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Regional Case Study

Utilization of Organic and Plastic Waste as Solid Fuel for Steam Power Plants 3 Parit Baru Site Bengkayang

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Abstract

The problem of organic and non-economic LDPE plastic waste, which is abundant in the Singkawang City landfill, is accompanied by the reduced availability of coal as a fuel for steam power plants. Therefore, this study utilizes organic and plastic waste as biomass fuel that can be used in steam power plants using the co-firing method. This research aims to identify the characteristics, analyze the optimal composition based on SNI 8966:2021, and examine the influence of solid fuel composition. The research method used four composition variations: 100:0%, 95:5%, 85:15%, and 75:25. The best average water content, volatile matter, ash, fixed carbon, and calorific value were 4%, 60.67%, 11.33%, 2.67%, and 5,374.29 Kcal/kg, respectively. The characteristics of the solid fuel comply with SNI 8966:2021, except for the fixed carbon content. Based on the Kruskal-Wallis test, the fuel compositions for the characteristics of water content, volatile matter, ash, and calorific value are significantly different, with values of 0.035, 0.056, 0.041, and 0.016. Based on Spearman rank correlation analysis, water and ash contents decreased as the percentage of plastic increased, with correlation coefficients of -0.753 and -0.302. Meanwhile, the calorific value and volatile matter increased, with correlation coefficients of 0.811 and 0.972.

Keywords: Co-firing; LDPE plastic waste; organic waste; solid fuel; steam power plant

1. Introduction

Coal is a fuel derived from non-renewable natural resources therefor; the continuous use of coal over a long period can deplete its availability. Coal is a fossil fuel used as an energy source in power plants, including steam power plants. The use of coal as fuel can have environmental consequences, particularly in terms of pollution. The issue of coal availability and its associated impacts has led to the need for a planned strategy by the government, as outlined in the Presidential Regulation of the Republic of Indonesia Number 22 of 2017 in the National Energy General Plan (Praevia and Widayat, 2022).

One of the efforts that can be undertaken to enhance and support sustainable national development, particularly the percentage of New and Renewable Energy (NRE), is to implement biomass and coal co-firing in steam power plants with an NRE ratio of 5%. Co-firing involves the combustion of different types of materials, such as more efficient alternative fuels, mixed with fossil fuels, which can reduce coal consumption and lower the operating cost of the electricity industry (Xu et al., 2020).

By 2022, Singkawang City will have an average daily volume of waste transported to the Wonosari landfill of approximately 70.90 tons per day. The volume of waste that can be managed every day is 0.01%, which is achieved through the composting of organic waste and the pyrolysis of inorganic waste (Badan Pusat Statistik Kota Singkawang, 2023). The lack of effort and less than optimal waste processing has caused the Wonosari landfill land, or what is usually called the zone cell, to exceed its carrying capacity. It was recorded that the height of the pile of waste from the zone-cell embankment reached 7 m. Inorganic waste, particularly LDPE plastic in the form of plastic bags, has no economic value. LDPE plastic waste is one of the causes of rubbish in landfills because it cannot be degraded by nature or reused. Therefore, the waste volume problem at the Wonosari landfill can be overcome by utilizing organic waste and LDPE plastic waste as energy sources in the form of solid fuel. The Indonesian government has issued SNI 8966:2021, or Indonesian National Standard 8966:2021, concerning solid fuel standards to accelerate the use of biomass waste as a raw material for the production of recycled solid fuel in power plants. The SNI 8966:2021 Solid Fuel Standards for Power Plants are shown in Table 1.

Table 1. Solid fuel standards for power plants

Parameter	Unit	Class		
		1	2	3
Organic Material Levels	%, min	≥ 95	87.5 ≤ x < 95	80 ≤ x < 87.5
Moisture Content (ar)	% mass	< 15	< 20	< 25
Ash Content (ar)	% mass	< 15	< 20	< 25
Volatile Matter Content (ar)	% max mass	65	70	75
Fixed Carbon Content (ar)	% mass	> 15	>10	>5
Net Calorific Value (ar)	mJ/kg	≥ 20	≥ 15	≥ 10
Total Sulfur Content (ar)	% mass	≤ 1.5	≤ 1.5	≤ 1.5
Chloride Levels (ar)	% mass	≤ 0.2	≤ 0.6	≤ 1

The solid fuel produced will be used as fuel at the steam power plant 3 Parit Baru Site Bengkayang (PBSB), which employs a Circulating Fluidized Bed (CFB) boiler type. The Circulating Fluidized Bed (CFB) boiler is one of the combustion methods used for fluidized bed combustion. This technology is well known in the power generation industry owing to its economic aspects and the resulting exhaust gas emissions (Yuliyani et al., 2019). The use of alternative fuels is expected to reduce costs and pollution generated during the operation of the power plant.

