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Development of Biopellets as a Renewable Energy Solution to Replace Fossil Fuels - A Review

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ABSTRACT

The fossil fuel crisis and the global goal of increasing renewable energy use to 23% by 2025 are driving the development of alternative fuels derived from biomass. One such solution is biopellets, which overcome the weaknesses of conventional biomass, such as high moisture content and suboptimal combustion. This study reviews the use of various biomass waste feedstocks, including palm oil wood, coffee grounds, coffee husks, teak wood, mahogany wood powder, and rice husk waste, in biopellet production. Most biopellets generally meet the SNI 8021:2014 standards for moisture content and calorific value; however, high ash content remains a challenge. Adding additives such as activated charcoal and vegetable oil and using a ball mill grinding method increased the density and compressive strength of the biopellets. Using non-edible waste supports sustainability and energy diversification principles, demonstrating biopellets' great potential as a clean energy transition solution in Indonesia.

Key words: Biopellets, palm oil waste, coffee waste, wood waste.

1. INTRODUCTION

The issue of fossil fuel availability and sustainability has recently become a hot topic of discussion both domestically and globally. In fact, global fossil fuel consumption continues to increase by 1.6-1.8% annually [1]. ASEAN has agreed upon mitigation efforts to address these concerns, setting a goal of 23% renewable energy use by 2025 [2]. Consequently, significant progress has been made in developing high-quality, efficient renewable energy technologies capable of replacing fossil fuels.

Research into renewable energy development has identified many types of renewable energy, one of which is biomass. Biomass is a renewable fuel derived from organic materials produced through photosynthesis, whether as a product or waste [3]. One challenge of using organic feedstock is its high moisture content and low flammability [4]. Biopellets have emerged as a solution to enhance the combustibility of biomass [5]. Furthermore, the fuel consumption rate of biomass processed into biopellets is more efficient than that of unprocessed biomass [6].

According to previous studies, biopellets have some shortcomings, one of which is their relatively high ash content. Consequently, some biopellet products do not meet the SNI 8021:2014 standard. Several studies have focused on developing biopellets that meet these standards. For example, [5] added pine wood charcoal to produce biopellets that met all SNI 8021:2014 parameters. In addition to regular charcoal, [1] used a mixture of HCl-activated charcoal as a biopellet mixture from palm wood, producing pellets with an ash content of 2.22%. [7] also used activated charcoal as a biopellet mixture from bamboo raw materials and produced biopellets that met the SNI 8021:2014 standard. The production of renewable fuels, especially biopellets, is promising because the raw materials are non-edible. [8] sought the best biopellet formula from water hyacinth, rice husks, rice bran, sawdust, and corn cobs. They produced biopellets that met the SNI 8021:2014 standard with the following composition: Water hyacinth and sawdust at a ratio of 50:50, with a diameter of 8 mm [8]. Using sawdust and palm kernel shell waste, [9] produced biopellets with a burning rate of 23 minutes. Biopellets can also be made from household waste. [10] used coconut shell waste mixed with sago pulp to produce biopellets with the following properties: moisture content, 9.96%; density, 0.31 g/cm³; calorific value, 4,182 kcal/g; ash content, 11.3%; and volatile matter, 73.69%.

1.1 Biopellets from Palm Oil Waste

This review begins by examining the characteristics of biopellets made from three types of palm oil waste: palm wood with charcoal, palm tree powder, and a mixture of palm shells and wood powder. Indonesia has hundreds of thousands of hectares of palm oil plantations that will certainly produce an abundance of palm wood waste. This waste has great potential for development into biopellets.

