. 3c and d) corresponds to associated hydroxyl groups, which probably originate from the decomposition of phenolic hydroxyls (Cao *et al.*, 2013).

Table 1. Percent yield of charcoal and wood vinegar and proximate composition of charcoals from banana peel and banana bunch

|                                         | Banana peel | Banana bunch |
|-----------------------------------------|-------------|--------------|
| % Yield of Charcoal (weight/weight)     | 57.00       | 58.60        |
| % Yield of Wood vinegar (volume/weight) | 7.53        | 6.76         |
| % Ash (dried weight)                    | 35.52       | 31.86        |
| % Volatile matter (dried weight)        | 28.31       | 29.21        |
| % Fixed carbon (dried weight)           | 36.17       | 38.93        |

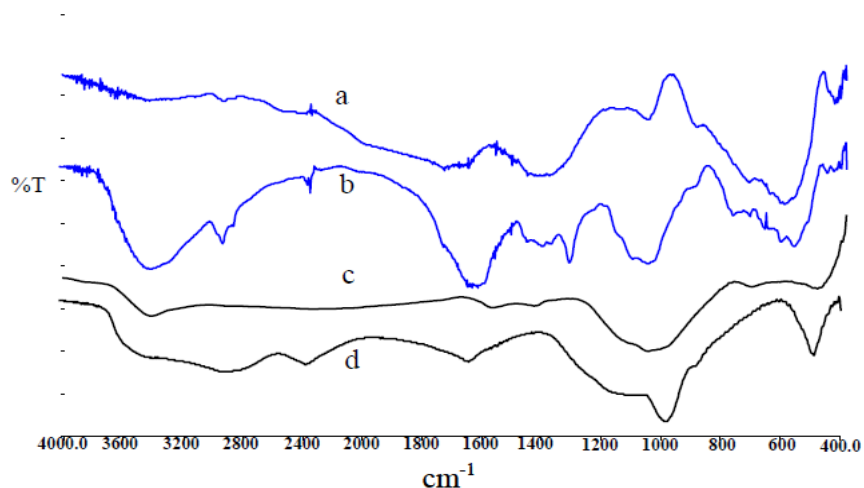


Fig. 3. Transmittance FTIR spectra of (a) banana peel (b) banana bunch (c) banana peel charcoal (d) banana bunch charcoal

