IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: Dewi A Iryani *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1187** 012007

Physicochemical Characterization of Wood Mixed with Coffee Waste Pellet

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Abstract Recently, the demand for wood pellets as solid biofuel for co-firing process in the industry has increased. However, the increase in demand is not accompanied by the availability of sawdust (SD) as a raw material. Thus, seeking alternative biomass is needed to substitute wood. One of the alternative biomasses that can be considered as raw material for bio-pellet is the solid waste from the coffee industry. Meanwhile, the coffee industry annually produces large amounts of organic waste such as spent coffee grounds (SCG) and coffee husks (CH). Both solid wastes have organic compounds contained so that they can be utilized as solid biofuel. In this research, We investigated the quality changes of wood pellets before and after the addition of coffee waste in different mass ratios (1:1, 1:3). A densification method with a pressure of 2 tons is used in the wood pellet-making process. Physicochemical characterization of wood pellets such as density, durability, compressive strength, calorific value, and proximate and composition analysis using SCG and CH are conducted. The result shows that the addition of SCG into wood pellet increased the calorific value of wood pellet from 21.03 $MJ.kg^{-1}$ to 21.71 $MJ.kg^{-1}$. The calorific value with a ratio of 50: 50 of SD: SCG produces a better calorific value than CH (20.64 $MJ.kg^{-1}$). The mechanical test of the pellet shows that the addition of SCG and CH slightly decreases the mechanical durability from 99.34% to 97.02%. Thus, increase the appearance density from ρ = 892.46 $kg.m^{-3}$ to ρ = 1119.33 $kg.m^{-3}$.
Keywords: wood pellet; waste management; coffee waste, calorific value, mechanical durability

1. Introduction

Coffee plants are one of the most important agricultural commodities in the world that have long been cultivated to become a source of income for the people [1], especially in Indonesia. This makes Indonesia become one of the largest coffee-producing countries that produce around 50% of the world's coffee production along with Brazil, Vietnam, and Colombia [2]. In 2020 coffee production in Indonesia reached 773,409 tons with a harvested area is 1,264,331 Ha, and this amount of data will be increasing every year based on the Central Bureau of Statistics in the year 2021. Furthermore, based on data from the International Coffee Organization Board (ICO) in the period September 2019, the share of Indonesia's consumption level among producing countries in Asia and Oceania is the highest at a rate of 13.5%. Along with the increase in coffee consumption, it also increases the amount of waste generated by the coffee industry which can cause very serious environmental pollution.

Coffee waste such as coffee husk (CH), coffee skin, and spent coffee ground (SCG) are included types of solid biomass. According to the Directorate of Postharvest and Business Development, Ministry of Agriculture Republic Indonesia, in 2010 each 1 ha of coffee plantation area produce around 1.8 tons of fresh coffee husk (CH) and coffee skin waste. Meanwhile, in the coffee industry, the largest producer of waste is spent coffee grounds (SCG) [3]. As a result, 1 kg of coffee beans produced in a large-scale industry will produce 400 g of instant coffee and the rest of the material is 600 g of SCG [4]. Coffee waste contains large organic compounds such as protein, carbohydrates, fats/oil, caffeine, fiber, cellulose, hemicellulose, tannin, lignin, amino acids, and minerals [4]. Direct disposal of waste into surrounding or landfills can be able to lead very high pollution in the environment due to its organic compounds which very easily to decay and cause unpleasant odors. In addition, the content of caffeine, tannins, and polyphenols in the waste is very toxic if directly discharged into the environment [3]. Thus, proper sustainable processing of this coffee waste is needed.