Based on research conducted by Haiqyastri and Kamal (2022) in a mixture of pellets from riverbank tree waste, coconut shells, and plastic, the addition of LDPE plastic waste to the fuel increases its quality, including its calorific value. This study aimed to describe the characteristics of solid fuel derived from organic waste and plastic based on its composition, analyze the optimal composition based on SNI8966:2021, and analyze the effect of differences in composition on the characteristics of solid fuel. Therefore, this study was conducted to reduce and utilize urban waste and reduce the use of coal. Waste utilization is carried out as an alternative for handling non-economic organic and inorganic wastes.

2. Methodology

The method employed in this study is an experimental approach that involves variations in the composition of the solid fuel. The equipment used for the solid fuel experiment included 12 plastic baskets, a weighing scale, a dry organic waste shredder, a wet organic waste shredder (composting machine), scissors, an MC (Moisture Content) meter, and a pellet-making machine. The raw materials utilized consisted of dry organic waste (dry leaves), wet organic waste (vegetable and fruit scraps), and Low-Density Polyethylene (LDPE) plastic waste.

Variations in the composition of solid fuel raw materials in this research refer to the research conducted by Faizal et al., 2018 and Suryaningsih and Pahleva (2020). However, what differentiates this study from previous research is the addition of a comparison of the percentages of organic waste and LDPE plastic waste. The compositional variations are presented in Table 2.

Table 2. Variations in solid fuel composition

Variations	Organic Waste (%)	Plastic Waste (%)
I	100	0
II	95	5
III	85	15
IV	75	25

There were four variations of solid fuel compositions made from a mixture of organic and plastic waste, with a total sample weight of 3 kg, and the experiments were repeated three times (in triplicate). The ratio of dry organic waste to wet organic waste was 1:1 based on the total weight of organic waste.

The results of the solid fuel manufacturing process were subjected to laboratory tests to determine the characteristics of the solid fuel. The characteristics tested included calorific value and proximate analysis, which consisted of moisture, volatile matter, ash, and fixed carbon contents. The data obtained from the characteristics were then analyzed using the Statistical Package for Social Sciences (SPSS) program to determine the influence and relationship of the composition on the solid fuel characteristics.

2.1 The Stages of Solid Fuel Production

The stages of making solid fuel from a mixture of organic waste and LDPE plastic waste in this research refer to research by Brunner et al., (2021). The first stage involves sorting, collecting, and weighing organic and LDPE plastic waste at the Wonosari landfill site based on predetermined composition variations. The next stage is waste shredding, where dry organic waste is shredded using a makeshift shredding machine, wet organic waste is shredded using a composting machine, and LDPE plastic waste is cut using scissors after being cleaned beforehand. Subsequently, the shredded waste was dried under sunlight. The shredding process aims to reduce the amount of waste for a quicker drying process. Drying continued until the Moisture Content (MC) reached 15%, as measured by an MC meter, indicating that the moisture level in the waste was not excessively high.

The dried organic and plastic wastes were then mixed and weighed again based on compositional variations. At this stage, the Moisture Content (MC) was measured once more using an MC meter. Subsequently, fuel pellet production was performed using a pellet molding machine for each predetermined composition. The produced fuel pellets were then left to cool to reduce the temperature and humidity after exiting the pellet-molding machine. Once the temperature of the solid fuel was lowered, it was packaged in airtight plastic bags. The solid fuel samples were ready for laboratory testing.

2.2 Analysis of Solid Fuel Characteristics

The stages of analyzing the characteristics of solid fuel are as follows:

1. Moisture Content Analysis

The procedure for measuring moisture content, according to SNI 03-1971-1990, involved taking a sample of approximately ± 5 g and placing it in a porcelain dish. The sample was then placed in an oven at 105°C for 2 h, after which it was cooled in a desiccator for 30 min and re-weighed. Calculation of moisture content weight using the formula in Equation 1.

$$\text{Moisture Content} = \frac{(a-c)}{(a-b)} \, x \, 100\% \tag{1}$$

Where a is the total weight of the container and sample, b is the weight of the empty container, and c is the total weight of the container and sample after heating. The moisture content was determined by dividing the weight loss of the sample during heating by the initial weight of the sample, expressed in grams, and multiplying by 100% to obtain the percentage.

2. Volatile Matter Content Analysis

The procedure for measuring the volatile matter content, according to Standard Method 2540 E, involves taking a sample from the moisture content measurement and heating it again in a furnace at 550°C for 60 min. Subsequently, it was cooled in a desiccator for 30 min and the samples were re-weighed. The volatile matter content was calculated using Equation 2.

$$\text{VM Content} = (\frac{(a-c)}{(a-b)}\ x\ 100\%\ ) - \text{Moisture Content} \quad (2)$$

Where a is the total weight of the container and sample, b is the weight of the empty container, and c is the total weight of the container and sample after heating. The volatile matter content was determined by dividing the weight loss of the sample during heating by the initial weight of the sample, expressed in grams, and then multiplying by 100%. After the percentage of volatile matter was obtained, the final volatile matter content was subtracted from the moisture content.