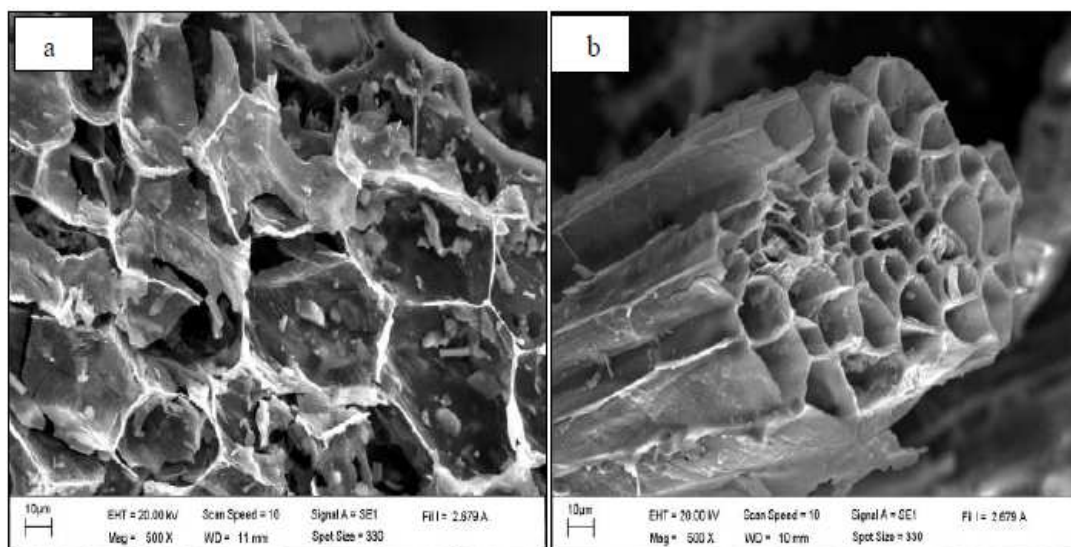


Fig. 4. SEM morphology of (a) banana peel charcoal (b) banana bunch charcoal

Both raw materials also displayed a small band in the region of  $2923\text{ cm}^{-1}$ , typical of the stretching vibrations of the C-H bonds in hemicelluloses and cellulose (Elyounssi and Halim, 2014). This band was of lower intensity in the spectra of both charcoals. The very small band at  $2351\text{ cm}^{-1}$  of both raw materials corresponds to C = O vibrations of ketone groups of lignin (Zhao *et al.*, 2014). It was observed that the band at  $2351\text{ cm}^{-1}$  of

banana bunch charcoal was also present (Fig. 3d). This suggests that the lignin in banana bunch was not completely carbonized at  $350^\circ\text{C}$ . The broad band between  $1700$  and  $1550\text{ cm}^{-1}$  in the spectrum of the raw materials corresponds to vibrations of the acetyl and uronic ester groups of hemicelluloses or to the ester linkages of carboxylic group of the ferulic and p-coumaric acids of lignin. It could also reveal that

conjugated aromatic rings and conjugated carbonyl groups exist in the polyphenolic structure of lignin (Tibolla *et al.*, 2014). These peaks almost completely disappeared after carbonization. However, the peak at about  $1600\text{ cm}^{-1}$  still remained in the spectrum of banana bunch charcoal, which suggested that the sample contained lignin residues; i.e., carbonization did not remove lignin completely. This band is also refers to  $\text{C}=\text{C}$  vibration originating from phenyl rings. It was suggested that the chains of phenyl rings can be transformed into polycondensated aromatic rings. (Cao *et al.*, 2013). Indeed, the peaks assigned to the cellulose C-H groups stretching in the  $1500\text{-}1200\text{ cm}^{-1}$  region disappeared after carbonization for both charcoals as compared with the raw materials. The band at  $1050\text{ cm}^{-1}$  of both raw materials was assigned to associated hydrogen bonds in cellulose. The small peaks between  $800\text{-}500\text{ cm}^{-1}$  in the spectra of the raw materials refer to typical cellulose structures and correspond to aromatic ring C-H groups in the lignin (Tibolla *et al.*, 2014). These peaks have also disappeared after carbonization for both charcoals, confirming the removal of lignin, hemicelluloses and celluloses. The peak at about  $400\text{-}500\text{ cm}^{-1}$  found in the raw materials represents the  $\text{-C-C-}$  stretching of cellulose (Chand *et al.*, 2014). The broad band at about  $900\text{-}1100\text{ cm}^{-1}$  found in the spectra of the charcoals represented aromatic C-H bond bending. This indicates that macromolecular aromatic molecules began to rearrange (Cao *et al.*, 2013). It also corresponds to  $\text{C}=\text{O}$  stretching vibrations originating from partial oxidation of carbon by oxygen (Elyounssi and Halim, 2014). Finally, the band at about  $500\text{ cm}^{-1}$  found in the charcoals corresponds to aliphatic C-C vibrations (Cao *et al.*, 2013). It indicates that the cellulose and lignin with aliphatic carbons remained in charcoals after pyrolysis at  $350^{\circ}\text{C}$ .

Figure 4 shows the SEM morphology of banana peel charcoal (Fig. 4a) and banana bunch charcoal (Fig. 4b). It demonstrates that the structures of both charcoals are highly porous. Therefore, they have low density resulting in problems with handling and mechanical properties (Kusumaningrum and Munawar, 2014). Therefore, their density should be increased to improve these problems. However, the porosity of charcoals has advantages for the properties of the briquettes. The porous shapes of charcoals are honeycomb and tube structure in banana peel charcoal and banana bunch charcoal, respectively. These porous structures may be responsible for the increase in briquette strength through capillary binding of porous particles and mechanical interlocking of rough particle surfaces (Bazargan *et al.*, 2014).

