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Conversion of Edamame Pods (*Glycine max*) and Cassava Peel into Biobriquettes Using a Mixture Fly Ash and Bottom Ash: Thermal Characteristics and Optimization

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Abstract

The increase in population has led to a rise in energy demand, resulting in the depletion of energy reserves, particularly non-renewable sources. One solution to this issue is the development of alternative energy sources, such as biomass-derived biobriquettes. This study investigates the impact of material composition and mesh size on the thermal characteristics of biobriquettes. The raw materials used include edamame pods, bottom ash, and cassava peel as an adhesive. The pyrolysis of edamame pods was conducted at 250 °C for 30 min. An experimental method was employed to test the thermal characteristics, including calorific value, moisture content, ash content, volatile matter content, and combustion rate. The results of the biobriquette test were compared to the standards set by SNI 01-6235-2000, which pertains to wood charcoal briquettes. The test results indicate that the optimal briquettes consist of 90% edamame pods charcoal and 10% bottom ash, with a mesh size of 40. These briquettes exhibit a calorific value of 20,717.1 J/g, a moisture content of 2.72%, an ash content of 18.67%, a volatile matter of 61.49%, and a burning rate of 0.146 g/min.

Keywords

biobriquettes, edamame pods, fly ash, bottom ash, cassava peel

1 Introduction

The global energy crisis continues to intensify due to the rapid depletion of non-renewable energy resources, driven by population growth and industrialization. As a result, there is an urgent need to develop sustainable and renewable energy alternatives. Biomass energy, which leverages agricultural and organic waste, represents one of the most promising solutions to address these challenges [1].

Among various biomass materials, agricultural residues such as edamame pods hold significant potential as raw materials for energy conversion. Edamame, widely cultivated in Jember Regency, East Java, generates large quantities of pods as waste. According to the Statistics Agency of Jember Regency, soybean production reached 4,456.40 tons in 2022 [2], resulting in a substantial surplus of pod waste (BPS) [2]. However, the utilization of this waste is limited due to its high moisture content, which complicates storage and processing [3].

Coal serves as the primary energy source at Jawa Bali Power Generation Company. The uninterrupted combustion of coal has led to a notable accumulation of solid waste in the form of fly ash and bottom ash (FABA). In the year 2022, Jawa Bali Power Generation Company produced 110,000 tons of FABA waste, which equates to 350–400 tons/day. The mass of bottom ash is greater than that of fly ash. Following the combustion of the coal, bottom ash will descend directly to the base of the boiler, whereas fly ash will merge with the flue gas. The fixed carbon content of bottom ash is in the range of 27,196 to 28,451 J/g, representing a proportion of approximately 4 to 42%. Fly ash or coal fly ash is typically deposited in landfills situated in industrial zones [3]. In the absence of further processing, the FABA waste presents a significant environmental hazard, with the potential to pollute the surrounding area [4]. In accordance with Government Regulation

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No. 22 of 2021 [5] regarding the implementation of environmental protection and management, it is specified that FABA is not classified as hazardous or toxic waste.

This study aims to investigate the production of biobriquettes from edamame pods and FABA using cassava peel as a natural binder. Specifically, the research evaluates the influence of raw material composition and mesh size on the thermal characteristics of biobriquettes, including calorific value, moisture content, ash content, volatile matter, and combustion rate. It is anticipated that this research will result in the development of an alternative energy source that can replace fossil fuels.

2 Materials and methods

2.1 Materials

The primary materials used in this study were edamame pods, coal FABA, cassava peel and water. Edamame pods and cassava peel employed in this study are presented in Figs. 1 and 2, respectively.

(a)

(b)

Fig. 1 Fresh and dried edamame as raw materials for bio-briquettes: (a) fresh edamame pods; (b) dried edamame pods

(a)

(b)

Fig. 2 Fresh and dried cassava peel as biomass binder for briquette production: (a) fresh cassava peels; (b) dried cassava peels

The tools used in this study comprises a pyrolysis apparatus, a sieve with mesh sizes of 40, 60, and 80, a briquette moulding apparatus, a flouring apparatus, an analytical balance, a blender, a stopwatch, a bomb calorimeter (IKA Calorimeter Brand, type C 2000 Basic Version 1., Artisan Technology Group, USA), an oven manufactured by Memmert, a furnace, a wooden mortar, a pestle, a stove, and an LPG gas cylinder (Charcoal Pyrolysis Machine, BEJE Brand, Type UPK 08., Bahagia Jaya Sejahtera Ltd., Indonesia).

2.2 Experiment design

This research is a quantitative study that employs experimental data collection techniques. The objective of this research was to ascertain the thermal characteristics of biobriquettes, including calorific value, moisture content, ash content, fly content and combustion rate. The research design incorporates a number of variables, which facilitate the analysis of the research efficiently. The variables and sample data employed in this study are presented in Tables 1 and 2, respectively.

2.3 Batch study experiments

The research comprises a series of stages, including the preparation of raw materials, the production of adhesives, the carbonisation process, the manufacture of biobriquettes, the drying of biobriquettes, the testing of biobriquettes, and the subsequent data analysis. A detailed schematic diagram of the experimental procedure is presented in Fig. 3.

Table 1 Research variables

Dependent Variable	Control Variable	Independent Variable
Caloric value Moisture content Ash content Burning rate Combustion rate	The process of carbonisation is completed in 30 min. The optimal carbonisation temperature is 250 °C. The dimensions of the biobriquette are 3 × 3 × 3 cm. The adhesive composition constitutes 25% of the total composition	The composition ratio of edamame pods : fly ash is 90:10; 70:30; and 50:50. The composition ratio of edamame pods : bottom ash is 90:10; 70:30; and 50:50. The sieve sizes are 40, 60, and 80 mesh.

