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## Utilization of sengon wood sawdust as bio-pellet feedstock: characteristics, potential, and feasibility for renewable energy

Eko Yohanes Setyawan\* and Samuel Pומר Paepenan

Mechanical Engineering, National Institute of Technology Malang, Malang, 57423, Indonesia

\*Corresponding author: yohanes@lecturer.itn.ac.id

### Abstract

The pellet-making process involves stages of drying, compaction, cooling, and size separation. Considering that Indonesia has great potential for biomass supply, this research aims to identify the characteristics of bio-pellets produced from sengon wood sawdust based on the pellet standard SNI8675:2018. The results showed that the highest calorific value at the Dry Basis (DB) condition was 4703 Kcal/kg, meeting national and international standards. The moisture content in the As Received (AR) condition was recorded at 10.36%, while the lowest ash content was 1.72%. The highest combustion rate was found in sample 3, with a value of 0.174 gr/min, indicating good combustion performance. The utilization of sengon wood sawdust as bio-pellets can be an efficient and environmentally friendly renewable energy solution, and has the potential to be further developed to support diversification and national energy security.

### Keywords:

Wood pellets, sengon wood, biomass, renewable energy.

## 1 Introduction

Currently, the need for fuel energy is increasing along with the development of human life needs. Indonesia, as a tropical country with a large area, has great potential for providing biomass. The growing agricultural industry sector in Indonesia produces a lot of waste from its processing. The opportunity to utilize such waste as fuel can provide many benefits, including reducing dependence on fossil fuels that adversely affect the greenhouse effect and increase CO<sub>2</sub> emissions [2]. The Indonesian government has encouraged the use of New Renewable Energy (NRE) as a priority, given NRE's great potential to guarantee future national energy provision. The use of renewable energy is important in the context of energy diversification because it is in line with sustainable development and environmentally friendly due to its relatively low greenhouse gas emissions. This has been accommodated in Presidential Regulation No. 5/2006 on the National Energy Policy (NEP) [3].

One alternative renewable fuel is biomass. Biomass is organic material produced through photosynthesis that can be utilized as energy even though it has low economic value or is waste from its primary product [4]. Indonesia has 50,000 MW of biomass energy potential from various agricultural wastes such as sengon wood sawdust, palm oil, cocoa, mahogany, and other agricultural wastes. However, only about 320 MW has been utilized, or only 0.64% of the entire potential. This shows that the utilization of biomass energy is not optimal [5]. The largest waste from the wood industry is wood chips and sawdust. Zinc in wood sawdust, as waste from sawmills, has the opportunity to be utilized as

renewable energy, such as bio-pellets [6]. Utilization of sengon wood sawdust as a raw material for alternative energy production is done by changing its shape into a denser and uniform mass [7] [8]. Pellets are useful for improving the combustion quality and fuel efficiency of biomass. Research is needed to determine the characteristics of bio-pellets produced from sengon sawdust based on the SNI 8675:2018 pellet standard.

To diversify energy sources, research on bio-pellets from sengon sawdust is expected to provide solutions for the utilization of agricultural waste as an efficient and environmentally friendly energy source. This research aims to identify the potential and characteristics of bio-pellets from sengon sawdust and provide recommendations to improve their utilization in the future.

The use of bio-pellets as a renewable energy alternative can improve combustion efficiency and reduce greenhouse gas emissions. In addition, bio-pellets have a higher energy density than raw biomass forms, making them easier to store and transport. Bio-pellets can also be used in various applications, including power generation and industrial heating. The utilization of sengon wood sawdust into bio-pellets not only provides a sustainable energy solution but also helps solve the waste problem of the wood industry. By turning waste into value-added products, we can reduce the burden on the environment and create new economic opportunities for local communities.