### Charcoal Briquettes Production

Charcoal fines are materials totally lacking in plasticity and therefore need the addition of a sticking or

agglomerating material to enable a briquette to be formed. A non-combustible binder that is effective at low concentrations may be suitable (Rousset *et al.*, 2011). The banana peel charcoal and banana bunch charcoal show low density, which was augmented by a densification method for increasing density (Kusumaningrum and Munawar, 2014). In this process, clay was preferred as the binder. The mixtures have shown that clay improves plasticity and flowability of the mixtures. The flowability improvement provided by clay can be attributed to the fact that it reduces impact of friction forces on the contact male/female roller configuration in a roller press briquetter (Jezerska *et al.*, 2014). The clay set through the loss of water, binding the banana peel charcoal and banana bunch charcoal into briquettes, which could be handled like ordinary lump charcoal in domestic stoves (Rousset *et al.*, 2011).

### Characterization of Charcoal Briquettes

#### The Calorific Value of Charcoal Briquettes

Table 2 shows the calorific value and proximate composition of banana peel charcoal briquettes and banana bunch charcoal briquettes with 0-15% clay. The calorific value of both charcoal briquettes decreased with increasing ratios of clay and ash content. This is because the carbon content has an influence on the calorific value of charcoal. Generally, the higher the carbon content is the higher the calorific yield (Yazdani *et al.*, 2012). Furthermore, clay and ash are inorganic materials, which are stable and possess no calorific value. Therefore, it cannot be combusted and thus it cannot be converted into energy (Yazdani *et al.*, 2012; Nuriana *et al.*, 2014). However, calorific values of all briquettes remained higher than the Thai Industrial Standards Institute requirement of not less than  $5,000\text{ cal g}^{-1}$  (Prasityoussil and Muenjina, 2013). It was observed that banana bunch charcoal briquettes have a higher calorific value than banana peel charcoal briquettes containing the same ratio of clay. This is because of banana bunch charcoal briquettes have a higher carbon content and lower ash than banana peel charcoal briquettes. As compared with sugar-cane bagasse fly ash briquettes with an average density of  $1.12\text{ g cm}^{-3}$  and an average calorific value of  $25,551\text{ kJ kg}^{-1}$  (Teixeira *et al.*, 2010), both charcoal briquettes presented herein have a lower calorific value. This can be explained by the fact that both charcoal briquettes have low densities and the clay binder cannot be converted into energy.

### Hardness of Charcoal Briquettes

The hardness properties of briquettes comprise resistances to crushing, impact, abrasion and water penetration (Richards, 1990). The hardness of

briquettes was enhanced by increasing the inter-particle contact area or by decreasing the inter-particle distance (Li *et al.*, 2012). The hardness of the briquettes is dependent on cohesion forces, which can be divided into true and apparent cohesion. Apparent cohesion is the force that keeps particles agglomerated by capillary forces and mechanical interlocking of rough particle surfaces. The apparent cohesion forces allow for deformation and agglomeration of the particles but are mostly lost upon drying. The true cohesion forces keep the particles together even after drying. These include electromagnetic and electrostatic forces of particles and cementing agents (Bazargan *et al.*, 2014). The results of hardness properties for briquettes containing 5% (w/w) of clay binder are presented in Table 3. Higher amounts of clay were not practical as briquettes with higher clay content were difficult to ignite. The banana bunch charcoal briquettes have higher hardness than the banana peel charcoal briquettes. They also give off lower amounts of dust, total CO but have lower burn time and combustion efficiency (Table 3). This is due to the fact that the banana bunch charcoal briquettes have more pore spaces and gaps than the banana peel charcoal briquettes (Fig. 4). In comparison with spruce sawdust briquettes, which were prepared with 5-20% starch binder (Jezerka *et al.*, 2014), the banana bunch charcoal briquettes and the banana peel charcoal briquettes have lower hardness ( $\geq 50$  kg). This was explained by the fact that the banana bunch charcoal briquettes and banana peel charcoal briquettes contain pore spaces and gaps, which can reduce the pellet resistance to deformation. This was confirmed from the SEM morphologies of both briquette types (Fig. 4), in which clear gaps and spaces were identified. During the hardness test, the existing gaps and spaces promote the relative movement of particles within the