Table 2 Research sample data

Mesh Size	Edamame Pods : Bottom Ash			Edamame Pods : Fly Ash		
	50 : 50	50 : 50	70 : 30	90 : 10	70 : 30	90 : 10
40	A1	A1	A2	X1	Y1	Z1
60	B1	B1	B2	X2	Y2	Z2
80	C1	C1	C2	X2	Y3	Z3

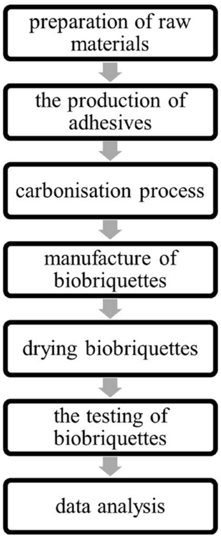

Fig. 3 Diagram of the experimental procedure

2.3.1 Raw material preparation

The raw materials were prepared by drying the edamame pods and cassava peel in the sun for four days. The edamame pods and cassava peels were sun-dried for four days to reduce their moisture content. This step is critical to ensuring optimal performance during the carbonization and briquetting processes. The dried materials were then stored in a dry and ventilated area to prevent reabsorption of moisture prior to further processing.

2.3.2 Adhesive preparation

The initial stage in the production of cassava peel adhesive entails the pulverisation of the desiccated cassava peel using a flouring machine, resulting in a fine powder. Subsequently, water is to be added to the cassava peel flour in a ratio of 1:3. The final step is to cook on a low heat and stir until the mixture is evenly distributed, in order to prevent the formation of lumps.

2.3.3 Carbonization

The initial phase of the carbonization process entails the preparation of the pyrolysis apparatus and ancillary equipment. The carbonisation temperature was 250 °C and lasted for 30 min in air-free atmosphere.

2.3.4 Biobriquette production

The initial stage of the biobriquette production process entails the combination of edamame pods charcoal and fly ash in a 50:50, 70:30, or 90:10 ratio, respectively. Similarly, the same process can be applied to bottom ash treatment. Subsequently, the mixture should be transferred to a briquette moulding machine and blended five times in order to ensure an even distribution and a smooth consistency. The final stage of the process is to shape the dough into briquettes using a briquette moulding machine with dimensions of 3 × 3 cm.

2.3.5 Drying of biobriquettes

In this study, biobriquettes were dried in an oven maintained at a temperature of 105 °C for a period of five hours.

2.3.6 Biobriquette testing

The biobriquette testing aims to determine key characteristics, including calorific value, moisture content, ash content, fly substance content, and combustion rate. To provide a clearer understanding an image of the finished biobriquettes is provided in Fig. 4.

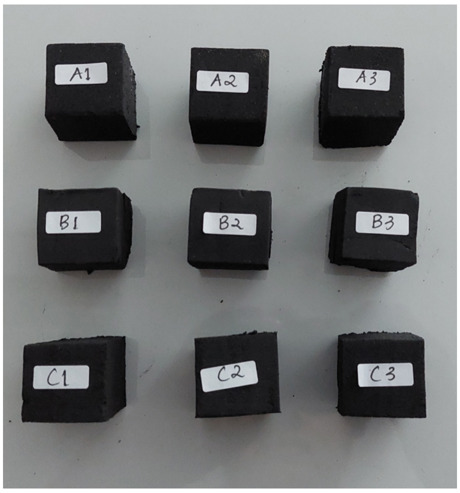

Fig. 4 The biobriquettes

2.3.7 Data analysis

The data analysis involves a quantitative assessment of these parameters based on the test results. The data was processed using multiple linear regression tests with the Rstudio application [6].

3 Results and discussion

3.1 Calorific value of biobriquettes

3.1.1 Analysis of the influence of raw material composition on calorific value of biobriquettes

The results of the analysis of the effect of raw material composition on the calorific value of biobriquettes mixed with edamame pods and FABA are presented in Fig. 5.

Fig. 5 illustrates that an increase in the proportion of coal FABA raw material utilized is associated with a reduction in the calorific value of the resultant biobriquette sample. This is influenced by the silica content and ash content in FABA, whereby the higher the silica and ash content in the briquette, the lower the calorific value. Additionally, coal fly ash exhibits a high ash content, reaching approximately 35.45% and 46.99% silica dioxide [7]. The high heat insulator properties of silica result in the inhibition of heat transfer from the briquette to the environment. This can lead to a reduction in the level of combustion efficiency and calorific value of the briquette [8].

Edamame pods contain hemicellulose and cellulose carbon compounds, which are carbohydrate polymers that can be broken down into sugars through the pyrolysis process when burned. During combustion, these compounds will generate heat as a result of oxidation reactions [9]. Consequently, an elevated hemicellulose and cellulose content will result in a heightened calorific value, as the combustion process generates a greater quantity of energy.

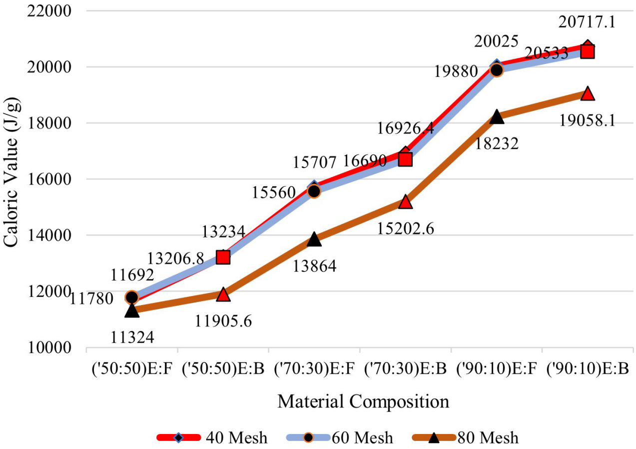

Fig. 5 Analysis of the influence of raw material composition on calorific value (B: bottom ash; E: edamame peel; F: fly ash)

Additionally, the high calorific value can be attributed to the carbonization process undergone by the edamame pods biomass, which results in a high carbon value. The carbonization process increases the carbon value and facilitates the removal of hydrogen and oxygen content, resulting in a carbon-rich product [10]. This finding aligns with previous research, which observed that the optimal composition of biobriquettes comprised a 90:10 ratio of alaban wood charcoal biomass and bottom ash, with an average heating value of 24,577.82 J/g [7].