Meanwhile, the demand for wood pellets as solid biofuel for co-firing process in the industry has increased. However, an increase in demand is not accompanied by the availability of sawdust (SD) as a raw material. Thus, the proper alternative biomass to substitute wood that can be considered as raw material for bio-pellet is the coffee waste from the coffee industry. Previous studies have reported the use of coffee waste blend with SD is suitable to use considering their high calorific value [4, 5, 6] and could increase the calorific value of the wood pellet from 17.15 $MJ.kg^{-1}$ to 21.08 $MJ.kg^{-1}$ [6] with low CO emissions during the combustion process in the boiler [7]. Furthermore, the sawdust blending with these waste pellets becomes very advantageous as solid biofuel, which would be able to reduce waste and obtain a renewable energy source at the same time.

So far, there has been no research on the manufacture of solid fuels using variations of coffee waste such as spent coffee grounds and coffee husks mixed with sawdust. There for, based on the available literature review [3-7], the present paper is explained the physicochemical characterization of SD as wood pellet mixed with coffee waste in varied mass ratios. The process of making pellets is carried out by using a laboratory hydraulic pellet press. The evaluation is carried out on varied ratios of mass mixture between SD and coffee waste on the thermal quality of wood pellets. In addition, the investigation also discussed about the effect of mass ratio into high mechanical strength values.

2. Materials and methods

2.1. *Sample Preparation*

The sample preparation process consists of several methods, such as drying, grinding, and raw material characterization analysis. Before the pelletizing, all the samples were sun-dried for 3 days. Further, the coffee and SD as raw materials were analyzed with several characterization methods such as proximate analysis, calorific value, and composition analysis (cellulose, hemicellulose, and lignin). The coffee and SD biomass samples were ground using a hammer mill and then sieved using 20 mesh sieves. The samples that passed the sieve then proceeded into wood pellets.

2.2. *Wood Pellet Production*

The process of making wood pellets were prepared into 4 combinations in each mass ratio of coffee waste (CH and SCG) and SD with a ratio of (1:1), (1:3). Pelletizing of each sample took approximately one to two minutes. Due to the low strength of the pellets, the procedure for pellet making press was usually repeated 2 times using a hydraulic pellet press with a pressure of 2 tons.

2.3. *Wood Pellet Characterization*

The pellet physicochemical characterization consists of several analysis methods such as appearance density, mechanical Durability (EN ISO 17831-2), compressive strength was carried out by using a universal testing machine series IX version 8.27.00, proximate analysis was carried out by using the ASTM standard E-870-06, calorific value assessment performed using Bomb Calorimeter (PARR Model 6775 Digital Thermometer), chemical composition analysis (cellulose, hemicellulose, and lignin) was analyzed following to the modified Chesson-Datta method [8], and ash composition analysis using X-ray Fluorescence Spectroscopy (Panalytical Epsilon 3 XLE). Thus, all the chemical analysis data obtained were compared with the Indonesian Industrial standard for wood pellets (SNI 8021:2014. While the physical analysis such as mechanical durability and compressive strength were compared with European standards (EN 14961-2).

3. Result and discussion

3.1. *Pretreatment*

The initial water content of SCG, CH, and SD were high, namely 59%, 22%, and 23%. The air-dried treatment was able to reduce the water content SCG from 59% to 9.6% as well as CH and SD raw material analysis was then carried out in a dry air base. The result is shown in Table 2.

Table 1. Characteristics of SCG, CH, and SD

Parameter	SCG	CH	SD
Moisture (%)	9.60	12.39	12.77
Volatile Matter (%)	82.56	65.78	82.34
Ash (%)	1.54	6.18	0.70
Fixed Carbon (%)	6.30	15.66	4.19
Hemicellulose (%)	36.38	22.39	19.19
Cellulose (%)	13.88	14.13	45.06
Lignin (%)	11.58	29.84	24.98
Extractive Substance (%)	33.11	35.35	14.41
Calorific Value ($MJ.kg^{-1}$)	21.61	17.73	17.29