briquette matrix (Li *et al.*, 2012), leading to the lower hardness for the banana bunch charcoal briquettes and banana peel charcoal briquettes. Ultimate strength of both charcoal briquettes with 5% clay binder (Table 3) is lower than  $3.8 \text{ kg cm}^{-2}$  or 0.38 MPa (Richard, 1990). Hence, they might break easily during transport or storage.

#### Dust and CO Emissions from Charcoal Briquettes

Addition of clay up to 5% (w/w) results in briquettes that are relatively easy to ignite. Both charcoal briquettes containing 5% (w/w) clay are smokeless during combustion and produce red-brown ash after combustion. The ash formed from the combustion of both briquettes still has the initial form of the briquettes. This result confirms the positive role of the clay binder on dust emission from charcoal briquettes during combustion.

The dust and CO emissions are related to the hardness of the briquettes. The higher hardness results in lower dust and CO emission. Consequently the banana bunch charcoal briquettes had lower dust and CO emissions than the banana peel charcoal briquettes (Table 3). Another important parameter is the fixed carbon content. Higher amounts of fixed carbon increase the probability of extensive combustion and more complete oxidation. This may be attributed to the higher kindling temperature of the briquettes, resulting in higher combustion and lower CO emissions. Therefore dust and CO emissions are low for briquettes with high amounts of fixed carbon. The average CO emission rate for banana bunch charcoal briquettes is lower than that for banana peel charcoal briquettes. This is likely due to higher carbon content resulting in more complete combustion. The increased fixed carbon content also results in shorter burning time.

Table 2. Proximate composition and calorific values of banana peel charcoal briquette and banana bunch charcoal briquette with differences ratios of clay

| Samples                                       | Ash % | Volatile matter % | Fixed carbon % | Calorific value (cal/g) |
|-----------------------------------------------|-------|-------------------|----------------|-------------------------|
| Banana peel charcoal briquette with 0% clay   | 32.52 | 28.30             | 39.17          | 5,989.55                |
| Banana peel charcoal briquette with 5% clay   | 35.39 | 26.88             | 37.73          | 5,894.00                |
| Banana peel charcoal briquette with 10% clay  | 38.27 | 25.47             | 36.26          | 5,687.72                |
| Banana peel charcoal briquette with 15% clay  | 41.14 | 24.06             | 34.80          | 5,115.51                |
| Banana bunch charcoal briquette with 0% clay  | 28.86 | 29.21             | 41.93          | 6,396.66                |
| Banana bunch charcoal briquette with 5% clay  | 31.92 | 27.75             | 40.33          | 5,953.55                |
| Banana bunch charcoal briquette with 10% clay | 34.97 | 26.30             | 38.73          | 5,564.61                |
| Banana bunch charcoal briquette with 15% clay | 38.03 | 24.83             | 37.14          | 5,434.09                |

Table 3. Hardness, ultimate strength, dust and CO emission, burn time and combustion efficiency of charcoal briquettes with 5% clay

| Samples                         | Hardness (kg) | Ultimate Strength (kg/cm <sup>2</sup> ) | Dust emission (g/m <sup>3</sup> ) | Average CO rate (ppm/s) | Total CO (ppm) | Burn time (min) | Combustion efficiency (%) |
|---------------------------------|---------------|-----------------------------------------|-----------------------------------|-------------------------|----------------|-----------------|---------------------------|
| Banana peel charcoal briquette  | 23.31         | 2.00                                    | 15.38                             | 3.76                    | 3463           | 114             | 9.10                      |
| Banana bunch charcoal briquette | 25.90         | 2.26                                    | 11.97                             | 1.72                    | 1584           | 92              | 8.38                      |



The dust emissions from banana peel charcoal briquettes and banana bunch charcoal briquettes are 15.38 and 11.97  $\mu\text{g m}^{-3}$ , respectively. These values are less than the levels set in the WHO guidelines for air quality with 50  $\mu\text{g m}^{-3}$  for particle matter with size <10  $\mu\text{m}$  and 25  $\mu\text{g m}^{-3}$  for particle matter with size <2.5  $\mu\text{m}$  (Fullerton *et al.*, 2008).