3. Ash Content Analysis

The procedure for measuring the ash content according to ASTM E 830-87, involves taking the residue of the sample from the volatile matter measurement at a temperature of 550°C. The residue was heated in a furnace at 750°C for 30 min. Subsequently, the samples were cooled in a desiccator and weighed again. Calculation of ash content weight using the formula in Equation 3.

$$\text{Ash Content} = \frac{(c-b)}{(a-b)}\ x\ 100\% \quad (3)$$

Where a is the total weight of the container and sample, b is the weight of the empty container, and c is the total weight of the container and sample after heating. The ash content was determined by dividing the weight of the sample after heating by the initial weight of the sample, expressed in grams, and multiplying by 100%. This calculation provides the percentage of ash content in the sample.

4. Fixed Carbon Content Analysis

The fixed carbon content is analyzed using the ASTM D-3172-89 method. The fixed carbon content was calculated using Equation 4.

Fixed Carbon Content (%) = 100 - (Moisture Content + Ash + Volatile Matter) (4)

To obtain the fixed carbon content, the moisture content, volatile matter, and ash content percentages were summed and the total was subtracted from 100%. This provided the percentage of fixed carbon in the sample.

5. Calorific Value Analysis

The principle of determining the calorific value is by using a bomb calorimeter device based on ASTM D5865, titled "Standard Test Method for Gross Calorific Value." The procedure for using A bomb calorimeter was used with a total of 0.5 grams of sample and one iron coil was placed in a platinum cup. The bomb calorimeter was closed until it was tight, then the "bomb" was filled with O2 to a pressure of 25 atm, and then the "bomb" was inserted into the calorimeter filled with water. A certain amount of electricity was applied to the iron wire, and after combustion occurred, the temperature increase was measured as the time after ignition. When bomb combustion is high, a uniform temperature of the surrounding water must be maintained with a stirrer. The heat capacities of the "bomb," calorimeter, stirrer, and thermometer were determined through separate experiments.

2.3 Data Analysis Method

Following laboratory testing, the features of the solid fuel data were examined using the Statistical Package for Social Sciences (SPSS) application, which includes Spearman's rank correlation analysis and the Kruskal-Wallis test. When analyzing data from more than two unrelated samples, the Kruskal-Wallis test was employed to determine how composition affects solid fuel properties. The degree of similarity, direction of the link, and significance of the relationship between the solid fuel composition and features were evaluated using Spearman rank correlation analysis. The relationship between the calorific value and moisture content, volatile matter content, ash content, and fixed carbon content was also investigated using Spearman rank correlation analysis.

3. Result and Discussion

3.1 Solid fuel production result

The production of solid fuel begins with the sorting and collection of raw materials, including organic waste (dry leaves, vegetables and fruit scraps) and inorganic waste (LDPE plastic waste). Dry leaf waste weighing 15.975 kg and vegetables, fruit scraps waste weighing 15.975 kg are required, whereas LDPE plastic waste weighing 4.05 kg is needed. These raw materials were used to produce solid fuel with three repetitions for each composition. The raw materials used for the solid fuel are shown in Figure 1.

(a) (b) (c)

Figure 1. (a) Dry leaves (b) vegetables and fruit scraps (c) LDPE plastic waste

The next process involves the shredding and drying of the raw materials. Shredding is performed to reduce the size for more effective drying and subsequent pellet molding, whereas drying aims to reduce the moisture content in the waste. Organic and LDPE plastic wastes were shredded using shredding machines and scissors. The shredding equipment used is shown in Figure 2.

(a) (b) (c)

Figure 2. (a) Shredding vegetables and fruits (b) Shredding dry leaves (c) Shredding LDPE plastic waste

The raw materials were dried for 6 days under sunlight, and the Moisture Content was measured using a moisture content (MC) meter. Vegetable and fruit scrap waste initially had a moisture content of 45.3%, which was reduced to 20%–25% after drying, whereas dry leaf waste had a moisture content of 20%. The drying process of the raw materials is shown in Figure 3.