A. Characteristics of Biopellets Made from Palm Oil, Wood, and Charcoal

Palm wood is used as the raw material to produce hybrid biopellets, which are made with natural activated charcoal (NAC) from coconut shells and tapioca flour as a binder. The amount of NAC used varies from 200 to 400 grams per kilogram of raw material. The biopellets are produced using a roller wood pellet machine and dried in the sun. Quality testing was conducted based on the SNI 8021:2014 standard. The results showed that all hybrid biopellets except for
HBC-0 (without NAC) met the standard for moisture content (<12%). However, the ash content of all types of biopellets exceeded the standard (>1.5%). Fixed carbon and calorific value mostly met the standard. The HBC-400 biopellet had the highest calorific value (4822 kcal/g) and the lowest moisture content (7.33%). It also had the highest fixed carbon (62.12%) and density (0.886 g/cm³). Adding activated charcoal significantly increased density, fixed carbon, and calorific value but did not fully reduce ash content to within standard limits [1]. The following are the physical characteristics of biopellets mixed with palm wood and charcoal (table 1):

Table 1: Results of biopellets mixed with palm wood and charcoal:

Parameter	**HBC-0 (0g NAC)**	**HBC-200 (200g NAC)**	**HBC-300 (300g NAC)**	**HBC-400 (400g NAC)**
Density (g/cm³)	0,657	Higher	Higher	0,886
Mois Content (%)	12,83	Decreased	Decreased	7,33
Ash Content (%)	2,22	Slightly Decreased	Slightly Decreased	1,64
Volatile Matter (%)	69,83	Decreasing	Decreasing	47,33
Fixed Carbon (%)	23,25	Increasing	Increasing	62,12
Heat Value (kcal/g)	2847	Increasing	Increasing	4822
Compliance with SNI 8021-2014	Not fully compliant	Almost fully compliant	Fully compliant (except ash)	Fully compliant (except ash)

B. Characteristics of Biopellets from Palm Tree Powder Raw Materials

To obtain the best quality, various types of powder sizes and adhesives are used to make biopellets from palm oil trunk waste. The adhesives used are tapioca flour and sago flour in the following sizes: 10-20 mesh, 20-40 mesh, 40-60 mesh, and >60 mesh. The biopellets are produced using a household meat grinder and then dried at 60–70°C for 24 hours. Quality testing is conducted according to the SNI 8021:2014 standard. The research results show that the moisture content of all the biopellets meets the standard of less than 12%, while the ash content exceeds the standard of less than 1.5%. The volatile matter and bound carbon content mostly met the standards. The 10–20 mesh biopellets with tapioca adhesive had the highest calorific value (4451.67 cal/g), the fastest boiling time (6 minutes for 1 liter of water), and the highest biopellet consumption rate (1.86 kg/hour). The type of binder and particle size significantly affect calorific value but not moisture content, ash content, volatile matter content, or bound carbon [11]. The following are the physical characteristics of palm tree powder biopellets (table 2):

Table 2: Results of palm tree powder biopellets:

Particle Size (Mesh)	**Binder**	**Mois Content (%)**	**Ash Content (%)**	**Volatile Matter (%)**	**Bound Carbon (%)**	**Heat Value (%)**	**Boiling Time for 1L Water (minutes)**
10-20 mesh	Tapioca	6,75	4,69	73,71	21, 60	4451,67	6
20-40 mesh	Tapioca	5,86	6,03	72,62	21,35	3990,33	7
40-60 mesh	Tapioca	5,27	7,96	76,54	15,50	4147,33	7
>60 mesh	Tapioca	6,28	8,73	73,98	17,29	3799,00	8
10-20 mesh	Sago	6,56	8,51	77,46	14,02	4228,00	7
20-40 mesh	Sago	6,64	6,54	76,99	16,47	3854,67	8
40-60 mesh	Sago	5,85	8,58	73,57	17,85	3719,67	8
>60 mesh	Sago	6,60	5,79	75,64	18,57	4074,33	7