3.1.1. *Proximate Analysis*

Proximate analysis is an analysis that can estimate the performance of fuel during heating and combustion, including water content, ash, volatile Matter, and fixed carbon from biomass samples [9]. The water content of the raw materials SCG, CH, and SD has high water content, however, the water content is still accepted for the densification process with the content in a range of 8-23% [10]. The high water content in the raw material should be overcome because the raw material will not be able to provide optimal heat when it becomes fuel. It is because the water content in fuel will be removed by using the heat generated from the fuel. In addition, the high water content can cause low calorific value because water (H_2O) has no calorific value [11]. Meanwhile, for the value of the ash content obtained from the three raw materials, only CH has a high ash content value. But, at the same time, CH also has a low volatile content with a high fixed carbon value.

3.1.2. *Chemical Composition Analysis*

Biomass consists of extractive substances, hemicellulose, cellulose, and lignin. Hemicellulose in biomass has a branched structure that can simplify the hydrolysis process. The high hemicellulose of the three raw materials supports the densification process for the manufacture of wood pellets. While cellulose is a polysaccharide consisting of thousands of glucose bonds, it is also considered an abundant carbon site in biomass. The lignin content in biomass is a component that has a major influence on the densification process because lignin allows adhesion to the wood structure and could act as a natural adhesive in wood pellets [12]. The presence of high lignin content in SCG and CH allows the manufacture of wood pellets without the addition of adhesive.

3.1.3. *Calorific Value*

The calorific value is one of the important parameters for solid fuels. The high calorific value of biomass has produced good quality pellets. The calorific value produced by SCG, CH, and SD before the densification process showed a very satisfactory value. Especially for SCG, which has a very high calorific value. This shows that SCG has a high potential to be used as a pellet fuel.

3.2. *Wood Pellet Fuel Characteristics*

3.2.1. *Wood Pellet Results*

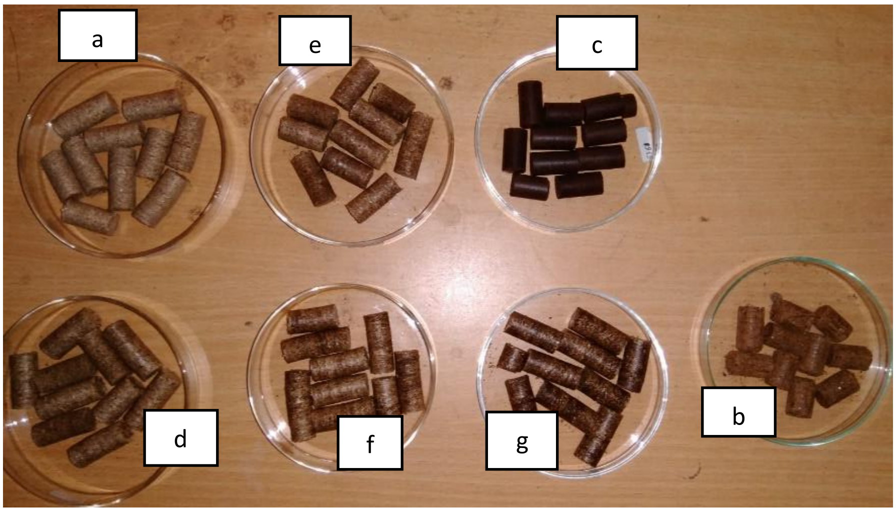

Figure 1. Wood pellet samples: (a) 100% SD, (b) 100% CH, (c) 100% SCG, (d) 25% CH + 75% SD, (e) 50% CH + 50% SD (f) 25% SCG + 75% SD, (g) 50% SCG + 50% SD.

