Densification of bio-char produced through a slow pyrolysis of Arabica coffee-pulp at various pressures

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ABSTRACT

A rise in annual coffee production poses an increase in coffee residuals which is a potential source of renewable energy. The use of coffee pulp, the outer skin of coffee cherry as a raw material for bio-briquettes may be an effective way to minimize their wastage as landfill. This study aims to examine the characteristics of densified bio-char produced through a slow pyrolysis process and pressed at a pressure of 100, 150 and 200 kg/cm^2. Prior to densification process, bio-char was ground and sieved to mesh 20. A mixture was then made by adding 40 wt% starch binder followed by molding and drying processes. Characterization of the briquette employs a number of techniques including SEM, bomb calorimeter and proximate analyses as well as mechanical testing. The results show that the calorific value of the coffee-pulp briquette is 16.86 MJ/kg containing 11.29 % of moisture, 12% volatile matter, 59.68% fixed carbon and 17.03.% ash. The average rate of combustion is 0.53 g/s with ignition time ranging from 609 to 795 s. Increasing briquetting pressure prolongs the time required for ignition as the density is increased. However, no significant change was observed on the rate of combustion upon increasing the briquetting pressure. This investigation concludes the potential use of coffee industry by-product as feedstock for solid biomass fuel production.

Keywords: Slow pyrolysis; coffee pulp; bio-char; briquettes

INTRODUCTION

Coffee is one of the most popular drinks in the world. From time to time the number of coffee consumers in either importing or exporting countries is increasing, leads to a rise in annual coffee production. In term of currency traded throughout the world, coffee is the second largest commodity where in September 2018, total world coffee exports reached 9.43 million 60-kg-bags [1]. In fact, processing of coffee produces waste of around 30% - 50% of its total weight depending on the type of processing [2]. Coffee husk and pulp are the main residues obtained after removing coffee beans during the dry or wet process. This requires an effective method of use as disposing this residual into the environment can bring serious environmental problems.

In many countries, a number of studies have been devoted to investigate the potential utilization of coffee waste however profitable and technically feasible methods are still under development. Currently, there are a number of strategies have developed for utilizing coffee industry-by-product including (1) mushroom cultivation, (2) production of enzymes, (3) biofuel production, (4) organic acid production, (5) bioactive compounds, (6) dietary fiber, (7) composting and vermicomposting [3]. Among these options, the conversion of coffee waste into biofuel looks like more potential and applicable for agriculture regions.

Basically, this biomass waste can be directly used as fuel, however the combustion process cannot be maximized due to several factors, including low density, non-competitive calorific value per unit volume, higher moisture contains and produces smoke [4]. Thus, briquetting is one of the most common strategies used for enhancing fuel quality and helps in establishing more effective fuel distribution, storage and utilization.

It is widely accepted that pyrolysis is one of the few biofuel technologies that can handle a wide range of biomass feed-stocks (agri-residues, forest residues, energy crops, municipal solid wastes). This method is an attractive option for expanding the possibilities of using less desirable biomass. Biochar is mostly used for water purification, power generation [5][6], and for amendment of soil in order to enhance the soil quality and sequester carbon [7][8]. Additionally, small pyrolysis plants are compatible with existing agriculture and forestry infrastructure, providing considerable flexibility for the feedstock[9]. Consequently, there is increasing attention on furthering applications of this technology.

In this study, biochar were produced from coffee pulp through a slow pyrolysis process at temperature below 600 °C. The main objective is to evaluate the combustion characteristic as well as finding the physical and mechanical properties of densified biochar.