3.1.2 Analysis of the influence of mesh size on calorific value of biobriquettes

The results of the analysis of the impact of varying mesh sizes on the calorific value of biobriquettes mixed with edamame pods and FABA are presented in Fig. 6 below.

Fig. 6 illustrated he 40 mesh particle size is identified as the optimal particle size among the three variations. This is due to the fact, that as the particle size increases, the heating value produced also increases. This assertion is consistent with the findings of Jaswella et al.'s [11] research, which also indicates that the calorific value is higher with larger particle sizes. A larger particle size will result in a larger gap or cavity between the particles, which will consequently lead to a lower density level. During the drying process, water is more readily evaporated from the pores of the briquette, thus producing briquettes with a reduced water content. A reduction in water content will result in an increase in the calorific value of the briquette itself [12].

The density of the briquette affects the oxygen supply within the briquette. A smaller particle size results in a higher density, which in turn decreases the oxygen supply. This hinders the combustion process and results in

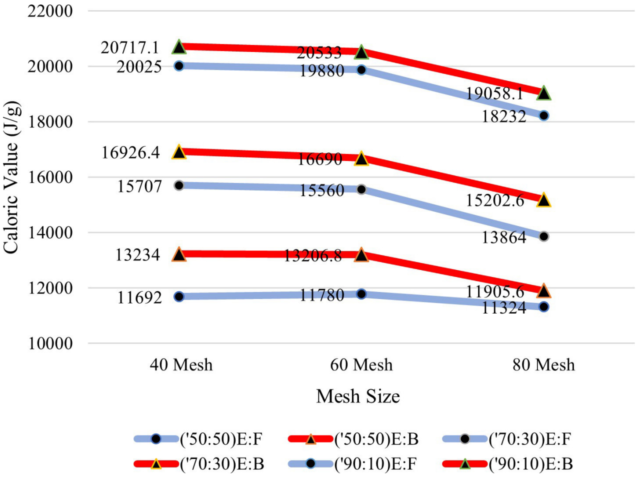

Fig. 6 Analysis of the influence of mesh size on calorific value (B: bottom ash; E: edamame peel; F: fly ash)

a lower calorific value [13]. This finding is consistent with the results of the study conducted by Sahoo et al. [14], which demonstrated that the highest calorific value of biobriquettes mixed with cassava peel and coal was observed in a 40:60 composition variation with a 20 mesh size variation of 21,200.58 J/g. Conversely, the lowest calorific value was observed in a 30:70 composition variation with a 30 mesh size variation of 19,022.83 J/g.

3.1.3 Statistical analysis of the effect of material composition and mesh size on the calorific value of biobriquettes

Statistical data analysis on calorific value is done by calculating multiple linear regression tests. The results of the calorific value multiple linear regression tests are shown in Table 3.

Based on the data in Table 3, the mesh size shows a p-value < 0.05, which means that the variation of mesh size has a significant effect on the calorific value. For the composition of the edamame pods, the p-value < 0.05 indicates that the variation of the composition of the edamame pods has a significant effect on the calorific value. The equation model of the effect of variation in composition of edamame pods and variation in mesh size on calorific value based on the results of multiple linear regression test analysis in Rstudio [6] is as follows:

$$y = 1154.118 + \left(-88.679 x_1\right) + 45.115 x_2 .$$

Based on the model equation, each unit reduction of mesh size percentage will increase the calorific value and each unit increase of edamame pods composition will increase the calorific value. The normality test results show that the p-value of 0.2557 > 0.05 so that the residuals are normally distributed and the assumptions are met. The heteroscedasticity test results show that the p-value is 0.6458 > 0.05 so there is no heteroscedasticity and the assumptions are met. The autocorrelation test results show that the p-value of $1.472 \times 10^{-8} < 0.05$ so that there is no autocorrelation and the assumptions are met. The multicollinearity test results show that the variance inflation factor (VIF) value is 1 < 10 so there is no strong correlation between the independent variables and the assumptions are met.

Table 3 Multiple linear regression test results of biobriquette calorific value

Term	Estimate	p-value	Description
Intercept	1154.12	2.75×10^{-8}	Significant impact
Mesh size	–8.68	1.42×10^{-5}	Significant impact
Composition of edamame pods	45.12	$< 2 \times 10^{-16}$	Significant impact

3.2 Moisture content of biobriquettes

3.2.1 Analysis of the influence of raw material composition on moisture content of biobriquettes

The results of the analysis of the effect of raw material composition on the moisture content of biobriquettes mixed with edamame pods and coal fly ash are presented in Fig. 7.