The study also looked at the technical and economic aspects of bio-pellet production. An analysis of the production cost and market potential of bio-pellets gave an idea of the feasibility of this project. In addition, the research will examine the environmental impact of bio-pellet production and use to ensure that the process was truly environmentally friendly. The pellet standard SNI 8675:2018 was used as a reference to assess the quality of the bio-pellets produced. This standard covers various aspects, including the size, shape, water content, and ash content of the pellets. By following this standard, we can ensure that the bio-pellets produced are of consistent quality and meet the technical requirements for various applications. Utilizing biomass as a renewable energy source is also in line with global efforts to reduce carbon emissions and mitigate climate change. By reducing dependence on fossil fuels and switching to renewable energy sources, we can contribute to the achievement of global emission reduction targets [10] [11].

The Indonesian government prioritizes renewable energy, with strong support for developing the bio-pellet industry. This sector can create jobs and increase income for farmers and the wood industry, contributing to sustainable economic and social development. The research will explore potential collaboration between the private sector, government, and community to ensure smooth project execution. Developing bio-pellets from sengon wood sawdust can serve as a model for utilizing other biomass waste, reducing untreated waste, and supporting national energy diversification. This initiative also helps reduce deforestation by using wood industry waste, promoting sustainable forest management.

This research examined the technical, economic, and environmental aspects of bio-pellet production. It identified opportunities and challenges, leading to effective policy recommendations. The goal was to contribute to Indonesia's renewable energy development, advancing sustainable goals and minimizing environmental impacts. Utilizing sengon wood sawdust for bio-pellets was seen as a key step toward achieving green energy in Indonesia.

## 2 Methods

### 2.1 Material

The characteristics of sengon wood are strongly influenced by the growing environment and local climate. Sengon trees can grow up to 1,800 meters above sea level, but their growth is more

optimal in areas with high humidity and rainfall between 1,000 mm and 5,000 mm per year. Therefore, this study used sengon wood from the Malang region, Indonesia, which has ideal climatic and rainfall conditions as well as a large number of cultivated sengon trees in the area. The main chemical components of sengon wood include cellulose, hemicellulose, lignin, and extractives.

The first stage was the drying of sengon sawdust using a 12,000 mm rotary kiln (Fig. 1c), which reduced the moisture content from 80% to 19%. Once the moisture content was low enough, the sawdust was fed continuously into the MZLH-420 pellet mill (Fig. 1d) through a steel ring with 8 mm holes. This process compacted the sawdust into pellets with a diameter of 8 mm and a length varying between 3 cm and 5 cm. Friction during the compaction process generated heat that helped bind the material and reduces the moisture content to 5%-10%.

The raw material for wood pellets comes from sengon sawmill waste, which consists of powder, wood chips, and unused branches. This waste has an initial moisture content of 40%-45% (Fig. 2a). The initial crushing process was carried out using a wood shredder to a size of 15 mm (Fig. 2b), then further pulverized into 5 mm powder using a hummer mill machine (Fig. 2c). After that, the wood powder was dried in a rotary drum dryer to reduce the moisture content to 15%-19% (Fig. 1c).

After drying, the powder was cooled (Fig. 1e) and then processed in a wood pellet machine. After the pellets were formed, the final product was cooled in a wood pellet cooling machine to prevent the pellets from breaking due to the high temperature that reached around 80°C after the pelletizing process. The last step was to separate the pellets according to the standard size using a vibrating screen machine (Fig. 2d), ensuring the pellets were 8 mm in diameter and 3-5 cm long. Pellets that did not fit the size

were separated automatically. Thus, the production process of sengon wood pellets involved the stages of crushing, drying, compacting, cooling, and size separation, all of which contribute to the final quality of the pellets produced.

## 2.2 Defining the Quality of Wood Pellet

### 2.2.1 Proximate Analysis

Proximate analysis is an analysis that aims to determine the composition of a material and to determine the quality of pellets. Generally proximate analysis has several types of analysis methods, including:

1. As Received (AR)

As Received (AR) is the surface moisture still present in the sample. Moisture analyzed using as received is called total moisture. Fixed carbon, moisture, volatile matter, and ash content are calculated from samples that still contain surface moisture. The as received method of analysis is based on conditions where the sample is assumed to be as received.