A. Characteristics of Biopellets from Palm Kernel Shell Raw Materials

Biopellets are made from a mixture of palm kernel shells and wood powder in the following compositions: 100%:0%, 70%:30%, 50%:50%, and 30%:70%. The manufacturing process uses 80-mesh powder and a molding pressure of 200 kg/cm². Research results show that biopellet moisture content ranges from 7.6% to 11%, volatile matter content from 67.6% to 68.08%, ash content from 1.53% to 2.57%, fixed carbon content from 19.38% to 22.23%, and calorific value from 3,563.05 to 4,366.73 kcal/g. Density ranges from 1.03 to 1.32 g/cc. As the wood powder content increases, so do the moisture content, volatile matter content, and density, while the ash content, fixed carbon content, and calorific value decrease. The highest quality biopellets were obtained from a 70:30 mixture of palm kernel shells and wood powder (Biopellet B). These pellets had a moisture content of 10.43%, an ash content of 1.96%, a fixed carbon content of 19.78%, a calorific value of 4,262.67 kcal/g, a density of 1.15 g/cc, and underwent complete combustion in 23 minutes [9]. The following are the physical characteristics of biopellets mixed with palm kernel shells and wood powder (table 3):

Table 3: Results of biopellets mixed with palm kernel shells and wood powder

Type of Biopellet	Composition (Shell:Wood Powder)	Mois Content (%)	Volatile Matter Content (%)	Ash Content (%)	Bound Carbon (%)	Heat Value (cal/g)	Density (g/cc)	Burn-out Time (minutes)
A	100%:0%	7,6	67,6	2,57	22,23	4366,73	1,03	18
B	70%:30%	10,43	67,82	1,96	19,78	4262,67	1,15	23
C	50%:50%	10,66	68,04	1,71	19,58	3687,47	1,25	24
D	30%:70%	11,00	68,08	1,53	19,38	3563,05	1,32	26

1.2 Biopellets from Coffee Waste

A. Characteristics of Biopellets Made from Coffee Grounds and Pine Charcoal

Biopellets are made from a mixture of coffee grounds and pine charcoal to improve combustion quality and calorific value. The coffee grounds and pine charcoal are mixed at ratios of 4:6 and 6:4, with the addition of a 5% tapioca adhesive. The mixture is molded using a manual press and dried at 120°C for 24 hours. Quality testing was conducted according to the SNI 8021:2014 standard. The results showed that the moisture content of all biopellets met the standard of ≤12%. The volatile matter and fixed carbon content also met the standard, but the ash content and density did not. All biopellet variations met the calorific value standard (≥4000 kcal/kg). Biopellets with ball mill (BM) particles have a higher density, compressive strength, and longer burning time than hammer mill (HM) pellets. The ratio of SCG to pine charcoal affects the properties of biopellets; a 4:6 ratio produces biopellets with better compressive strength and burning duration [5]. The following are the physical characteristics of biopellets mixed with coffee grounds and pine charcoal (table 4):

Table 4: Results of biopellets mixed with coffee grounds and pine charcoal

SCG Ratio: Pine Wood Charcoal	Grinding Method	Mois Content (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Calorific Value (kcal/kg)	Flame Duration (minutes)	Burning Rate (g/minutes)
4:6	Hammer Mill (HM)	Low	High	Moderate	Sufficient	>4000	24,30	0,0407
6:4	Hammer Mill (HM)	Slightly high	High	Slightly higher	Slightly decreasing	>4000	23,01	0,0375
4:6	Ball Mill (BM)	High	Low	Low	High	>4000	29,10	0,0379
6:4	Ball Mill (BM)	High	Low	Slightly Higher	Slightly Decreasing,	>4000	26,06	0,0427

A. Characteristics of Biopellets Made from Coffee Bean Husks

The potential of biopellets made from coffee husk waste as an alternative solid fuel was evaluated by analyzing various characteristics of the pellets. The biopellets were made from dried, uniform-sized coffee husks (1 mm in diameter) that were carbonized. Then, they were tested for moisture content, ash content, volatile matter, fixed carbon, and calorific value. This testing was conducted using a moisture analyzer, a furnace for ash testing, and an AC-350 bomb calorimeter. Results showed that the moisture content of the biopellets ranged from 8.30% to 8.90%, and the ash content ranged from 7.05% to 8.98%. The calorific value of the biopellets was 16,897.54 kJ/kg. While the moisture content of coffee husk biopellets met the standard (<10%), the ash content far exceeded it (<0.5%), and the calorific value was slightly below the European standard (17,500–19,500 kJ/kg). The high volatile matter content (74.20%) supports combustion efficiency, and the carbon content increases after carbonization [12]. The following are the physical characteristics of coffee husk biopellets (table 5):