All wood pellet samples were produced with the same diameter of 12 mm, but the length and weight are not uniform. From the analysis that has been obtained, the analysis of the pellets are as follows:

Table 2. Chemical analysis of wood pellet samples

Parameter	**SNI 8021:2014**	**Samples**						
		a	b	c	d	e	f	g
Moisture (%)	Max. 12	6.79	5.80	7.21	4.21	4.92	4.57	4.36
Volatile (%)	Max. 80	84.97	68.41	88.18	81.31	83.01	85.83	86.05
Ash (%)	Max. 1,5	1.39	10	1.85	3.11	6.54	1.72	1.76
Fixed Carbon (%)	Min. 14	6.85	15.79	2.75	11.38	5.53	7.88	7.84
Calorific Value ($MJ.kg^{-1-}$)	Min. 16.75	21.03	18.30	22.94	20.64	20.30	21.37	21.71
Enhancement Energy	-	-	-	-	0.98	0.96	1.016	1.032
Appearance Density ($kg.m^{-3}$)	Min. 600	892.46	974.23	1143.52	962.56	1119.33	905.28	986.18
Energy Density ($MJ.m^{-3}$)	-	18768.36	17828.36	26232.45	19867.17	22722.42	19345.92	21409.89
Hemicellulose (%)	-	21.92	24.24	43.13	20.53	22.05	28.11	34.20
Cellulose (%)	-	46.90	17.66	18.55	40.74	32.24	33.84	30.87
Lignin (%)	-	24.21	29.26	15.63	24.21	30.28	20.90	17.48
Extractive Substance (%)	-	9.69	29.77	23.98	14.07	20.14	14.09	18.06

Notes: (a) 100% SD, (b) 100% CH, (c) 100% SCG, (d) 25% CH + 75% SD, (e) 50% CH + 50% SD (f) 25% SCG + 75% SD, (g) 50% SCG + 50% SD.

3.2.1.1. *Density*

Appearance density is a measurement of the mass per unit volume of an object.. All of the assessments of the wood pellets showed in Table 2 have satisfactory results for their appearance density values if compared with the Indonesian pellets standard. However, the wood pellet after being mixed with CH and SCG the appearance density has increased because of the weight of CH and SDG is higher than SD. The appearance density data of each sample were then multiplied by their calorific value to estimate the Energy Density. The data shows that the pellet with a high ratio of 50% CH + 50% SD has the highest energy but the lowest calorific value.

3.2.1.2. *Proximate Analysis*

Moisture content was determined by calculating the weight loss of the biomass pellet after being heated at 105°C. For the ash content of the pellet, it was determined by the ratio between the amount of remaining material and the amount of burned material. The sample was heated in the furnace at a temperature of 575°C for 3 hours. The results obtained in Table 2 show that the addition of SCG and CH decreases the water content but increases the ash content of wood pellets. The pellet with a ratio of 25% CH + 75% SD has the lowest water content. However, a pellet with a ratio of 50% CH + 50% SD has a high ash value, and it has an impact on the calorific value results obtained. The high ash content also causes slagging in the combustion room. Meanwhile, pellet with a ratio of 50% SCG + 50% SD has an ash content lower than CH, although the results obtained are incompatible with the Indonesian pellets standard.

Meanwhile, in the case of volatile Matter and fixed carbon content, they were determined by heating the samples in a furnace at 950°C for 7 minutes. Table 2 shows that the addition of SCG and CH did not match the Indonesian pellets standard. The more addition of coffee waste to wood pellet produced a higher volatile and lower fixed carbon value. So further research is needed to get the most suitable pellet ratio to match the Indonesian pellet standard.

3.2.1.3. *Calorific Value*

The results of the calorific value test using a bomb calorimeter in Table 2 show that mixed wood pellets with SCG increase the calorific value of wood pellets. The highest calorific value is found in a ratio of 50% SCG + 50% SD. These results indicate that the more SCG was mixed, the higher the calorific value was produced. Meanwhile, for a ratio of 50% CH + 50% SD, there was a decrease in the calorific value as well as after the addition of CH. This may be due to differences in the water and ash content produced by the pellet after being mixed with SCG and CH. The calorific value of fuel pellets is known to be inversely proportional to the value of the water content, the higher the moisture content of a pellet, the lower the calorific value was produced. The calorific value is closely related to the moisture content and density of the resulting pellet [13]. The results show that pellets with higher hemicellulose content also produced a high calorific value.