Fig. 7 illustrates that the average high water content is produced in briquettes mixed with coal fly ash and edamame pods, while in bottom ash briquettes with edamame pods, the average water content is relatively lower. As Yaashikaa et al. [15] have observed, the charcoal content in edamame soybean pods exhibits a relatively low moisture content. As elucidated in Aransiola et al.'s [16] paper, the water content of edamame soybean pods charcoal is influenced by the ratio of hemicellulose to cellulose carbon compounds, which in turn affects the water absorption capacity of briquettes. The aforementioned carbon compounds are instrumental in the binding of water. The content of hemicellulose and cellulose exhibits hygroscopic properties, whereby this property enables the absorption and retention of water. In light of the aforementioned evidence, it can be posited that the incorporation of edamame pods into briquettes may serve to enhance the overall water content. This is due to the hydrophilic properties of biomass, which readily absorbs water, in contrast to FABA [17]. This finding is consistent with the research of Das et al. [18], which demonstrated that the highest average water content of biobriquettes mixed with alaban wood charcoal and bottom ash was observed in the 90:10 material composition variation, with an average water content of 4.10%. Conversely, the lowest average water content was observed in the 80:20 material composition variation, with an average water content of 2.95%.

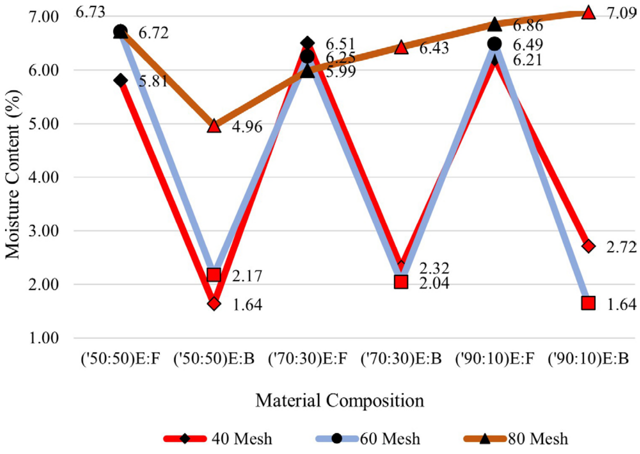

Fig. 7 Analysis of the influence of raw material composition on moisture content (B: bottom ash; E: edamame peel; F: fly ash)

A review of the data presented in Fig. 7 leads to the conclusion that the water content of the nine briquette samples tested meets the quality standards set forth in SNI 01-6235-2000 [19], as the water content of the biobriquettes is less than or equal to 8%. The optimal water content in briquettes is also a consequence of the optimal drying process of the briquettes.

3.2.2 Analysis of the influence of mesh size on moisture content of biobriquettes

The results of the analysis of the impact of varying mesh sizes on the moisture content of biobriquettes mixed with edamame pods and coal FABA are presented in Fig. 8.

Fig. 8 illustrated the water content of briquettes produced with fly ash is notably higher than those manufactured with bottom ash. This is attributable to the distinctive characteristics of fly ash, which is notably finer in particle size than bottom ash. The particle size of the charcoal (and thus the mesh size) is inversely proportional to the moisture content of the briquettes. The small particle size of the charcoal results in the formation of a limited number of cavities or pores in the biobriquette, which in turn facilitates the retention of water within it during the drying process. As stated by Ngene et al. [12], the water content of a briquette increases with a reduction in its particle size. Particle sizes that are larger have a diminished capacity to absorb water in comparison to smaller and more finely divided particle sizes. This evidence corroborates the assertion made in the Ngene et al. [12] that the moisture content of the nine briquette samples is directly proportional to their particle size. This finding is consistent with the research of Sahoo et al. [14], which revealed that the highest average water content of biocoal briquettes was observed in the 30 mesh size variation (6.77%), while the lowest average water content was observed in the 10 mesh size variation (5.26%).

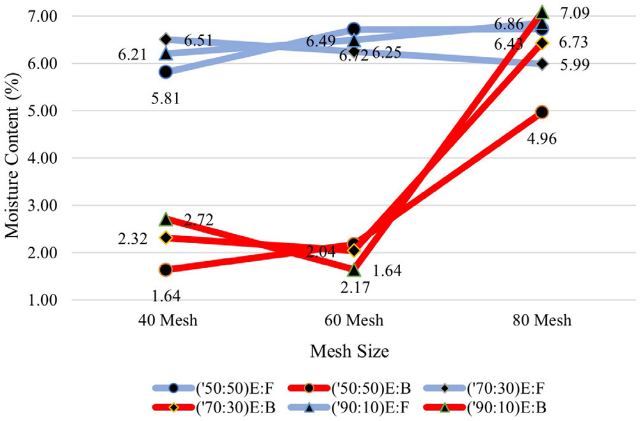

Fig. 8 Analysis of the influence of mesh size on moisture content (B: bottom ash; E: edamame peel; F: fly ash)

3.2.3 Statistical analysis of the effect of material composition and mesh size on the moisture content of biobriquettes

Statistical data analysis on moisture content is done by calculating multiple linear regression tests. The results of the calorific value multiple linear regression tests are shown in Table 4.

Based on the data in Table 4, the mesh size shows a p-value < 0.05, which means that the variation of mesh size has a significant effect on moisture content. For the composition of the edamame pods, the p-value > 0.05 indicates that the variation of the composition of the edamame pods does not significantly affect the moisture content. The equation model of the effect of variation in composition of edamame pods and variation in mesh size on moisture content based on the results of multiple linear regression test analysis in Rstudio [6] is as follows:

$$y = 0.84201 + 0.05354 x_1 + 0.01240 x_2 .$$

Based on the model equation, each additional unit of mesh size increases the moisture content and each additional unit of percentage composition of edamame pods has no significant effect on increasing the moisture content. The normality test results show that the p-value of $0.09461 > 0.05$, so the residuals are normally distributed and the assumptions are met. The results of the heteroscedasticity test show that the p-value is $0.2513 > 0.05$, so there is no heteroscedasticity and the assumptions are met. The results of the autocorrelation test show that the p-value is $5.765 \times 10^{-13} < 0.05$, so there is no autocorrelation and the assumptions are met. The results of the multicollinearity test show that the VIF value is $1 < 10$, so there is no strong correlation between the independent variables and the assumptions are met.