Table 5: Coffee husk biopellets

Parameter	Value
Mois Content (%)	8,30–8,90 (average 8,67)
Ash Content (%)	7,05–8,98 (average 8,07)
Volatile Matter (%)	74,20
Fixed Carbon (%)	Not specified
Heat Value (kJ/kg)	16.897,54

The biopellets produced from coffee husk waste are of moderate quality. All samples met the moisture content standard of less than 10% in accordance with the European standard EN 14961-1. The moisture content ranged from 8.30% to 8.90%. However, the ash content far exceeds the maximum standard of 0.5%, ranging from 7.05% to 8.98%. High ash content can damage combustion equipment, so this poses a significant challenge [12]. The high volatile matter content (74.20%) aids faster and more efficient combustion. The biopellets' calorific value is 16,897.54 kJ/kg, which is slightly below the European minimum standard of 17,500 kJ/kg [12].

1.3 Biopellets from Wood Waste

A. Characteristics of Teak Wood Biopellets

To produce high-quality biopellets from PERHUTANI teak wood waste, various material compositions and compaction pressures were used. The material variations included using tapioca starch as a binder at 5%, 10%, or 15% and adding water at 10%, 15%, or 20% of the teak wood waste's weight. The production process uses a flat die mill pelletizer machine at a speed of 1,660 RPM. Compaction pressure variations were achieved by adjusting the roller and die gap to 0.5, 1, and 1.5 mm. The biopellets were tested for geometric standards (diameter: 5–7 mm; length: 25–36 mm) and then underwent quality testing according to the SNI 8021:2014 standard [13].

The results showed that the biopellets only met the geometric standards at a 1.0 mm gap. Furthermore, biopellets with codes P-1 to P-6 were tested for physical characteristics. All of the biopellets met the SNI standards for calorific value (>4,000 cal/g), fixed carbon content (≥14%), volatile matter content (≤80%), ash content (≤1.5%), and density (≥0.8 g/cm³). However, all specimens had a moisture content above the SNI standard limit of 12% [13]. The following are the physical characteristics of the wood biopellets (table 6):

Table 6: Teak wood biopellet results

Sample	Mois Content (%)	Ash Content (%)	Volatile Matter (%)	Bound Carbon (%)	Density (g/cm³)	Heat Value (kcal/g)
P-1	16,0	1,35	65,48	17,16	0,94	4518,3
P-2	13,7	1,22	60,12	18,06	1,07	4642,2
P-3	21,8	1,65	66,54	16,85	0,76	4472,4
P-4	15,2	1,64	64,88	18,28	0,91	4667,9
P-5	15,6	1,37	66,08	16,93	1,09	4484,9
P-6	16,2	1,17	66,74	15,88	1,04	4345,7

B. Characteristics of Biopellets from Wood Powder and Rice Husk

Various formulations of rice husk and wood powder mixtures were used to produce biopellets as an environmentally friendly alternative fuel. The tested formulations consisted of KS-1 (low husk content), KS-2 (medium husk content), and KS-3 (high husk content), all with the same amount of wood powder. The biopellet production process includes grinding the rice husks, mixing the raw materials, molding the pellets using a machine, and cooling them. Testing the characteristics of the biopellets refers to the SNI 8021:2014 and SNI 9125:2022 standards, which include parameters such as moisture content, density, calorific value, and a combustion test [14].