The initial stage of CO release was probably due to the decarbonylation reaction of alkyl side-chains with carbonyl groups (-CO), while the increase of CO emission at high temperatures probably resulted from secondary reactions due to incomplete combustion of biomass (Cao *et al.*, 2013). The decarbonylation reaction also results in the loss of oxygen bound to aromatic rings linked with the disappearance of phenolic and carboxylic carbons. The CO formation is attributed to decarbonylation reactions, specifically to the breakdown of COC and C = O bonds, due to the decomposition of the ring-opened intermediates (Benítez-Guerrero *et al.*, 2014). These results are demonstrated in the FTIR spectra of charcoal briquettes (Fig. 3c and d), which still have the C = O functional groups (at 2351  $\text{cm}^{-1}$  and at about 1600  $\text{cm}^{-1}$ ).

Figure 5 presents the emission of CO of banana peel charcoal briquettes (Fig. 5a) and banana bunch charcoal briquettes (Fig. 5b) as a function of time. The CO emissions for both briquettes are not constant with time. This may be attributed to the effect of ash which forms during the combustion the ash hinders the flow of oxygen through to inner texture of the briquettes resulting in incomplete combustion and high CO emissions. However, at later stage oxygen flow through the briquettes is renewed resulting in reignition, more complete combustion and lower CO emissions (Huangfu *et al.*, 2014). The CO emissions from banana peel charcoal briquettes are higher than that from banana bunch charcoal briquettes. The average rates of CO emission for banana peel charcoal briquettes and banana bunch charcoal briquettes are 3.76 and 1.72  $\text{ppm s}^{-1}$ , respectively, during the combustion period. This is due to the higher carbon content of banana bunch charcoal briquettes, which results in high temperature of fume gas and high oxidation of banana bunch charcoal briquettes during combustion. In comparison general wood and charcoal have CO emission in the range from 19-136  $\text{g kg}^{-1}$  or 1.9-13.6% (Bhattacharya *et al.*, 2002). The total CO emissions of the briquettes presented herein are much lower. Banana peel charcoal briquettes and banana bunch charcoal briquettes give total CO emissions of 3463 ppm (0.35%) and 1568 ppm (0.16%), respectively. It is also due to the high extent of oxidation or high combustion efficiency of these briquettes. It was concluded that gas mixtures of atmosphere with a low concentration of CO, up to about 0.5%, do not present any toxic threat to consumers as established by the International Standard for the Determination of Toxicity of Gases (Luo *et al.*, 2002).

## Burning Time and Combustion Efficiency of Charcoal Briquettes

### Burning Time and Water Temperature Measurements

Figure 6 shows the relationship between the combustion time and water temperature during the combustion of the briquettes. It can be seen that the maximum temperatures of water reached are 88 and 84°C for banana peel charcoal briquettes and banana bunch charcoal briquettes, respectively. This is due to the lower kindling temperature of banana peel charcoal briquettes. It was observed that higher carbon content of briquettes results in higher temperature of fume gas, which leads to higher loss of energy out of the stove (Birzer *et al.*, 2014). Therefore the maximum temperature of water reached with banana bunch charcoal briquettes combustion is lower than for banana peel charcoal briquettes combustion. A higher fixed carbon increases the calorific value and tends to increase the burning rate. Therefore, it is also affects the time needed to reach the maximum temperature of water. Thus, the time to reach the maximum temperature of water was 36 and 48 min for combustion of banana bunch charcoal briquettes and banana peel charcoal briquettes, respectively. In comparison, the time needed to reach the maximum water temperature with the combustion of wood pellets is 19.4-30.5 min (Huangfu *et al.*, 2014). The banana peel and bunch charcoal briquettes release energy at a lower rate leading to the longer times required to boil water. Burning rate is an indicator of the intensity of the combustion i.e. the rate of the fuel burning affects the rate of energy being delivered (Huangfu *et al.*, 2014). The higher burning rate thus results in shorter burning time. Therefore, the burning time of banana bunch charcoal briquettes is shorter than for banana bunch charcoal briquettes (Table 3).