METHODOLOGY

MATERIALS

The raw material, Arabica coffee-pulp was collected from Bener Meriah District of Aceh Province, Indonesia. Initially, coffee pulp was sun-dried for three days and fed to pyrolysis reactor for carbonization. Figure 1 shows the set-up of pyrolysis apparatus used for carbonization process and bio-char densification tool. This set-up consists of pyrolysis reactor, condenser, tar separator, gas burner and furnace. There are three points of temperature measurements were monitored during pyrolysis process, i.e. at the bottom, middle and top of vessel. For densification, bio-chars was ground and sieved to mesh 20 followed by adding 40 wt% of starch binder. A 120 g of resulting paste was then pressed by a home-made briquetting machine at pressures of 100, 150 and 200 kg/cm^2, later denoted as P100, P150 and P200 respectively. Briquette was then naturally dried for five days. Figure 2 shows a photograph of densified bio-chars with final diameter of 49 mm and height of 57, 54 and 47 mm respectively for P100, P150 and P200. It is noteworthy that the difference in height obtained in this briquetting process is due the difference in pressure applied with constant mass of 120 g of paste filled in the die.

TESTING AND CHARACTERIZATION

Combustion test was simply performed on stainless steel wire mesh placed on a stainless steel dish. Prior to testing, sample was weighted and dipped into kerosene. Ignition is started by using a lighter and temperature was monitored by using infrared thermometer. To analyse the content of moisture, ash, volatile mater and fixed carbon, proximate analysis was carried out following ASTM D1762-84 procedure as described in literature [10]. Bomb calorimeter Koehler K88900 is used to find-out the caloric value. Density of bio-briquettes ware measured according to ASTM B311 – 93 (1997) method [11]. Compressive strength of bio-briquettes were tested according to the standard test method as described in literature [12][13]. Determination of the relative size stability friability was carried-out based on ASTM D440 – 86 method [14]. SEM micrographs were captured by JEOL JSM-6510 machine.

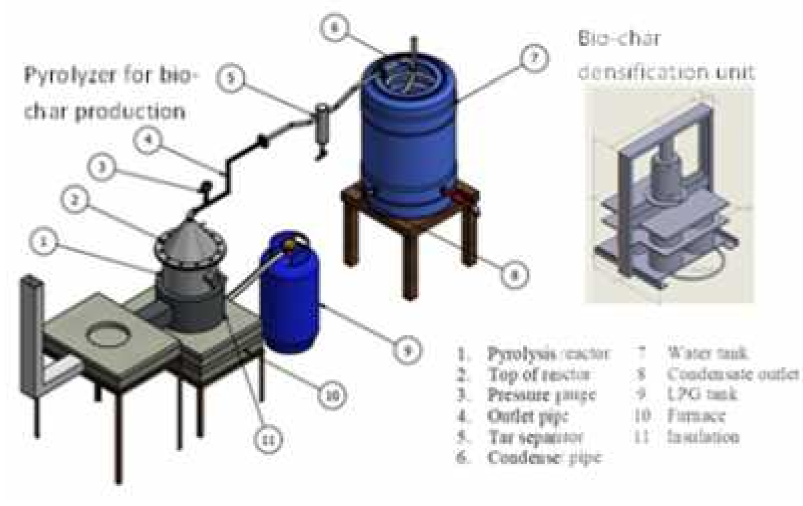

FIGURE 1. Apparatus set-up for coffee-pulp carbonization and densification

FIGURE 2. Densified biochar after drying

RESULTS AND DISCUSSION

Figure 3 displays the temperature profile recorded during pyrolysis process of coffee pulp. The maximum temperature reached at the bottom of the reactor was 580 °C after 2 h carbonization process at the heating rate of 3.7 °C/min. No more liquid smoke was produced after 4 h suggesting a maximum time for completed thermal decomposition of 3 kg coffee pulp. Table 1 summarizes products distribution of coffee pulp pyrolysis indicating biochar as the main product. There are 1.193 kg of char was produced from 3 kg feedstock (39.77% of total product) while tar and bio-oil are 7.33 % and 26.7 % respectively.