The study's results show that all formulas meet the standards for moisture content and density. Formula KS-3 produced the best biopellets, with a moisture content of 7.27%, a density of 1.322 g/cm³, and a calorific value of 3,983.94 kcal/g. While the calorific values of all samples exceeded the minimum standard for rice husk biopellets (3,200 kcal/kg), they did not meet the standard for wood biopellets (4,000 kcal/kg). In the combustion test, KS-3 biopellets exhibited the highest flame temperature and combustion duration and boiled 1,000 mL of water more quickly than the other formulas [14]. The following are the physical characteristics of wood powder and rice husk biopellets (table 7):

Table 7: Results of wood powder and rice husk biopellets

Formula	Mois Content (%)	Density (g/cm³)	Heat Value (kal/g)	Ignition Time (seconds)	Flame Temperature (°C)	Flame duration (seconds)	Boiling Time (seconds)	Water Temperature (°C)
KS-1	6,45	1,104	3669,47	130	449	493	280	96,8
KS-2	6,28	1,173	3968,30	183	500	601	219	99,7
KS-3	7,27	1,322	3983,94	285	517	642	280	100

C. Characteristics of Biopellets from Candlenut Shells and Sago Trunks

Candlenut shells, sago trunks, and sawdust waste are used to make biopellets, which are an environmentally friendly alternative fuel. This study tested four biopellet formulations: P1 (low biomass addition), P2 (moderate biomass addition), P3 (high biomass addition), and P4 (very high biomass addition). A fixed amount of tapioca adhesive was used for all formulations. The production process includes drying the raw materials, grinding them, mixing them, molding them into pellets, and testing their characteristics based on the SNI 8021:2014 standard. This standard provides parameters for moisture content, density, calorific value, ash content, and volatile matter [10].

The results showed that all formulas met the standards for moisture content, calorific value, and volatile matter but not for density and ash content. Formula P2 produced the highest quality biopellets, with a moisture content of 9.96%, a density of 0.31 g/cm³, a calorific value of 4,182 cal/g, an ash content of 11.3%, and a volatile matter content of 73.69%. While the density and ash content values do not comply with

SNI standards, the calorific value and moisture content meet the requirements for an alternative energy source [10]. The following are the physical characteristics of the biopellets from candlenut shells and sago trunks (table 8):

Table 8: Results of biopellets from candlenut shells and sago trunks

Formula	Mois Content (%)	Density (g/cm³)	Heat Value (kal/g)	Ash Content (%)	Volatile Matter Content (%)
P1	9,86	0,36	4.032	13,86	61,11
P2	9,96	0,31	4.182	11,30	73,69
P3	10,60	0,26	4.232	9,00	73,76
P4	10,84	0,23	4.281	6,85	76,68

D. Characteristics of Biopellets from Eucalyptus Waste and Gondorukem

In an effort to produce environmentally friendly alternative fuels, solid waste from eucalyptus and gondorukem processing is used to make biopellets. The tested formulation used a fixed mixture of 70% eucalyptus waste and 30% gondorukem waste. Research variations included powder size (20, 40, 60, and 80 mesh) and molding temperature (120°C, 150°C, 180°C, 200°C, 230°C, and 260°C). The biopellet production process involved grinding the raw materials, screening them, and mixing them. Then, the materials were molded using a hydraulic press and tested for characteristics according to SNI 8021:2014. These characteristics included moisture content, ash content, volatile matter content, fixed carbon content, compressive strength, and calorific value [15].

The results of the study indicate that using a 40-mesh powder size with a molding temperature of 230°C produces the best biopellets, which have a low moisture content, a high calorific value, and an optimal compressive strength. Biopellets produced under these optimal conditions have a moisture content of 1.905%, an ash content of 3.955%, a volatile matter content of 72.189%, a fixed carbon content of 21.949%, a calorific value of 5,097.5 kcal/kg, and a compressive strength of 53.746 kgf/cm² [15]. The following are the physical characteristics of the white wood and gondorukem biopellets (table 90:

Table 9: Results of white wood and gondorukem biopellets

Particle Size	Molding Temperature (°C)	Mois Content (%)	Ash Content (%)	Volatile Matter (%)	Bound Carbon (%)	Heat Value (kkal/kg)	Compressive Strength (kgf/cm²)
40 mesh	230	1,905	3,955	72,189	21,949	5097,5	53,746

E. Characteristics of Biopellets from Mahogany Wood Powder and Cotton Seed Oil

Mahogany wood powder is combined with cottonseed oil and tapioca starch adhesive to produce biopellets, which are an environmentally friendly alternative fuel. The tested composition variations were 40% mahogany wood powder, 10%, 15%, or 20% cottonseed oil, and tapioca starch adhesive. The biopellet production process involves grinding the powder, mixing the ingredients, molding them with a hydraulic press, and testing the characteristics of the biopellets. These characteristics include calorific value, combustion rate, moisture content, and surface morphology and functional group analyses using SEM and FTIR, respectively [16].