2. Air Dried Basis (ADB)

Air Dried Basis (ADB) is a basis where the weight percentage of fixed carbon, moisture, volatile matter, and ash content is calculated without surface moisture. Samples are analyzed after receiving air drying treatment so that surface moisture is not calculated in the sample. The air dried basis method of analysis is based on sample conditions with water content in equilibrium with the laboratory atmosphere.

3. Dry Basis (DB)

Dry Basis (DB) is the basis for calculating weight percentage in carbon, moisture, volatile matter, and ash content where the sample is reduced by total moisture. The sample is calculated as a dry sample.

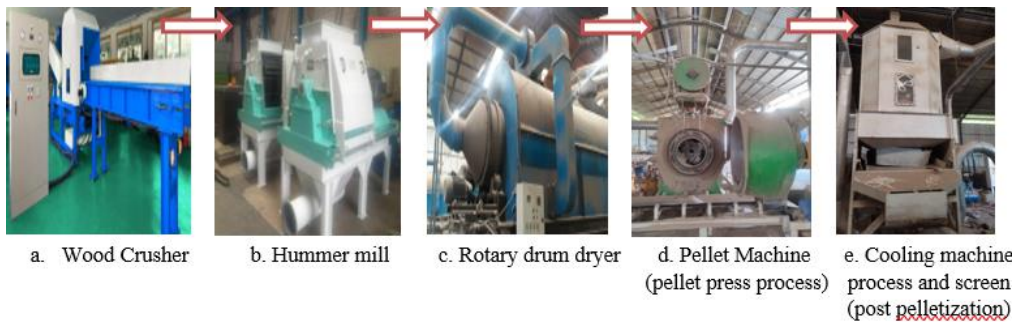


Fig. 1. Wood pellet manufacturing process.



Fig. 2. Process material into wood pellet.

### 2.2.2 Calorific Value

Calorific value is the amount of heat produced per weight of the combustion process of enough material that is easy enough to burn. Calorific value measurement can be done using a bomb calorimeter with the SNI 01-6235-2000 test method with Eq. 1.

$$Hg \text{ (cal/g)} = \frac{\Delta t \times w}{m} \quad (1)$$

Where  $Hg$  is calories per gram of pellets,  $\Delta t$  is the temperature rise on the thermometer (°C),  $w$  is the calorie capacity of the tool of 2565.446 calories/°C at the time of calibration, and  $m$  is the

weight of the pellets. Pellets derived from sengon wood waste generally have a moisture content ranging from 6% to 10%.

### 2.2.3 Water Content

Moisture content is the water content contained in solid fuel. The higher the moisture content in solid fuel, the lower the calorific value. To determine the moisture content of wood pellets made from sengon wood waste, Eq. 2 can be used. In this equation,  $w_1$  is the weight of the sample (gr) before drying, and  $w_2$  is the weight of the sample after drying in a kiln (gr).

$$\text{Water content}(\%) = \frac{w_1 - w_2}{w_2} \times 100\% \quad (2)$$

### 2.2.4 Ash Content

Ash in solid fuels is the unburned mineral residue that remains after combustion and associated reactions. The presence of ash can degrade the quality of the solid fuel by reducing its calorific value. Ash content can be measured by reducing the heating value of the fuel. To determine the ash content, Eq. 3 can be used.

$$\text{Ash content}(\%) = \frac{w_1 - w_2}{w_2} \times 100\% \quad (3)$$

Where  $w$  is the weight of pellets before frying (gr),  $w_1$  is the weight of wood pellet cup after frying (gr) and  $w_2$  is the weight of empty cup (gr).