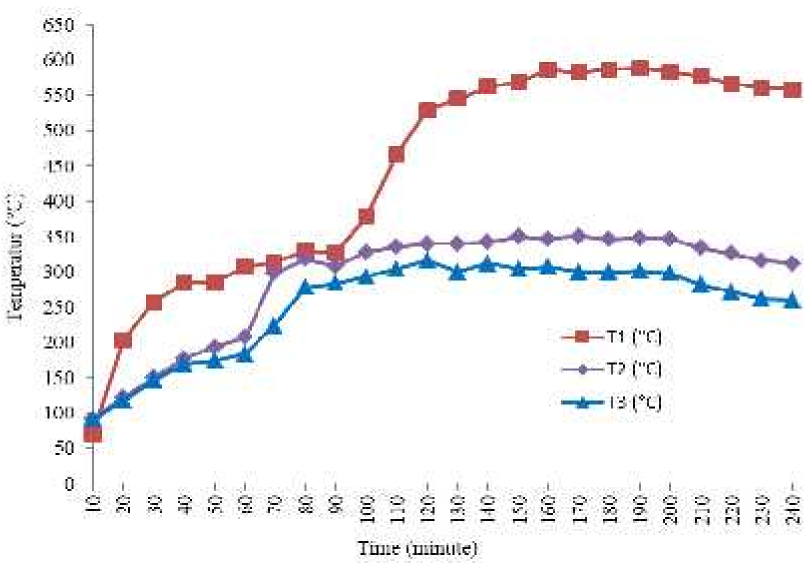

FIGURE 3. Temperature profile during coffee-pulp pyrolysis process

TABLE 1. Product distribution of pyrolysis of coffee-pulp

Parameter	Amount (kg)	Percentage (%)
Coffee pulp, raw material	3	100
Bio-char	1.193	39.77
Bio-oil	0.801	26.70
Tar	0.220	7.33
Un-condensable gas	balanced	balanced

Table 2 provides bomb calorimeter and proximate analysis results of densified biochar. The caloric value is ca. 16.86 MJ/kg which is comparable to bio-briquette caloric values reported in literature [15][16]. Proximate analysis result suggests that densified biochar contains 11.29 % moisture, 12.0 % volatile matter, 59.68 % fixed carbon and 17.03 % ash. A high content of fixed carbon obtained in this work is due to carbonization process under slow pyrolysis as the pyrolysis temperature was set below 600 °C [17][18].

TABLE 2. Proximate analysis results of densified bio-chars

Caloric value (MJ/kg)	Moisture (%)	Volatiles (%)	Fixed Carbon (%)	Ash (%)
16.86	11.29	12.00	59.68	17.03

The effects of densification pressure on the properties of bio-briquettes are summarized in Table 3. This table suggests that increasing briquetting pressure leads to increases in compressive strength, density and size stability. In term of compressive resistance, the maximum crushing load that can be withstand by a densified-biochar before breaking, the lowest value is 1.62 kgf/cm^2 obtained from P100 sample. By increasing densification pressure up to 200 kg/cm^2, the compressive strength enhances significantly becomes 7.41 kgf/cm^2. The density measured in this investigation is the particle density which is the apparent density of densified material considering the inner porosity. Density was measured after drying under the sun for five days by measuring the ratio of mass and sample volume including pore volume. Data in Table 3 indicates that the pressure applied for briquetting process significantly improves the apparent density where double-up the pressure increases density from 0.931 kg/cm^2 to 1.043 kg/cm^2. A similar relationship has been reported in the literature [19] where the density values were improved at higher compaction pressures, while porosity was significantly reduced. On the other hand, a slight change is observed in term of size stability and friability. Basically, this parameter is for measuring the relative resistance to breakage of densified biochar when handled during dispatching. Our data suggests a good ability of briquette to withstand breakage when subjected to handling although densification pressure is less.

TABLE 3. Properties of densified biochars

Parameter	Densification Pressure (kg/cm^2)		
	100	150	200
Density (g/cm^3)	0.931	0.962	1.043
Compressive strength (kgf/cm^2)	1.62	3.38	7.41
Size stability (%)	99.80	99.88	99.94

Friability (%)	0.19	0.12	0.06
Ignition time (s)	609	687	795
Burning rate (g/min)	0.57	0.53	0.48