3.2.1.4. *Chemical Composition Analysis*

Biomass consists of main components such as hemicellulose, cellulose, lignin, and also extractive substances. The percentage of hemicellulose and extractive Substance in coffee waste is higher than SD as a wood pellet. In opposite, cellulose content in coffee waste is lower than SD. This causes the addition of coffee waste to sawdust increasing the hemicellulose content yet decreasing the cellulose content. The data shows that the blending process in varied mass ratios of coffee waste and SD changes its chemical composition. Thus, it affects the calorific value of the pellet. The result shows that pellet with higher hemicellulose content also produced a high calorific value. It is clearly seen in the pellet with a mass ratio of 50% SCG + 50% SD. However, at a higher cellulose content, it can reduce the calorific value. From these results, it was concluded that hemicellulose greatly affects the calorific value.

3.2.1.5. *X-Ray Fluorescence Analysis*

This analysis aims to determine the mineral content of biomass pellet ash with the help of X-rays. The following figure is data on the mineral content of coffee grounds obtained from previous studies [2].

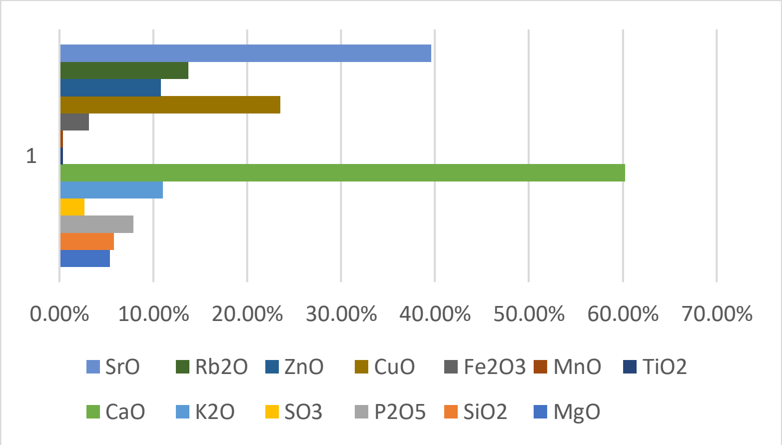

Figure 2. Mineral composition of spent coffee ground ash

XRF analysis was carried out on wood pellet samples with the highest calorific value, a ratio of 50% SCG + 50% SD. The results were compared with data on the mineral content of coffee grounds obtained from previous studies in Figure 2. This analysis was carried out to see the suitability of wood pellets if used as solid fuel.

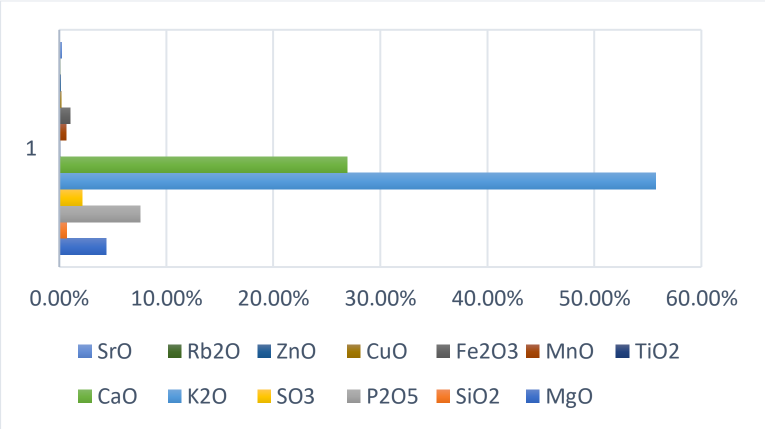

Figure 3. Mineral composition of 50% SCG + 50% Sawdust ash

The results show that the wood pellet with a ratio of 50% SCG + 50% SD increased the Potassium (K_2O) value. Potassium is one of the volatile substances in pellets. The high level of potassium in the pellets can cause ash to accumulate in the boiler, which will eventually affect slagging and fouling.