### 2.2.5 Combustion Rate

The combustion rate is the speed of energy release during combustion (Eq. 4), which greatly affects its quality and characteristics. The optimal combustion rate has a high calorific value and good energy efficiency. Factors affecting combustion rate include moisture content, ash content, density, size, and chemical composition. Low moisture content and low ash content will increase the combustion rate and efficiency.

$$\text{Combustion rate} = \frac{\text{Burned weight}}{\text{Combustion time}} \quad (4)$$

## 3 Results and Discussion

This study involved proximate analysis tests and combustion rate tests on the samples. The proximate analysis test aims to determine the composition of sengon wood, including its calorific value, moisture content, and ash content. The results were presented in tabular form and processed into graphs for each test. Combustion rate tests were conducted three times to identify the combustion characteristics of sengon wood, with the results also presented in tabular form and graphs to analyze the values obtained. All of these tests refer to the Indonesian pellet quality standard, SNI 8675:2018 (Table 1).

The quality of pellets can be seen from the results of tests conducted using proximity analysis testing (Table 2). From this test, we can find out the physical properties of the wood pellets themselves. And the test parameters greatly affect the combustion characteristics of wood pellets.

Table 1 Pellet standard

Parameters	Units	Indonesia (SNI 8675:2018)		Europe (EN Plus)	Germany (DIN57131)	Sweden (SS 18 71 20)	France (ITEBE)	Japan (JPA)
		Home	Industry					
Calorific value	MJ/kg	16.5	16.5	16.5 – 19	17.5 – 19.5	> 19.08	> 16.9	16.5 – 18
	Kcal/kg	3940.96	3940.96	3940.96	4179.80	4557.18	3843.03	3940.96
Water content	% wt	10	12	< 10	< 12	< 10	≤ 15	≤ 10
Ash content	% wt	5	5	< 3	< 1.5	< 0.7	≤ 6	≤ 1.0

Table 2. Proximate analysis testing results

Parameters	Unit	AR	ADB	DB	Test method
Total moisture	% wt	10.36	-	-	ASTM E 871 – 82
Ash content	% wt	1.72	1.90	1.92	ASTM D 1102 – 84
Volatile matter	% wt	73.78	81.28	82.29	ASTM E 872 – 82
Fixed carbon	% wt	14.14	15.59	15.79	ASTM D 3172 – 13
Total sulfur	% wt	0.12	0.13	0.13	ASTM D 4239 – 18
Gross calorific value	Kcal/Kg	4216	4645	4703	ASTM D 5865 – 19

As for the combustion rate, by using Eq. 4 the results are obtained:

- Specimen 1

$$\text{Combustion rate} = \frac{2.7 - 0.24}{16.10} = 0.152 \text{ gr/minute}$$

- Specimen 2

$$\text{Combustion rate} = \frac{3.1 - 0.33}{16.43} = 0.168 \text{ gr/minute}$$

- Specimen 3

$$\text{Combustion rate} = \frac{3.4 - 0.39}{17.26} = 0.174 \text{ gr/minute}$$

In the graph of test results as shown in Fig. 3, the heating value of sengon wood pellets in the As Received (AR) condition shows a difference of 10.1% compared to Air Dried Basis (ADB) and a difference of 11.5% compared to Dry Basis (DB). In the Air Dried Basis (ADB) condition, there is a 1.2% difference in value compared to the Dry Basis (DB). The graph shows an increase in heating value, especially in the Air Dried Basis (ADB) and Dry Basis (DB) conditions, due to the decrease in moisture content in the pellets. In contrast, in the As Received (AR) condition, the heating value is lower due to the high water content. The calorific values obtained have met several pellet standards listed in Table 1, such as the Indonesian National Standard (SNI 8675:2018), as well as standards from other countries such as Germany (DIN 51371), France (ITEBE), Sweden (SS 18 71 20) for ADB and DB conditions, Europe (EN Plus), and Japan (JPA).