The combustion test on each type of briquettes was performed at atmospheric pressure as described in previous section. Figure 4 shows temperature profile recorded during combustion tests. Initially, this solid fuel is burnt at temperature approximately 200 °C and reaches a maximum temperature of 535 °C after 50 minutes. This profile is similar to data reported in literature [20] where pine needle with clay as binder was densified and tested during the water boiling test. At any samples, the lowest temperature at which combustion begins and continues in a substance (ignition temperature) is *ca.* 200 °C. The effect of densification pressure on the ignition temperatures of the briquettes can be understood through ignition testing. Mostly, loose materials are easy to burn and also may have inconsistent burning characteristics. Indeed, densified materials should have uniform ignition temperatures [19]. In term of time required for starting ignition, as shown in Table 3, sample P100 takes 609 s to ignite while P200 starts ignition after 795 s. This means the more pressure the more time is required to start ignition. The flame time for each sample is varied depends on densification pressure. Not much effect was observed on the rate of burning upon increasing densification pressure.

The structure of the three coffee-pulp briquettes was examined under SEM in order to find differences between three levels of densification pressures. Figure 5 displays SEM images of sample P100, P150 and P200. These images indicate that during densification process there are wetting of particles and the agglomeration of the biochar particles since binder penetrates easily into pores [21]. These images support that densification pressure affects significantly the physical properties of the briquettes. As shown in SEM micrograph of P100 briquette (Figure 5a) the structure of the briquette is more porous compared to SEM micrograph of P150 (Figure 5b). Moreover, fewer pores can be observed in SEM micrograph of P200 briquette which indicates a higher density compared to P100 and P150 samples. This evidence is in line with density test result reported in Table 3 where apparent density is strongly affected by pressure applied during briquetting process.