Table 4 Multiple linear regression test results of biobriquette moisture content

Term	Estimate	p-value	Description
Intercept	0.84	0.66	No significant impact
Mesh size	0.05	0.01	Significant impact
Composition of edamame pods	0.01	0.54	No significant impact

3.3 Ash content biobriquettes

3.3.1 Analysis of the influence of raw material composition on ash content of biobriquettes

The results of the analysis of the effect of raw material composition on the ash content of biobriquettes mixed with edamame pods and coal fly ash are presented in Fig. 9 .

Fig. 9 illustrates a clear correlation between the ratio of coal FABA raw materials used in the sample and the resulting ash content of the briquettes. As the ratio of coal FABA raw materials increases, the ash content of the briquettes also increases. The presence of ash in briquettes can negatively impact their quality, particularly in terms of their calorific value. One of the components of the ash is silica, which has been demonstrated to reduce the calorific value of briquettes [8]. Additionally, the paper by Jaswella et al. [11] indicates that coal fly ash contains a high ash content of approximately 35% and silica dioxide of 47%. It is established that coal bottom ash contains approximately 60% silica. Consequently, the incorporation of bottom ash into the briquette mixture has the effect of increasing the ash content of the briquettes [18]. This finding aligns with the research of Makepa et al. [7], which revealed that the highest average ash content of biobriquettes mixed with alaban wood charcoal and bottom ash is in the 70:30 material composition variation, with an average ash content of 27%. Conversely, the lowest average ash content was observed in the 90:10 material composition variation, with an average ash content of 8%. It can be concluded from these data that an increase in the proportion of fly ash or coal bottom ash in the composition of briquettes will result in an increase in the ash content. This is due to the high ash and silica content of coal FABA. This is also pertinent to the calorific value of the briquettes.

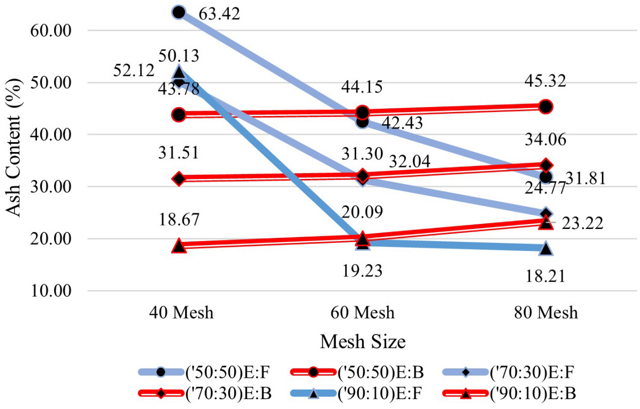

Fig. 9 Analysis of the influence of raw material composition on ash content (B: bottom ash; E: edamame peel; F: fly ash)

3.3.2 Analysis of the influence of mesh size on ash content of biobriquettes

The results of the analysis of the impact of varying mesh sizes on the ash content of biobriquettes mixed with edamame pods and coal FABA are presented in Fig. 10 below.

Fig. 10 illustrates there is a discernible correlation between particle size and the ash content of briquettes. The ash content of the briquettes is inversely proportional to the mesh size used and the particle size of the raw material. Conversely, the ash content is directly proportional to the mesh size used and the particle size of the raw material. This is due to the fact that particle size affects the density of the briquettes. The combustion of biobriquettes with small particle sizes is hindered due to their high density, resulting in incomplete combustion and the production of residual ash [20]. Fig. 10 illustrates a distinct graphical trend in the ash content of fly ash mixture briquettes. This phenomenon can be attributed to the inherent characteristics of fly ash, which possess a minute particle size and a density comparable to that of ash. The production of denser briquettes with a tighter structure is facilitated by the use of finer particle sizes, which also reduces the likelihood of ash formation during combustion. This finding is consistent with the results presented in the article by Senneca and Cerciello [21], which demonstrated a decrease in ash content with an increase in particle size. Additionally, the paper indicates that elevated ash levels are attributable to the relatively limited water content in the briquettes, which consequently results in a greater residual ash output during combustion.

A comparison of the data in Fig. 10 with the requirements set out in SNI 01-6235-2000 [19] indicates that all briquette samples tested have a very high ash content, exceeding the minimum requirement of 8%.

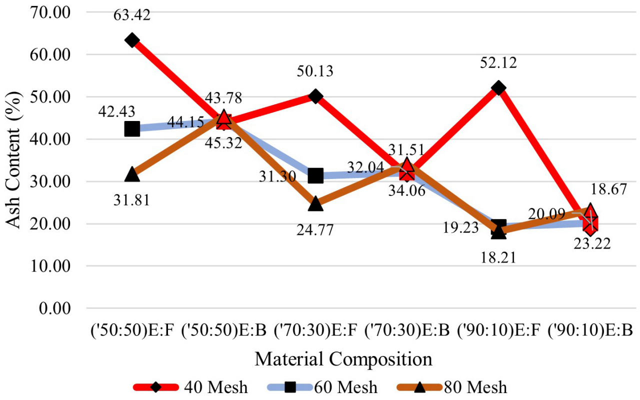

Fig. 10 Analysis of the influence of mesh size on ash content (B: bottom ash; E: edamame peel; F: fly ash)

3.3.3 Statistical analysis of the effect of material composition and mesh size on the ash content of biobriquettes

Statistical data analysis on ash content is done by calculating multiple linear regression tests. The results of the calorific value multiple linear regression tests are shown in Table 5.