In the graph of test results as shown in Fig. 4, the moisture content of sengon wood pellets in the Air Dried Basis (ADB) condition shows a 100% difference in value compared to As Received (AR). Likewise, in the Dry Basis (DB) condition, there is a 100% difference in value compared to As Received (AR). The graph only shows the moisture content in the As Received (AR) condition, while the Air Dried Basis (ADB) and Dry Basis (DB) conditions have no values listed. This is because in the ADB condition, before the test is carried out, the sample has been dried so that the surface moisture is not calculated. While in the DB condition, the samples were tested as dry samples. The results of this moisture content measurement are in accordance with several pellet standards listed in Table 1, such as the Indonesian National Standard (SNI 8675:2018) for industry, as well as standards from several other countries such as Germany (DIN 51371) and France (ITEBE).

In the graph of test results as shown in Fig. 5, the heating value of sengon wood pellets in the As Received (AR) condition shows a difference of 10.4% compared to Air Dried Basis (ADB) and a difference of 11.6% compared to Dry Basis (DB). In the Air Dried Basis (ADB) condition, there is a 1% difference in value compared to the Dry Basis (DB). The ash content test results have met the pellet standards listed in Table 1, namely the Indonesian National Standard (SNI 8675:2018). In addition, these values also meet the standards of several other countries, such as European (EN Plus), French (ITEBE), and Japanese (JPA) standards.

Tests and calculations have been carried out, with the results shown in Fig. 6, where each specimen shows different results. In the test, sample 1 has a value difference of 10.5% compared to sample 2 and a value difference of 14.4% compared to sample 3. Meanwhile, sample 2 has a difference in value of 3.5% compared to sample 3. The data in the graph shows an increase that is influenced by the different sizes and masses of the pellets tested. In addition, the volatile matter content can also affect the results, both in terms of increase and decrease in value.

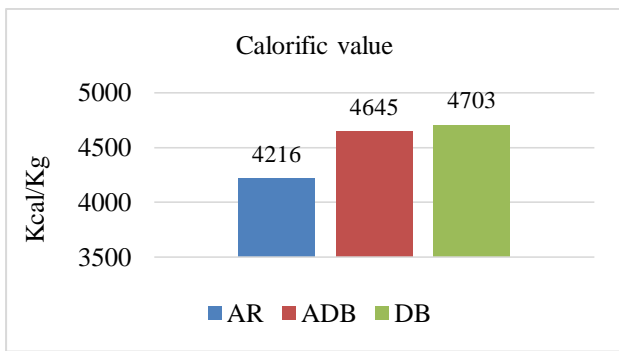


Fig. 3. Calorific value.

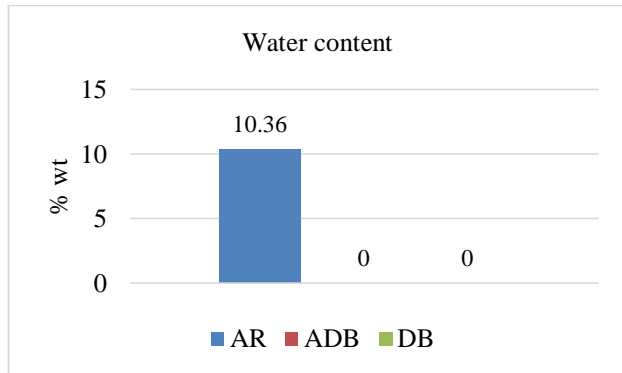


Fig. 4. Water content.

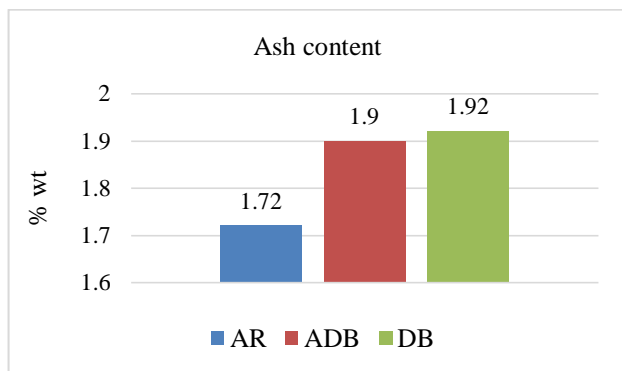


Fig. 5. Ash content.