(a) (b) (c)

Figure 3. Drying and MC measurement (a) vegetables and fruit scraps (b) dry leaves (c) LDPE plastic waste

The raw materials were mixed based on predefined compositional variations, with each variant using 3 kg of raw materials for each repetition. In this process, moisture measurements were taken for each variation, with the average moisture content of the mixed raw materials of organic and plastic waste in variations I, II, III, and IV being 32.5%, 27.53%, 27.26%, and 15.03%, respectively. This process is illustrated in Fig. 4. Making solid fuel from a mixture of organic waste and LDPE plastic waste does not require adhesives or fuel binders. This is because the pellet press produces heat and pressure, which can shrink and press a mixture of organic waste and LDPE plastic waste into a round mold. Thus, fuel pellets can be properly formed or printed without using a binder or adhesive mixture.

(a) (b) (c)

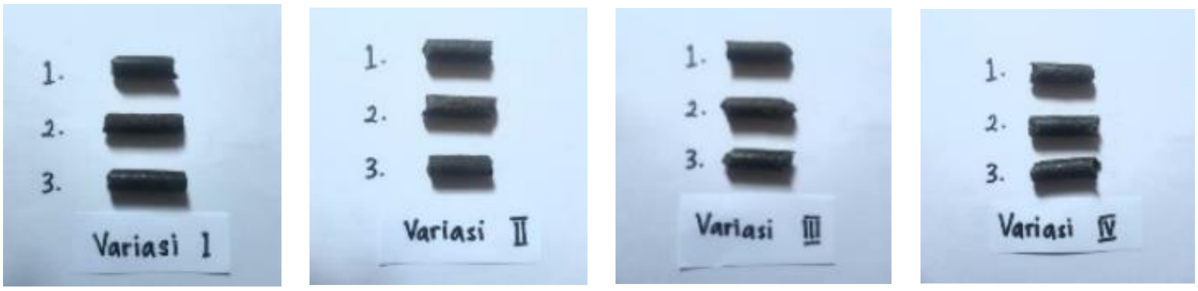
Figure 4. (a) Weighing (b) mixing (c) moisture content measurement

Solid fuel in pellet form will be well-formed if the raw materials have a moisture content in the range of 26%–35%. If the moisture content is less than 26%, the raw material becomes powdered because of excessive dryness. However, if the moisture content is more than 35%, the raw material is too wet, and the pellets will not form properly. This is because the pellet-making machine generates heat that can add additional moisture to the raw material and cause plastic shrinkage, allowing it to blend with other wastes. The moisture content of the raw material in variation IV was 15.03%; therefore, water was slowly added during the pellet-making process to bring the moisture content in the range of 26%–35%. The pellet formation process is illustrated in Figure 5.

(a) (b) (c)

Figure 5. (a) Solid fuel pellet molding (b) drying solid fuel (c) solid fuel packaging

The results of the raw material being shaped into pellets are shown in Fig. 6, with a length of approximately ± 2 cm or 20 mm and a diameter of 0.8 cm. The resulting length met the SNI 8966:2021 standard, which is ≤ 40 mm or 4 cm. Based on research by Gilvari et al., (2020), molded pellets are then dried or allowed to cool before being packaged in airtight plastic bags. After coming out of the molding machine, the pellets have a temperature ranging from 42°C to 46°C with an average of 44°C. This drying process is intended to lower the pellet temperature to approximately 20 - 25°C so that the pellets can be packaged in airtight plastic bags. The results of solid fuel pellets with four variations are shown in Figure 6.



(a) (b) (c) (d)

Figure 6. Solid fuel pellet results (a) variation 1 (b) variation 2 (c) variation 3 (d) variation 4

3.2 Results of the Solid Fuel Characteristics Analysis

The characteristics of the solid fuel, including moisture content, volatile matter content, ash content, fixed carbon content, and calorific value, are listed in Table 3.

Table 3. Results of solid fuel characteristics analysis

Variation	Repetition	Characteristics				
		Moisture Content (%)	Volatile Matter Content (%)	Ash Content (%)	Fixed Carbon Content (%)	Calorific Value (Kcal/kg)
I	1	10	60	28	2	2,961.06
	2	16	60	22	2	2,773.81
	3	12	62	24	2	2,946.24
Average		**12.67**	**60.67**	**24.67**	**2**	**2,893.70**
II	1	14	76	8	2	4,346.18
	2	10	76	10	4	4,315.99
	3	14	68	16	2	4,040.29
Average		**12.67**	**73.33**	**11.33**	**2.67**	**4,234.15**
III	1	6	74	18	2	4,451.83
	2	2	80	16	2	4,645.27

Variation	**Repetition**	**Characteristics**				
		Moisture Content (%)	**Volatile Matter Content (%)**	**Ash Content (%)**	**Fixed Carbon Content (%)**	**Calorific Value (Kcal/kg)**
	3	4	78	16	2	4,458.53
Average		**4**	**77.33**	**16.67**	**2**	**4,518.54**
IV	1	4	76	18	2	4,966.02
	2	8	76	14	2	5,501.57
	3	4	78	16	2	5,655.29
Average		**5.3**	**76.67**	**16**	**2**	**5,374.29**

3.2.1 Characteristics of the Solid Fuel Moisture Content

The moisture content characteristics of the solid fuel, a mixture of organic and plastic waste, based on SNI 8966:2021, are shown in Figure 7.