Based on the data in Table 5, for mesh size, p-value < 0.05 indicates that variation in mesh size has a significant effect on ash content. For the composition of edamame pods, the p-value < 0.05 indicates that the variation of the composition of edamame pods has a significant effect on the ash content. The equation model of the effect of variation of edamame pod composition and variation of mesh size on ash content based on the analysis of multiple linear regression test in Rstudio [6] is as follows:

$$y = 90.17528 + \left(-0.34277\right)x_1 + \left(-0.49727\right)x_2 .$$

Based on the model equation, each unit decrease in mesh size will increase the ash content and each unit decrease in the percentage composition of edamame pods will increase the ash content. The normality test results show that the p-value of 0.05242 > 0.05, so the residuals are normally distributed and the assumptions are met. The results of the heteroscedasticity test show that the p-value of 0.0008371 < 0.05 so that heteroscedasticity exists and the assumptions are not met. The results of the autocorrelation test show that the p-value of $2.134 \times 10^{-5} < 0.05$, so there is no autocorrelation and the assumptions are met. The results of the multicollinearity test show that the VIF value is 1 < 10, so there is no strong correlation between the independent variables and the assumptions are met.

3.4 Volatile matter

3.4.1 Analysis of the influence of raw material composition on volatile matter of biobriquettes

The results of the analysis of the effect of raw material composition on the fly substance content of biobriquettes mixed with edamame pods and FABA are presented in Fig. 11.

Fig. 11 ilustrated the fly ash content of bottom ash mixed briquettes is greater than that of fly ash mixed briquettes.

Table 5 Multiple linear regression test results of biobriquette ash content

Term	Estimate	p-value	Description
Intercept	90.18	1.38×10^{-12}	Significant impact
Mesh size	−0.34	0.00	Significant impact
Composition of edamame pods	−0.50	2.44×10^{-6}	Significant impact

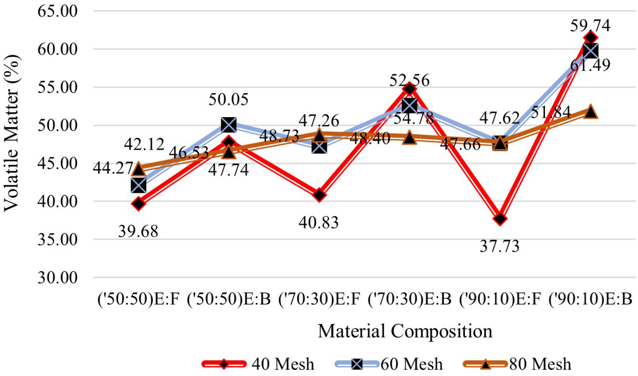

Fig. 11 Analysis of the influence of ingredient composition on volatile matter (B: bottom ash; E: edamame peel; F: fly ash)

The duration of the biomass charcoal carbonization process and the temperature employed during this process affect the level of fly ash content. A longer charring time and higher temperature will result in a lower fly ash content in the briquettes [17]. The carbon value remains subject to influence from the elevated levels of fly ash present in the biobriquettes. A reduction in the quantity of the flying substance present in the biobriquette results in an increase in both the fixed carbon value and the heating value produced [12]. This finding aligns with the research of Ngene et al. [12], which revealed that the highest average fly content of biobriquettes mixed with bottom ash, coconut fiber, and sub-bituminous coal is in the variation of material composition 0.5:1:1, with the lowest average fly content of 44.17%. Conversely, the highest average fly content is 56%.

As stated in the paper by Escalante et al. [22], coal fly ash contains a high ash content, approximately 35%, and a significant amount of silica dioxide, at 47%. It can be inferred from these data that an increase in the proportion of coal fly ash in the briquettes will result in a corresponding increase in the ash content. This is due to the high ash and silica content of the fly ash. Conversely, the proportion of flying substance will decrease. As illustrated in Fig. 11, the data pertaining to the fly substance content of fly ash mixture briquettes exhibit fluctuations. This phenomenon may be attributed to the lack of attention paid to humidity levels during the briquette manufacturing process. Additionally, the humidity conditions during the subsequent stages of production and storage can also influence the characteristics of the fly substance in the briquettes.

A review of the data in Fig. 11 reveals that the mean volatile matter of the samples falls within the range of 37 to 60. This is below the threshold specified in SNI 01-6235-2000 [19], which stipulates a maximum of

15%. Consequently, the samples do not meet the requirements set forth in the standard.

3.4.2 Analysis of the influence of mesh size on the volatile matter of biobriquettes

The results of the analysis of the impact of varying mesh sizes on the composition of biobriquettes mixed with edamame pods and FABA are presented in Fig. 12.

Fig. 12 illustrates a declining trend in the level of flying matter in bottom ash mixed briquettes with an increase in mesh size. This is attributed to the fact that particle size affects the density of the briquettes, with smaller particles containing higher levels of water, which in turn leads to elevated levels of flying matter. The elevated level of flying matter results in increased smoke production due to the reaction between carbon monoxide and the alcohol derivatives present in the briquettes [21]. This finding is consistent with the results of the study conducted by Velvizhi et al. [23], which examined the average concentration of flying substances in biobriquettes produced using a combination of bottom ash, sawdust, and coconut shell stems. The study revealed that the highest concentration of flying substances was observed in briquettes with a mesh size of 60, with an average concentration of 6.6%. Conversely, the lowest concentration of flying substances was observed in briquettes with a mesh size of 80, with an average concentration of 1.5%. As illustrated in Fig. 12, the graphical representation of the flying substance content of fly ash mixture briquettes demonstrates an upward trajectory in conjunction with an increase in mesh size. A low moisture content results in a considerable quantity of charcoal remaining in combustion, thereby reducing the fly ash content and limiting the formation of smoke during the combustion process of the briquettes [8]. The same results are also observed in the findings of Chidiebele et al. [1], where the discussion highlights that the higher flying substance content is associated with a reduction in particle size (an increase in mesh size). A reduction in particle size increases the surface area of the briquette, which facilitates the release of flying substances during combustion. Conversely, larger particles reduce the surface area, impeding the release of flying substances [1].