From the combustion rate tests that have been conducted, it can be seen that sample 3 has the best performance by producing an average value of 0.174 gr/min. The normal burning rate test lasts between 5.42 minutes and 7.29 minutes, but the test results showed the highest number in sample 3 at 17.26 minutes. This means that sample 3 not only meets but also exceeds the set standard value.

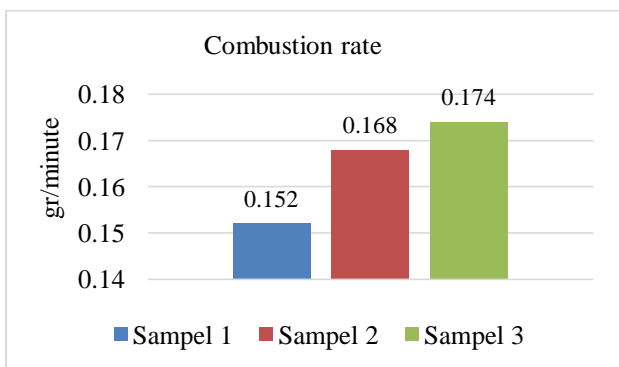


Fig. 6. Combustion rate.

The SEM-EDX test on wood pellets made from sengon wood aims to determine the purity of the elemental composition within the wood pellets, particularly the basic elements that constitute fuel. According to the SEM-EDX results, the highest content in

the wood pellets is the Oxygen (O) element at 52.08%, followed by the Carbon (C) element at 40.37%. The percentages of other elements present in smaller amounts include Calcium (Ca), Silicon (Si), Copper (Cu), Potassium (K), Chlorine (Cl), and Aluminum (Al), as shown in Table 3, which details the composition of burning wood pellets from sengon wood based on SEM-EDX analysis.

Table 3. Composition of wood pellet combustion from sengon wood SEM-EDX

Elements	Wt%	At%
O	52.08	49.22
C	40.37	47.68
Ca	1.29	0.30
Si	0.85	0.46
Cu	1.96	1.02
K	0.42	0.18
Cl	1.40	0.52
Al	1.64	0.60

To ensure high-quality wood pellets, it is essential to minimize the presence of inorganic elements such as alkali metals (K, Na) and significant amounts of Cl, S, and Si. These elements can introduce impurities, cause scaling, and lead to corrosion in combustion boilers, necessitating more frequent maintenance. Wood pellets derived from sengon wood, as observed in SEM-EDX tests, meet fuel standards but require further examination. Typically, biomass contains approximately 45% carbon (wt% dry fuel), whereas coal contains 60% or more. A higher carbon content correlates with an increased heating value.

Fig. 7 shows that the highest energy emission from atoms in wood pellets comes from Carbon (C), followed by Oxygen (O). Small amounts of energy emission are also observed from metals (Al, K, and Ca), semi-metals (Si), and non-metals (Cl). Based on the SEM micrograph in Test 1, the dark-colored areas appear more extensive compared to the lighter-colored areas, which likely indicate the presence of metal elements. Test data from Test 2 and Test 3 generally show that the combination of O and K elements is predominant, although Test 2 specifically indicates that C and K elements are highest, as detailed in Table 4.