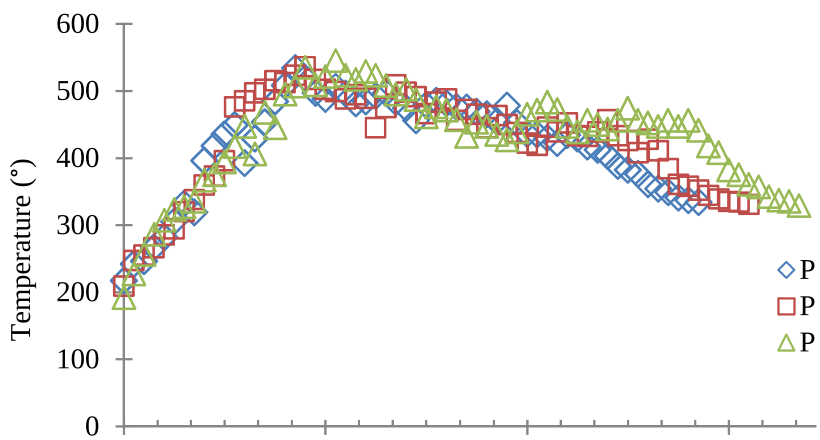

FIGURE 4. Temperature profile during coffee-pulp pyrolysis process

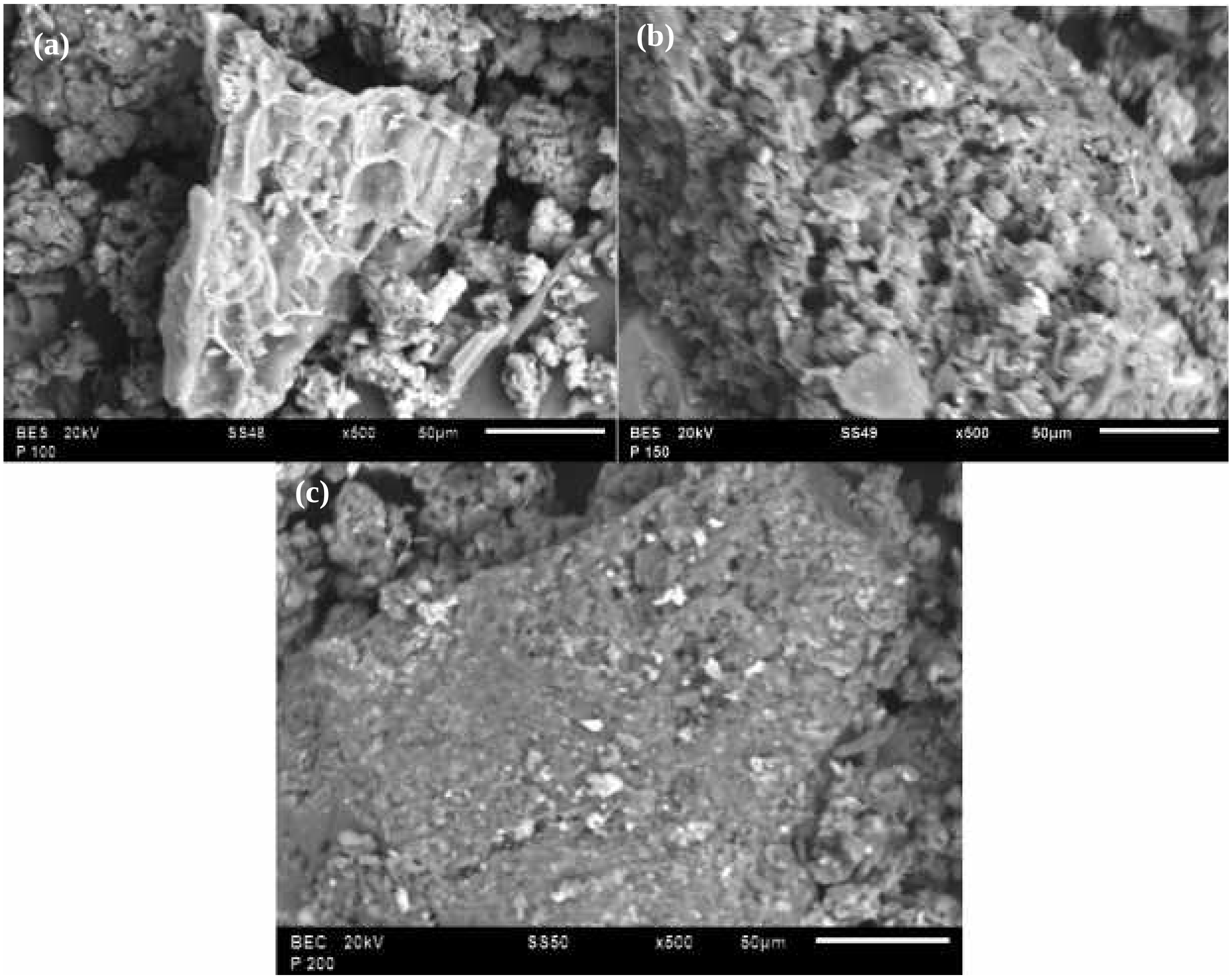

FIGURE 5. SEM images of densified biochars at pressure of (a) 100 kg/cm^2; (b) 150 kg/cm^2 and (c) 200 kg/cm^2

CONCLUSION

Coffee-pulp, a coffee agricultural residue, was successfully transformed into value-added products, i.e. biochar, bio-gas and bio-oil via slow-pyrolysis process. Carbonization of coffee-pulp together with adding 40 wt.% of starch binder resulted in an average caloric value of 16.86 MJ/kg and fixed carbon content of 59.68%. Densification of coffee-pulp char benefits in increased the energy density and mechanical properties. Burning test suggests an average of combustion rate is 0.53 g/s with ignition time ranging from 609 to 795 s. Increasing briquetting pressure slightly prolongs the time required for ignition as the density is increased. This investigation result highlights the potential use of coffee-pulp as raw material for solid biomass fuel production.