Table 3. Fouling and Slagging Index

Element Mineral (%)	Spent Coffee Ground Ash	50% SCG + 50% SD Ash
(B/A)	10,14	119,2
Fouling Index	0	0
Slagging Index	0,05	4,34
(TA)	0,41	1,96

Table 3 shows that there is an increase in the value of the slagging index at 50% SCG + 50% SD. According to the standard of the slagging index, the value obtained was high for used to be solid fuel. The use of coffee grounds as fuel provided a high calorific value but produced a high slagging index value. In this case, it is necessary to further improve the quality of pellets, one of which is leaching.

The second observed result was related to the visual conditions of produced wood pellet samples mixed with coffee waste. The analysis carried out includes physical analysis, which can be seen in the results below:

Table 4. Physical analysis of wood pellet samples

Parameter	EN 14961-2	Sample						
		a	b	c	d	e	f	g
Mechanical durability (%)	Min. 96.5	99.34	92.76	95.23	94.57	94.35	97.02	96.31
Compressive Strength ($N.mm^{-1}$)	-	270.78	33.66	39.05	101.58	81.68	215.06	137.25

Notes : (a) 100% SD, (b) 100% CH, (c) 100% SCG, (d) 25% CH + 75% SD, (e) 50% CH + 50% SD (f) 25% SCG + 75% SD, (g) 50% SCG + 50% SD.

Mechanical Durability (*DU*) is an indicator that represents the mechanical strength and capability of the pellets to withstand the impacts during the handling, shipment, or storage. *DU* is expressed as a mass percent ratio and is calculated by comparing all the initial weight of the pellets before and after the scrape of the material. This mechanical durability test used a vibrating sieve by inputting 50 pellets into a sieve for 10 minutes. From the results obtained in Table 4, the more SCG and CH are added to the wood pellet (a), the lower the *DU* value. The lowest value was obtained with a ratio of 50% CH + 50% SD. The addition of wood pellets with CH produces pellets with *DU* that do not meet the pellet's standard. Meanwhile, the value for the addition of wood pellets with SCG has reached the pellet's standard by a ratio of 25% SCG + 75% SD.

The mechanical indicator of Compressive Strength was applied to describe the stress of the pellet fuel in the application. The best results for compressive strength are obtained by a ratio of 25% SCG + 75% SD, which was expected because the *DU* values obtained were also the best. The compressive strength of wood pellet is not stated by any mandatory standards. Thus, there are no required levels to achieve [4]

4. Conclusion

From the results obtained, the addition of SCG and CH decreases the value of water content but increases the ash content of wood pellets. The result also shows that the addition of SCG into wood pellet increased the calorific value of wood pellet from 21,03 $MJ.kg^{-1}$ to 21,71 $MJ.kg^{-1}$. The calorific value with a ratio of 50% SCG + 50% SD produces a better calorific value than CH (20,64 $MJ.kg^{-1}$). The addition of more CH in the mixture with wood pellets must be reconsidered because CH has a very high ash content, so it results in a decrease in calorific value. For the mechanical analysis results, the best results were obtained at a ratio of 25% SCG + 75% SD. But, the addition of SCG and CS slightly decreases the mechanical durability from 99,34% to 97,02%. However, increase the appearance density from ρ = 892,46 $kg.m^{-3}$ to ρ = 1119,33 $kg.m^{-3}$.

Acknowledgment

The authors would like to thank the Analysis and Instrumentation Laboratory Department of Chemical Engineering University of Lampung, the Integrated Laboratory and Innovation Center University of Lampung, and also Nuju Coffee Shop as the supplier of coffee waste.

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