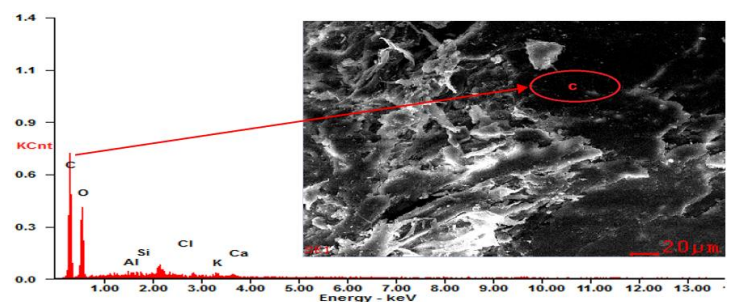
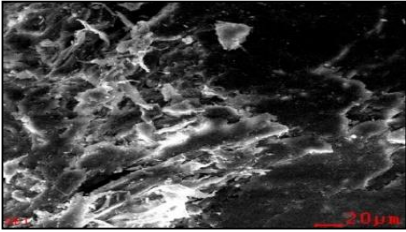
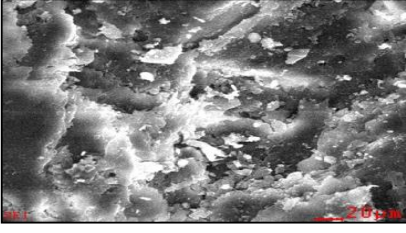
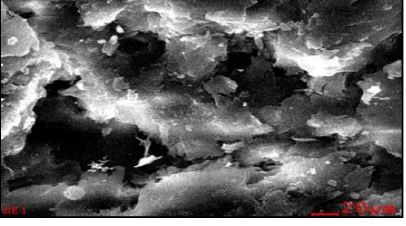


Fig. 7. Wood pellet energy.

SEM characterization was employed to analyze the morphology and structure of the samples detailed in Table 4. The SEM micrograph analysis specifically examined the surface of wood pellets, providing insights into their external characteristics. However, it did not reveal the internal structure, which likely differed in density from the surface. As indicated in Table 4, the density of the wood pellets was 796 kg/m<sup>3</sup>, illustrating varying pore sizes. During the pelleting process, rapid compression on the outer surface against steel molds created smaller and smoother pores compared to the interior. The rapid pressing could also lead to pellet breakage, forming additional pores and reducing overall porosity.

Furthermore, EDX analysis revealed that approximately 50% of the wood pellet composition comprised carbon-carbon bonds, suggesting heterogeneous particle formation due to the absence of binders in the pellet manufacturing process.

Table 4. SEM micrograph testing

Testing	Description
	It can be seen that the dark-colored part is larger. The lighter colored, or white parts are probably metallic elements.
	It can be seen that the bright part is wider and there are more debris.
	While dark parts appear in some places, there are also bright parts.

#### 4 Conclusion

In the research conducted, the results showed that the calorific value increased due to a decrease in the moisture content of the pellets. The highest heating value was found in the Dry Basis (DB) test, which amounted to 4703 Kcal/kg. Meanwhile, in the moisture content study, the results showed that in the As Received (AR) condition, the moisture content was recorded at 10.36%. However, in the Air Dried Basis (ADB) and Dry Basis (DB) conditions, the moisture content value was not recorded because the test did not calculate surface moisture and total moisture.

In the ash content study, the results varied. The lowest ash content was found in the As Received (AR) test, which amounted to 1.72%. Meanwhile, in the combustion rate study, the results showed an increase, which can be caused by differences in mass and size in each sample, which affect the combustion rate. The highest combustion rate was found in sample 3, with a value of 0.174 gr/min.

The results of the calorific value obtained are as follows: As Received (AR) of 4216 Kcal/kg, Air Dried Basis (ADB) of 4645 Kcal/kg, and Dry Basis (DB) of 4703 Kcal/kg. These values have met the standards set by the Indonesian National Standard (SNI 8675:2018) listed in Table 1, as well as international standards from several countries, such as Germany (DIN 51371), Sweden (SS 18 71 20), France (ITEBE), Europe (EN Plus), and Japan (JPA). For moisture content, the result obtained for As Received (AR) condition is 10.36%, which is also in accordance with SNI 8675:2018 and international standards such as those in Germany (DIN 51371) and France (ITEBE). For ash content, the results were 1.72% in the As Received (AR) condition, 1.9% in the Air Dried Basis (ADB) condition, and 1.92% in the Dry Basis (DB) condition. These values meet the SNI 8675:2018 standard as well as standards from Europe (EN Plus), France (ITEBE), and Japan (JPA). In the combustion rate study, the results showed that sample 1 was 0.152 gr/min, sample 2 was 0.168 gr/min, and sample 3 was 0.174 gr/min. This test showed a normal burning time between 5.42 minutes and 7.29 minutes. However, the highest result was found in sample 3, with a time of 17.26 minutes, which means it exceeds the set standard.