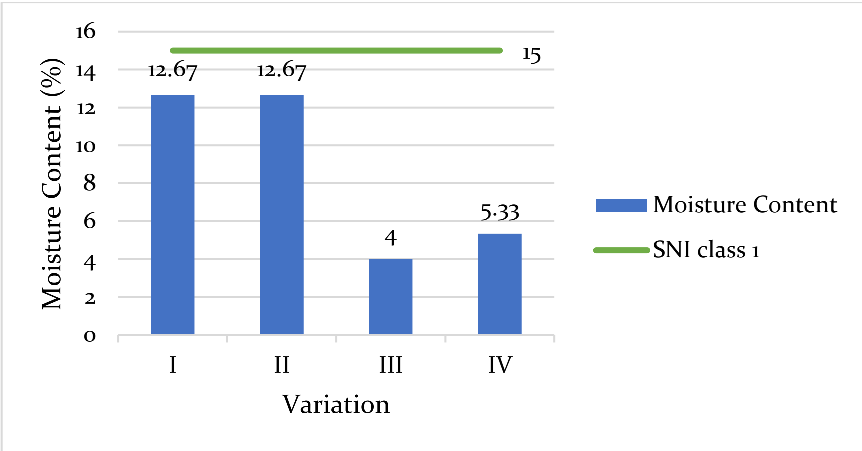


Figure.7. Moisture content vs. SNI 8966:2021

The average moisture content values for each variation complied with the SNI 8966:2021 standard for Class 1, which was <15%. The lowest average moisture content was found in Variation III, which was a mixture of 85% organic waste and 15% plastic waste, with a moisture content of 4%. The highest average moisture content was found in Variations I and II, which were a mixture of 100% organic waste and a mixture of 95% organic waste and 5% plastic waste, both with the same moisture content value of 12.67%.

The components of waste with high moisture content are organic waste and compost, whereas inorganic waste has a low moisture content (Novita and Damanhuri, 2010). As the percentage of LDPE plastic waste in the mixture increases, the moisture content of the solid fuel decreases. Faizal et al., (2018) stated that this is because the plastic content in organic fuel is resistant to absorbing water into the LDPE plastic. The low moisture content was also due to sufficient drying during the organic raw material process.

The moisture content of the solid fuel is the ratio of the weight of water contained in the solid fuel to the dry weight of the solid fuel itself (Dharma, 2013). Moisture content is directly related to calorific value and density, with a high moisture content leading to a decrease in calorific value (Saputro and Widayat, 2016). The moisture content of a fuel affects its calorific value and combustion power. A high moisture content can reduce the calorific value and vice versa. A high moisture content reduces the conversion efficiency and performance (Ruslinda et al., 2017). This is because energy is used to vaporize the water in the fuel, making ignition difficult and producing more smoke (Sukarta and Ayuni, 2016).

3.2.2 Characteristics of the Solid Fuel Volatile Matter Content

The characteristics of the volatile matter content in solid fuel, a mixture of organic and plastic waste, based on SNI 8966:2021, are shown in Figure 8.

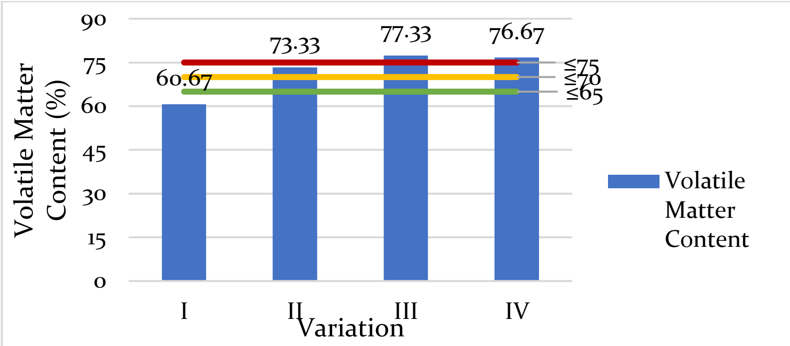


Figure 8. Volatile matter content vs. SNI 8966:2021

The average volatile matter content in Variation I complies with the SNI 8966:2021 Class 1 standard, in Variation II complies with the SNI 8966:2021 Class 3 standard, while in Variations III and IV, it exceeds the standards of Classes 1, 2, and 3. The lowest average volatile matter content was found in Variation I, which is a mixture of 100% organic waste with a volatile matter content of 60.67%. Meanwhile, the highest average volatile matter content was found in Variation III, which was a mixture of 85% organic waste and 15% plastic waste, with a volatile matter content of 77.33%.