### Combustion Efficiency

Combustion efficiencies of banana peel charcoal briquettes and banana bunch charcoal briquettes were 9.10 and 8.38%, respectively. It has been demonstrated by Birzer *et al.* (2014) that the temperature of fume gases affects the heat energy efficiency of stoves during the combustion process. The fume gas with higher temperature will result in higher energy loss from the stove and thus decrease the energy efficiency. In this research, the banana bunch charcoal briquettes contain higher amount of fixed carbon than banana peel charcoal briquettes. Therefore, the combustion of banana bunch charcoal briquettes leads to higher temperature of fume gases than for banana peel charcoal briquettes. The observed efficiency values fall in the efficiency range of 5-15% of traditional stoves in Asian countries (Bhattacharya *et al.*, 2002).

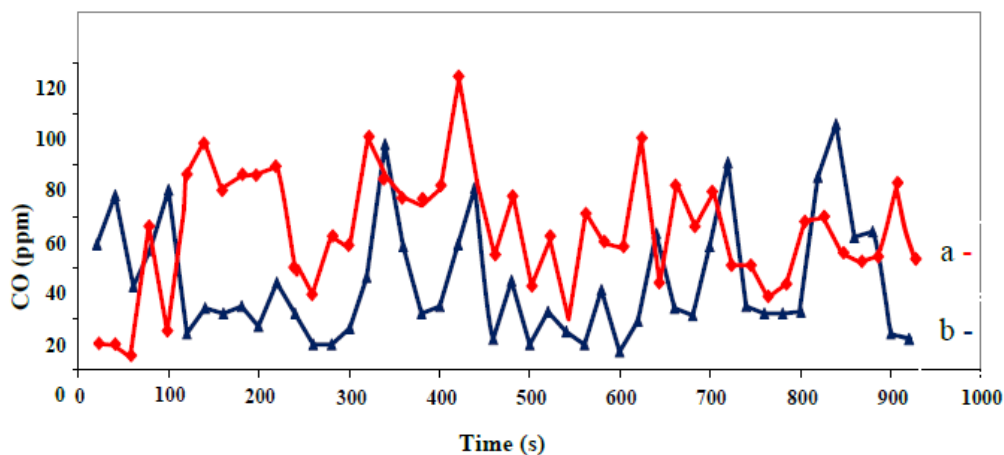


Fig. 5. The CO emission as function of time for (a) banana peel charcoal briquettes and (b) banana bunch charcoal briquettes