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REFERENCES

[1] ICO, International Coffee Organization: World coffee exports,2018. [Online]. Available: http://www.ico.org/. [Accessed: 04-Nov-2018].
[2] Oliveira, L.S. & Franca, A.S. 2015. An Overview of the Potential Uses for Coffee Husks. in Coffee in Health and Disease Prevention. Elsevier Inc.
[3] Janissen, B. & Huynh, T. 2018. Resources , Conservation & Recycling Chemical Composition and Value-Adding Applications of Coffee Industry-by-Products : A Review," *Resour. Conserv. Recycl* 128: 110–117.
[4] Haykiri-Acma, H. & Yaman, S. 2010. Production of Smokeless Bio-briquettes from Hazelnut Shell. *Proceedings of the World Congress on Engineering and Computer Science*, vol. II, pp. 20–22.
[5] Biederman, L.A. & Harpole, W.S. 2013. Biochar and its Effects on Plant Productivity and Nutrient Cycling : a Meta-Analysis. *GCB Bioenergy* 5: 202–214.
[6] Mahmood, A.S.N., Brammer, J.G., Hornung, A., Steele, A. & Poulston, S. 2012. The intermediate pyrolysis and catalytic steam reforming of Brewers spent grain. *J. Anal. Appl. Pyrolysis* 103: 328–342.
[7] Downie, A., Munroe, P., Cowie, A., Van Zwieten, L & Lau, D.M.S. 2011. Biochar as a Geoengineering Climate Solution: Hazard Identification and Risk Management. *J. Crit. Rev. Environ. Sci. Technol* 42(3): 1-6.
[8] Popp, J., Lakner, Z., Harangi-rákos, M. & Fári, M. 2014. The Efect of Bioenergy Expansion : Food, Energy, and Environment. *Renew. Sustain. Energy Rev* 32: 559–578.
[9] Laird, D.A., Brown, R.C., Amonette, J.E. & Lehmann, J. 2009. Review of the Pyrolysis Platform for Coproducing Bio-oil and Biochar. *Biofuels, Bioprod. Bioref.* 3:547–562.
[10] Aller, A., Bakshi, S. & Laird, D.A. 2017. Modified method for proximate analysis of biochars. *J. Anal. Appl. Pyrolysis* 124: 335–342.
[11] ASTM International, *ASTM B311-9. 1997. Test Method for Density Determination for Powder Metallurgy (P/M) Materials Containing Less Than Two Percent Porosity*. West Conshohocken, PA.
[12] Gilvari, H., de Jong, W. & Schott, D.L. 2019. Quality Parameters Relevant for Densification of Bio-Materials: Measuring Methods and Affecting Factors - A Review. *Biomass and Bioenergy*. 120: 117–134.
[13] ASTM International. 2010. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *Annual Book of ASTM Standards*, no. C. pp. 1–7.
[14] ASTM International. 2002. Standard Test Method of Drop Shatter Test for Coal. vol. 05, no. Reapproved. pp. 4–7.
[15] Rezania, S., *et al*. 2016. Evaluation of Water Hyacinth (Eichhornia Crassipes) as a Potential Raw Material Source for Briquette Production, *Energy* 111: 768–773.
[16] Rahaman, S.A. & Salam, P.A. 2017. Characterization of Cold Densified Rice Straw Briquettes and the Potential Use of Sawdust as Binder. *Fuel Process. Technol.* 158: 9–19.
[17] Hernandez-Mena, L.E., Pecora, A.A.B. & Beraldo, A.L. 2014. Slow Pyrolysis of Bamboo Biomass: Analysis of Biochar Properties. *Chem. Eng. Trans.* 37: 115-120.
[18] Angin, D. 2013. Effect of Pyrolysis Temperature and Heating Rate on Biochar Obtained

from Pyrolysis of Safflower Seed Press Cake," *Bioresour. Technol.*128: 593–597.
[19] Amarasekara, A., Tanzim, F.S. & Asmatulu, E. 2017. Briquetting and Carbonization of Naturally Grown Algae Biomass for Low-Cost Fuel and Activated Carbon production. *Fuel* 208: 612–617.
[20] Pandey, S. & Dhakal, R.P. 2013. Pine Needle Briquettes : A Renewable Source of Energy. *Int. J. Energy Sci.* 3(3): 254-260.
[21] Montiano, M.G., Díaz-Faes, E. & Barriocanal, C. 2016. Effect of Briquette Composition and Size on the Quality of the Resulting Coke. *Fuel Process. Technol.* 148: 155–162.

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