The volatile matter is composed of active substances found in coal, including easily combustible gases such as hydrogen (H), carbon monoxide (CO), and methane (CH_4) (M. Midiawati and Saptadi, 2018). The lower the percentage of LDPE plastic waste, the lower the volatile matter content. According to Faizal et al., (2018), an increase in the percentage of LDPE results in a higher volatile matter content in the fuel. This is because, as per research by Asip et al., (2014), LDPE plastic has the highest volatile matter content of 99.73%.

A high volatile matter content in the fuel results in more smoke (Wibawaputri et al., 2021). Additionally, a high volatile matter content causes the fuel to ignite quickly and burn at a high rate, resulting in increased fuel consumption (Suryaningsih and Pahleva, 2020). Research by Obernberger and Thek (2004) indicates that fuels with high volatile matter content release most of their calorific value as combustion vapors.

3.2.3 Characteristics of the Solid Fuel Ash Content

The characteristics of the ash content in solid fuel, which is a mixture of organic and plastic waste, based on SNI 8966:2021, are shown in Figure 9.

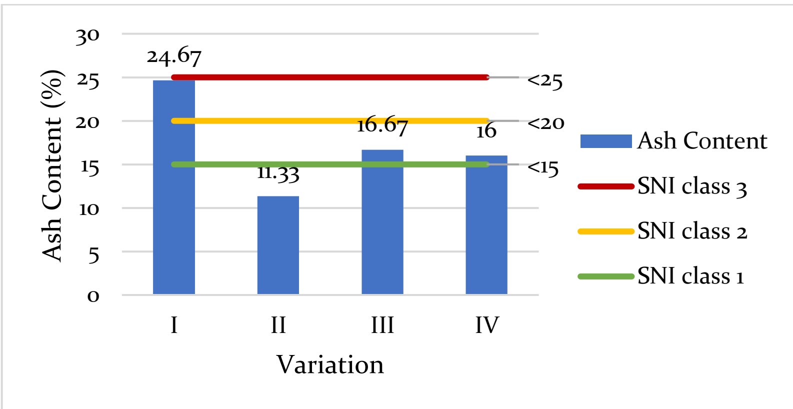


Figure 9. Ash content vs. SNI 8966:2021

The average ash content values in Variation I meet the SNI 8966:2021 Class 3 standard, in Variation II meet the SNI 8966:2021 Class 1 standard, while in Variations III and IV, they meet the SNI 8966:2021 Class 2 standard. The lowest average ash content was found in Variation II, which was a mixture of 95% organic waste and 5% plastic waste, with an ash content of 11.33%. Meanwhile, the highest average ash content was found in Variation I, which is a mixture of 100% organic waste with an ash content value of 24.67%.

Ash is the residual product of combustion and one of its components is silica. Non-combustible minerals remain and become ash (Iriany et al., 2023). An increase in the percentage of LDPE plastic waste decreases the ash content of the fuel. According to Wibawaputri et al., (2021), inorganic materials such as plastic contain substances that are easily combustible and evaporable, whereas ash is the residue of easily evaporated or volatile matter. However, a high ash content can cause pollution as impurities, leading to deposits and corrosion of the equipment used. An increased ash content in the fuel can lower the calorific value. However, a low ash content in fuel increases the calorific value, as supported by Faizal's research (2018).

3.2.4 Characteristics of the Solid Fuel Fix Carbon Content

The characteristics of the fixed carbon content in solid fuel, which is a mixture of organic and plastic waste, based on SNI 8966:2021, are shown in Fig. 10.