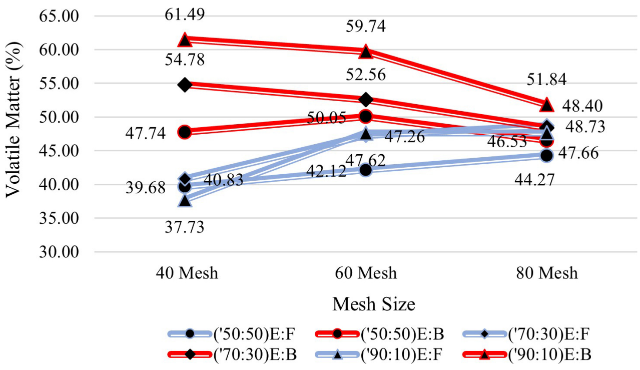

Fig. 12 Analysis of the influence of mesh size on volatile matter (B: bottom ash; E: edamame peel; F: fly ash)

3.4.3 Statistical analysis of the effect of material composition and mesh size on the volatile matter of biobriquettes

Statistical data analysis on volatile matter is done by calculating multiple linear regression tests. The results of the calorific value multiple linear regression tests are shown in Table 6.

Based on the data in Table 6, mesh size shows a p-value > 0.05, which means that variation in mesh size has no significant effect on the content of fly substances. For the composition of edamame pods, the p-value > 0.05 indicates that variations in the composition of edamame pods have no significant effect on the levels of fly substances. The equation model of the effect of variations in composition of edamame pods and variations in mesh size on fly content, based on the results of multiple linear regression test analysis in Rstudio [6], is as follows:

$$y = 39.496806 + \left(-0.003437\right)x_1 + \left(0.123667\right)x_2 .$$

Based on the model equation, each unit reduction in mesh size does not significantly affect the increase in fly content and each unit increase in the percentage composition of edamame pods does not significantly affect the increase in fly content. The normality test results show that the p-value is 0.8326 > 0.05, so the residuals are normally distributed and the assumptions are met. The results of the heteroscedasticity test show that the p-value is 0.0002707 < 0.05, so heteroscedasticity exists and the assumptions are not met. The results of the autocorrelation test show that the p-value of 1.701e-07 < 0.05, so there is no autocorrelation and the assumptions are met. The results of the multicollinearity test show that the VIF value is 1 < 10, so there is no strong correlation between the independent variables and the assumptions are met.

Table 6 Multiple linear regression test results of the biobriquette volatile matter

Term	Estimate	p-value	Description
Intercept	39.50	1.9×10^{-7}	Significant impact
Mesh size	–0.00	0.96	No significant impact
Composition of edamame pods	0.12	0.06	No significant impact

3.5 Combustion rate of biobriquettes

3.5.1 Analysis of the influence of raw material composition on the burning rate of biobriquettes

The results of the analysis of the effect of raw material composition on the burning rate of biobriquettes mixed with edamame pods and FABA are presented in Fig. 13.

Fig. 13 of the line graph of the results of the burning rate of bottom ash briquettes indicates that an increase in the composition of edamame pods biomass charcoal results in a higher burning rate of the resulting briquettes. Conversely, an increase in the composition of bottom ash results in a lower burning rate of the resulting briquettes. This is due to the fact that bottom ash contains a high proportion of ash, which obstructs the surface of the briquette and impedes the flow of air, thereby reducing the combustion speed [7]. Additionally, the high calorific value affects the burning rate of the briquettes, as a higher calorific value corresponds to a higher burning rate, given that the value of heat generated is greater [10]. This finding aligns with the findings of Makepa et al. [7], who observed that the highest average combustion rate of biobriquettes mixed with alaban wood charcoal and bottom ash was in the 100:0 material composition variation, with an average combustion rate of 0.26 g/min. Conversely, the lowest average combustion rate was observed in the 70:30 material composition variation, with an average combustion rate of 0.22 g/min.

As illustrated in Fig. 13, the line graph of the combustion rate of fly ash briquettes reveals that the highest average combustion rate is produced in the ratio of the composition of raw materials 70:30 and 90:10, while the lowest combustion rate is observed in the ratio of the composition of raw materials 50:50. The findings of Adjin-Tetteh et al.'s [24] research indicate that the water content of briquettes may influence the observed combustion rate. However, the results of the combustion rate test yielded different outcomes. This discrepancy could be attributed to the inclusion of additional combustion factors in the test that were not considered in the original research, such as the air flow speed and combustion temperature [8]. These variables may have contributed to the instability observed in the combustion rate test results.

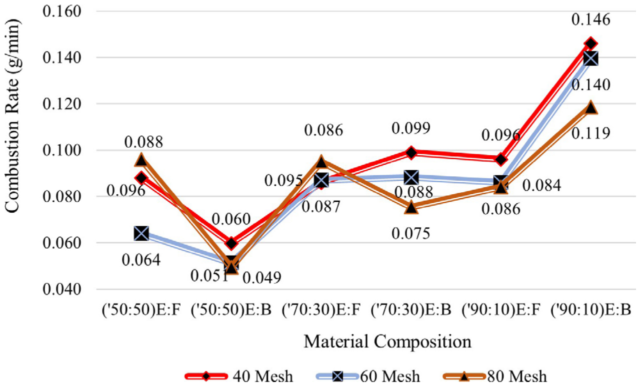

Fig. 13 Analysis of the influence of material composition on combustion rate (B: bottom ash; E: edamame peel; F: fly ash)

A review of the data presented in Fig. 13 leads to the conclusion that the average burning rate of the briquette mixture of edamame pods and coal fly ash is relatively low, with a range of 0.049 to 0.146 g/min.