The results of the study indicate that adding cottonseed oil increases the calorific value and combustion rate of biopellets and decreases their moisture content at certain compositions. The optimal formula is a 40:20:40 mixture of powder, oil, and binder, respectively, yielding a calorific value of 5,672 cal/gram and a combustion rate of 0.106 g/minute [16]. The following are the physical characteristics of the mahogany wood biopellets and cottonseed oil (table 10):

Table 10: Results of mahogany wood biopellets and cottonseed oil

Formula	Mois Content (%)	Heat Value (kal/g)	Burning Rate (gr/min)
40% Powder: 10% Oil: 50%, Binder	6,4587	5.207	0,093
40% Powder: 15% Oil: 45% Binder	7,2357	5.321	0,094
40% Powder: 20% Oil: 40% Binder	6,3162	5.672	0,106

2. DISCUSSION

The dwindling availability of fossil fuels and the global demand to increase renewable energy use to 23% by 2025 [2] are important factors in developing biopellets from biomass. As mentioned in the introduction, biomass is a renewable energy source due to its abundance; however, its use is hindered by its high moisture content and poor combustion properties [4].

A review of various studies in this paper shows that developing biopellets from different types of biomassa such as oil palm wood, oil palm tree trunks, oil palm shells, coffee grounds, coffee husks, teak wood, mahogany wood powder, and white wood waste—results in biopellets with different characteristics. Most biopellets generally meet the standards for moisture content (less than 12%) and calorific value (more than 4,000 kcal/kg) according to SNI 8021:2014. However, many samples exceed the maximum ash content limit of 1.5%.

Adding additives, such as natural activated charcoal from coconut shells [1] and cotton seed oil [16], has been shown to effectively increase the calorific value and fixed carbon content. This is in line with the need to improve the quality of biomass energy to match that of fossil fuels. Additionally, grinding techniques using a ball mill [5] produce biopellets with better density and a longer burning duration.
However, challenges remain regarding the high ash content of raw materials, such as coffee husk waste [12] and oil palm trunk powder [11]. This indicates that, although biomass is abundant, not all organic materials are directly suitable for biopellets without additional processes, such as activation or carbonization.

In terms of combustion performance, a mixture of raw materials, such as palm kernel shells and wood powder, produces biopellets with fairly good combustion times of 18–26 minutes [9]. This is important for meeting the energy needs of households and small industries as an alternative to solid fuels.

Additionally, efforts to improve biopellet quality by combining non-edible materials, such as wood waste, mahogany sawdust, and agricultural waste, are highly relevant to sustainability goals and circular economy principles, as mentioned in the introduction.

These developments demonstrate the strong potential of biomass-based biopellets to contribute to the national energy mix and support renewable energy usage targets. However, optimizing raw material formulation, carbonization processes, and printing technology is key to ensuring that produced biopellets meet quality and efficiency standards.

3. CONCLUSION

Biopellets made from various types of biomass waste, such as palm wood, coffee grounds, teak wood, and white wood waste, show great potential as an environmentally friendly alternative fuel. Most of these biopellets meet the moisture content and calorific value standards in accordance with SNI 8021:2014. However, the issue of high ash content still needs to be addressed. Improving quality through the addition of additives, such as activated carbon and vegetable oil, and the application of grinding technology has been shown to enhance biopellet performance. Using these non-edible waste materials supports sustainability and the diversification of renewable energy sources in Indonesia. Thus, biomass-based biopellets are a potential real-world solution that can support the transition to clean energy and reduce dependence on fossil fuels.

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