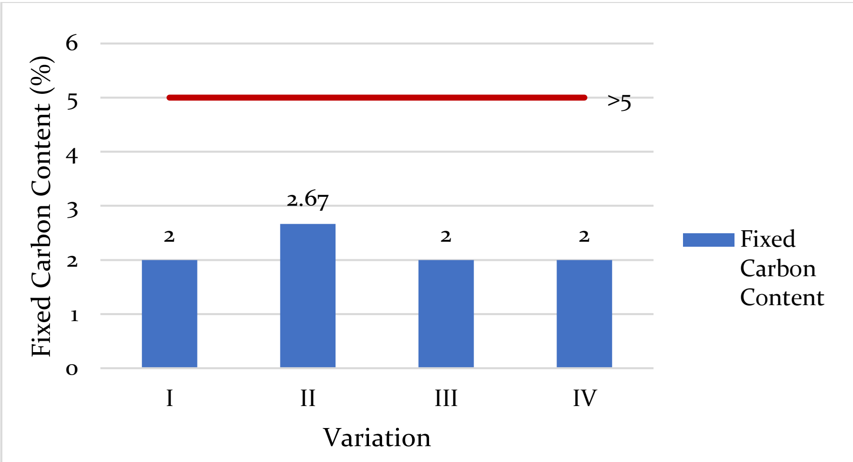


Fig. 10. Fixed Carbon Content vs. SNI 8966:2021

The average fixed carbon content values in each variation did not meet the SNI 8966:2021 standards for Classes 1, 2, and 3. The lowest average fixed carbon content was found in Variations I, III, and IV, which were a mixture of 100% organic waste, 85% organic waste and 15% plastic waste, 75% organic waste and 25% plastic waste, with a fixed carbon content of 2%. The highest average fixed carbon content was found in Variation II, which is a mixture of 95% organic waste and 5% plastic waste, with a fixed carbon content of 4%.

This fixed carbon value represents the carbon content that does not vaporize during high-temperature heating or when determining the volatile matter content (2021 Imani et al., 2021). The low fixed carbon content of the solid fuel mixed with organic and plastic waste is thought to be due to the organic waste not having a high lignin content. According to Ruslinda (2017), the fixed carbon content in 100% coconut shell fuel is 18.41%, and the high fixed carbon content is caused by the high lignin content in this fuel because lignin is a combination of several compounds whose contents are closely related to each other. It contains carbon, hydrogen, and oxygen, and the proportion of carbon is greater than that of the carbohydrate compounds. According to Saputro and Widayat (2016), lignin is a plant component that functions as a binder to bind cells together, making it usable as a natural adhesive for alternative fuels.

Therefore, organic waste, which is suitable for use as a fuel, is an organic material with a wood structure that contains lignin. Examples of organic wastes that are suitable for use are palm shells, empty fruit bunches, and coconut shells. This is supported by research by Suryaningsih and Pahleva (2020), Haiqyastri and Kamal, (2022), and Ruslinda et al., (2017), which states that coconut shells have the highest fixed carbon content and the highest carbon composition. Fuel mixed with palm shells or coconut shells had a higher percentage than that of plastic waste. This mixed fuel is suitable because its characteristics such as water content, volatile matter content, fixed carbon content, ash content, and calorific value meet the standards used.

3.2.5 Characteristics of the Solid Fuel Calorific Value

The characteristics of the calorific value of solid fuel, which is a mixture of organic and plastic waste, based on SNI 8966:2021, are shown in Figure 11.

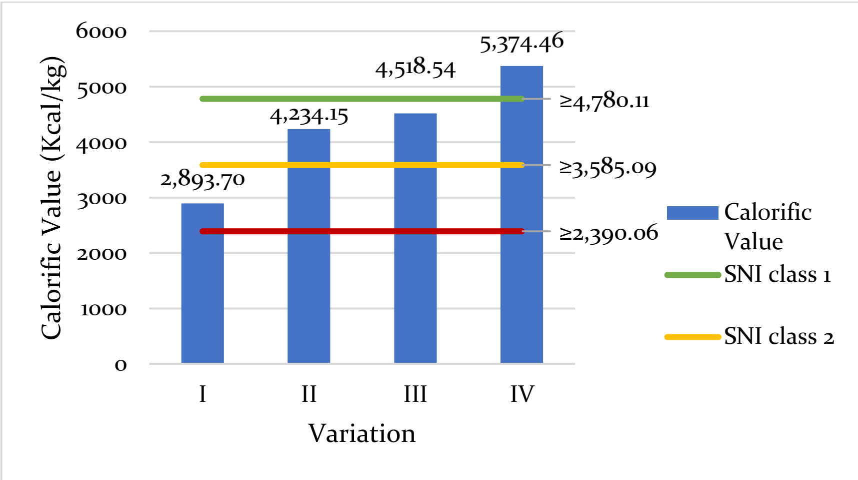


Figure 11. Calorific value vs. SNI 8966:2021

The average calorific value in Variation I complies with the SNI 8966:2021 Class 3 standard, in Variations II and III complies with the SNI 8966:2021 Class 2 standard, and in Variation IV complies with the SNI 8966:2021 Class 1 standard. The lowest average calorific value is found in Variation I, which is a mixture of 100% organic waste with a calorific value of 2,893.7 Kcal/kg. Meanwhile, the highest average calorific value was found in Variation IV, which is a mixture of 75% organic waste and 25% plastic waste, with a calorific of 5,374.46 Kcal/kg.

The amount of heat (kJ) evolved by the complete combustion of 1 kg of fuel is known as the calorific value of the fuel (kJ/kg) (Srinivas, T., 2017). The calorific value of solid fuel, a mixture of organic and plastic waste, increases with an increasing percentage of LDPE plastic waste. According to Ruslinda et al., (2017). this is because plastics consist of long carbon chains and other elements. This carbon content makes plastics highly combustible and gives them a high calorific value. The calorific value is an important quality parameter for fuels; the higher the calorific value produced, the better its quality (Sari et al., 2018).