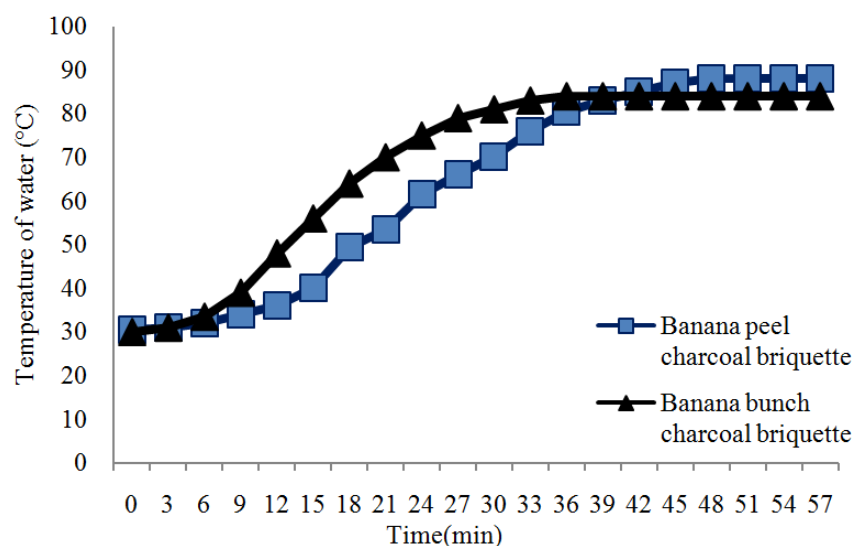


Fig. 6. Relationship between the time and water temperature during combustion of banana peel charcoal briquettes and banana bunch charcoal briquettes

## Conclusion

Charcoal briquettes from banana peel and banana bunch were produced using 200 L pyrolyzer and conducting the pyrolysis at about 350°C. The yields of charcoal were 57.0 and 58.6% w/w for pyrolysis of banana peel and banana bunch, respectively. The yields of wood vinegar, on the other hand, were 7.53 and 6.76% w/w for banana peel and banana bunch respectively. These results present a low yield and indicate a low of the pyrolysis process as well as low condensation capacity of the pyrolyzer. The charcoal product from banana peel and banana bunch retained strong peaks of some functional groups. This result confirmed the incomplete pyrolysis of the charcoal products. The porous shapes of charcoals are honeycomb

and tube structure in banana peel charcoal and banana bunch charcoal, respectively. These structures can help the hardness of the briquettes by employing capillary force and interlocking with the clay binder. The calorific value of both charcoal briquettes decreased with increasing ratios of clay and ash content. However, the calorific values of all briquettes with 0-15% of clay, which have values in the range from 5,115.51 to 6,396.66 cal g<sup>-1</sup>, are still higher than the Thai Industrial Standards Institute requirement of not less than 5,000 cal g<sup>-1</sup>. The hardness obtained with 5% w/w content of clay binder in banana peel charcoal briquettes and banana bunch charcoal briquettes is 23.31 kg and 25.90 kg, respectively. Both charcoal briquettes prepared with 5% clay are smokeless while the combustion results in a red-brown ash. The dust emission, average CO

concentrations, emission rate and total CO emission of banana peel charcoal briquettes and banana bunch charcoal briquette are  $15.38 \mu\text{g m}^{-3}$ ,  $3.76 \text{ ppm s}^{-1}$ ,  $3.46 \text{ g kg}^{-1}$  and  $11.97 \mu\text{g m}^{-3}$ ,  $1.72 \text{ ppm s}^{-1}$ ,  $1.58 \text{ g kg}^{-1}$ , respectively. These values are less than the levels set in the WHO guidelines and the International Standard for the Determination of Toxicity of Gases. It was shown that the combustion of charcoal briquettes proceeds to a high level of completion. Combustion efficiencies of banana peel charcoal briquettes and banana bunch charcoal briquettes were 9.10 and 8.38%, respectively. It was observed that the maximum temperatures of water are 88 and 84°C for banana peel charcoal briquettes and banana bunch charcoal briquettes, respectively. The time used to reach to maximum temperature during banana bunch charcoal briquette combustion (36 min) is shorter than for banana peel charcoal briquette combustion (48 min). The maximum burning times of 114 and 92 min were observed for banana peel and banana bunch charcoal briquettes, respectively. These results are a reflection of the composition of the charcoal materials (e.g., carbon and ash content) and clay binder. This research shows the possibility for improving the utilization of these charcoals by extrusion roller press briquetting along with utilization of clay binder to impart mechanical strength, limit CO and dust emissions and to modify burning time and combustion efficiency of the briquettes. These results can be considered a contribution to the development of more eco-friendly, sustainable and renewable utilization of banana waste.

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## Author's Contributions

**Sumrit Mopoung:** Contribute in: (a) Experimental design, (b) discussion and conclusion of the results.

**Vijitr Udeye:** Contributed in: (a) The study of the related experiment, (b) protocol testing.

## Ethics

The corresponding author states that this paper is original. Both authors have read the paper and approved of its content.

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