3.5.2 Analysis of the influence of mesh size on combustion rate of biobriquettes

The results of the analysis of the effect of mesh size variation on the combustion rate of biobriquettes mixed with edamame pods and FABA (Fig. 14).

According to Hoang et al. [8], the combustion rate of a briquette is inversely proportional to its particle size. Specifically, the smaller the particle size, the faster the briquette will burn. However, there is a limit to this relationship, as the burning rate of the briquette begins to decline as the particle size decreases further [25]. In testing the combustion rate of fly ash mixture briquettes, inconsistent results were obtained. This may be due to the fact that several combustion factors in the test were not considered, such as the speed of the air flow during the test, which was not constant, and also the air temperature during combustion [8]. This causes the value in the combustion rate test to be unstable.

Fig. 14 of the line graph of the combustion rate results of bottom ash briquettes indicates that a reduction in mesh size is associated with an increase in briquette particle size, resulting in a higher combustion rate. Conversely, an increase in mesh size is linked to a decrease in briquette particle size, leading to a lower combustion rate. This is due to the fact that particle size affects the density of the briquettes, as a larger particle size results in larger pores,

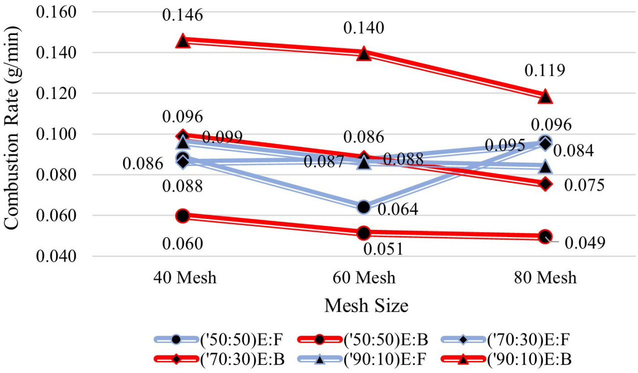

Fig. 14 Analysis of the influence of mesh size on combustion rate (B: bottom ash; E: edamame peel; F: fly ash)

thereby facilitating airflow into the briquettes during combustion [7]. This finding is consistent with the results of Velvizhi et al. [23], who observed that biobriquettes mixed with bottom ash, sawdust, and coconut shell stems exhibited the longest burning duration in the 80 mesh size variation, with an average of 750 s. Conversely, the fastest average burning duration was observed in the 60 mesh size variation, with an average of 390 s. The duration of combustion of biobriquettes affects the combustion rate of biobriquettes. It has been demonstrated that the longer the duration of combustion of biobriquettes, the lower the combustion rate of biobriquettes [18].

3.5.3 Statistical analysis of the effect of material composition and mesh size on the combustion rate of biobriquettes

Statistical data analysis on combustion rate is done by calculating multiple linear regression tests. The results of the calorific value multiple linear regression tests are shown in Table 7.

Based on the data in Table 7, the mesh size shows a p-value > 0.05, which means that the variation of mesh size has no significant effect on the combustion rate value. For the composition of the edamame pods, the p-value < 0.05 indicates that the variation of the composition of the edamame pods has no significant effect on the combustion rate value. The equation model of the effect of variation in composition of edamame pods and variation in mesh size on combustion rate based on the results of multiple linear regression test analysis in Rstudio [6] is as follows:

$$y = 0.0260764 + \left(-0.0002187\right)x_1 + \left(0.0010979\right)x_2 \cdot$$

Based on the model equation, each unit decrease in mesh size has no significant effect on increasing the combustion rate, and each unit increase in the percentage composition of edamame pods increases the combustion rate. The normality test results show that the p-value of 0.05391 > 0.05, so the residuals are normally distributed and the assumptions are met. The results of the heteroscedasticity test show that the p-value is 0.3951 > 0.05, so there is no heteroscedasticity and the assumptions are met. The results of the autocorrelation test show that the p-value is 0.1905 > 0.05, so there is autocorrelation and the assumptions are not met. The results of the multicollinearity test show that the VIF value is 1 < 10, so there is no strong correlation between the independent variables and the assumptions are met.

Table 7 Multiple linear regression test results bioriket combustion rate

Term	Estimate	p-value	Description
Intercept	0.03	0.17	No significant impact
Mesh size	–0.00	0.28	No significant impact
Composition of cassava pods	0.00	4.07×10^{-6}	Significant impact

4 Conclusions

This study demonstrates the feasibility of producing biobriquettes from edamame pod charcoal and FABA using cassava peel adhesive. The most important findings are summarized as follows:

1. The optimal biobriquette composition was achieved with a 90:10 ratio of edamame pod charcoal to bottom ash and a 40-mesh size, yielding a calorific value of 20,719.98 J/g, a moisture content of 2.71%, an ash content of 18.67%, and a combustion rate of 0.146 g/min.
2. The calorific value and combustion rate improved with higher proportions of carbonized biomass and finer mesh sizes, while the ash content and moisture content were primarily influenced by the composition and quality of FABA used.
3. Although the ash content exceeded the standard requirement of SNI 01-6235-2000 [19], the results highlight the potential of utilizing FABA as a supplementary material in biobriquette production, providing an alternative solution for managing coal combustion by products.
4. Future work should focus on optimizing the carbonization process, reducing ash content, and exploring alternative additives to enhance the thermal properties of biobriquettes and meet industrial standards.

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