3.3 Influence of Composition on Solid Fuel Characteristics

The results of the influence of the composition on the solid fuel characteristics using the Kruskal-Wallis test are listed in Table 4.

Table 4. Kruskal wallis test results of composition on solid fuel characteristics

Characteristics	Moisture Content	Volatile Matter Content	Ash Content	Fixed Carbon Content	Calorific Value
Asymp.Sig.	0.035	0.056	0.041	0.392	0.016

There were significant differences in the moisture content, volatile matter content, ash content, and calorific value concerning the composition of the solid fuel. This is because the Asymp.Sig value was < 0.05, indicating that the moisture content, volatile matter content, ash content, and calorific value of the solid fuel in each composition variation were significantly different. However, there was no significant difference in the fixed carbon content of the solid fuels. This was because the Asymp.Sig value was > 0.05, indicating that the fixed carbon content in each variation was not significantly different.

The influence of the relationship between the composition variations and solid fuel characteristics using the Rank Spearman correlation analysis method is shown in Table 5.
Table 5.

Table 5. Correlation analysis results of composition on solid fuel characteristics

Characteristics	Moisture Content	Volatile Matter Content	Ash Content	Calorific Value
Correlation Coefficient	-0.753**	0.811**	-0.302	0.972**
Sig.	0.005	0.001	0.340	0.000

The coefficient value of the moisture content correlation, which approaches 0.75, can be interpreted as a strong relationship between the composition variations and moisture content. The negative value indicates that the composition variations and moisture content have an inverse relationship, meaning that if the plastic waste composition increases, the moisture content in the solid fuel will decrease. The significance value of the composition variations on moisture content was 0.005 < 0.05, indicating a significant relationship between the composition variations and moisture content.

The coefficient value of the volatile matter content correlation, which approaches 0.75, can be interpreted as a very strong relationship between compositional variations and volatile matter content. A positive value indicates that composition variations and volatile matter content have a direct relationship, meaning that if the plastic waste composition increases, the volatile matter content in the solid fuel will increase. The significance value of compositional variations on volatile matter content was 0.001 < 0.05, indicating a significant relationship between compositional variations and volatile matter content.

The coefficient value of the ash content correlation, which approaches 0.50, can be interpreted as a moderate relationship between the composition variations and ash content. The negative value indicates that composition variations and ash content have an inverse relationship, meaning that if the plastic waste composition increases, the ash content in the solid fuel will decrease. However, the significance value of compositional variations on ash content was 0.340 > 0.05, indicating that the relationship between compositional variations and ash content was not significant.

The coefficient value of the calorific value correlation, which approaches 0.99, can be interpreted as a very strong relationship between the composition variations and calorific value. A positive value indicates that composition variations and calorific value have a direct relationship, meaning that if the plastic waste composition increases, the calorific value of solid fuel will increase. The significance value of composition variations on the calorific value is 0.000 < 0.05, indicating a significant relationship between composition variations and calorific value.

4. Conclusion

To the best of our knowledge, this study is the first to use a mixture of LDPE, dry organic, and wet organic plastic waste as raw materials for solid fuel. Wet organic vegetable and fruit wastes were randomly selected from the landfill. According to the results, the best average moisture content was 4% with a composition of 85% organic waste and 15% plastic waste. The best average volatile matter content was 60.67% in the 100% organic waste composition. The best average ash content was 11.33% with a composition of 95% organic waste and 5% plastic waste. The best average fixed carbon content was 2.67% with a composition of 95% organic waste and 5% plastic waste. The best calorific value was 5,374.29 Kcal/kg with a composition of 85% organic waste and 25% plastic waste. Solid fuel has characteristics that meet the SNI 8966:2021 standards, except for the fixed carbon content. This is because the fixed carbon content in each variation did not meet the class 1, 2, and 3 standards in SNI 8966:2021. However, the optimal composition based on the highest calorific value is found in solid fuel with a composition of 75% organic waste and 25% plastic waste, namely 5,374.29 Kcal/kg.

The effect of composition variations on solid fuel characteristics based on the Kruskal–Wallis test showed that there were significant differences in the moisture, volatile matter, ash contents, and calorific value of solid fuel for each variation. Based on the Spearman Rank correlation test, composition variations have an inverse relationship with moisture content and ash content, meaning that increasing the plastic content causes a decrease in the moisture content and ash content of the solid fuel. However, the volatile material content and heating value have a unidirectional relationship, meaning that increasing the plastic content causes an increase in the volatile material content and heating value. Therefore, in the future, further research is needed regarding the right mixture and the impact of solid fuel to produce optimal solid fuel.

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