#### References

- [1] Pelka, G.; Jach-Nocoń, M.; Paprocki, M.; Jachimowski, A.; Luboń, W.; Nocoń, A.; Wygoda, M.; Wyczęsany, P.; Pachytel, P.; Mirowski, T. Comparison of Emissions and Efficiency of Two Types of Burners When Burning Wood Pellets from Different Suppliers. *Energies* 2023, 16, 1695. <https://doi.org/10.3390/en16041695>
- [2] Prayudi Suparmin, Roswati Nurhasanah, Hendri Hendri & Muhammad Ridwan (2023) Biomass for dual-fuel syngas diesel power plants. Part I: The effect of preheating on characteristics of the syngas gasification of municipal solid waste and wood pellets, *Arab Journal of Basic and Applied Sciences*, 30:1, 378-392, DOI: 10.1080/25765299.2023.2223027
- [3] B. S. Nasional, "Pelet Biomassa Untuk Energi SNI 8675:2018," 2018.
- [4] Dafnomilis, I., Hoefnagels, R., Pratama, Y. W., Schott, D. L., Lodewijks, G., & Junginger, M. (2017). Review of solid and liquid biofuel demand and supply in Northwest Europe towards 2030—A comparison of national and regional projections. *Renewable and Sustainable Energy Reviews*, 78, 31–45. <https://doi.org/10.1016/j.rser.2017.04.108>
- [5] E. A. Nugraha, "Karakteristik Pelet Campuran Tandan Kosong Kelapa Sawit (*Elaeis guineensis* jacq.) dan Arang," 2014.
- [6] H. R. Prihandana R, "Energi Hijau," 2007.
- [7] M. Zamorano, V. Popov, M. L. Rodríguez, and A. García-Maraver, "A comparative study of quality properties of pelletized agricultural and forestry lopping residues," *Renew. Energy*, vol. 36, no. 11, pp. 3133–3140, 2011.
- [8] R. Godina, L. J. R. Nunes, F. M. B. C. Santos, and J. C. O. Matias, "Logistics cost analysis between wood pellets and torrefied Biomass Pellets: The case of Portugal," 2018 7th Int. Conf. Ind. Technol. Manag. ICITM 2018, vol. 2018-Janua, no. March, pp. 284–287, 2018.
- [9] E. Thiffault, J. Barrette, P. Blanchet, Q. N. Nguyen, and K. Adjalle, "Optimizing quality of wood pellets made of hardwood processing residues," *Forests*, vol. 10, no. 7, pp. 1–19, 2019.
- [10] W. Wattana, S. Phetklung, W. Jakaew, S. Chumuthai, P. Sriam, and N. Chanurai, "Characterization of Mixed Biomass Pellet Made from Oil Palm and Para-rubber Tree Residues," *Energy Procedia*, vol. 138, pp. 1128–1133, 2017.
- [11] R. Godina, L. J. R. Nunes, F. M. B. C. Santos, and J. C. O. Matias, "Logistics cost analysis between wood pellets and torrefied Biomass Pellets: The case of Portugal," 2018 7th Int. Conf. Ind. Technol. Manag. ICITM 2018, vol. 2018-Janua, no. March, pp. 284–287, 2018.
- [1] N. K. Dien, T. T. Tho, N. V. Thanh, N. V. A. Duy, A. Jannifar, and N. H. Tho, "Application of topology optimization technique in sand casting process of a complex product based on FDM 3D printing technology," vol. 19, 2021.
- [2] A. Akhyar, "Numerical-hydrodynamic analysis, vickers hardness, and tensile test of cast-brass alloy for boat propellers," *Jurnal Polimesin*, vol. 21, no. 2, Apr. 2023, doi: 10.30811/jpl.v21i2.3743.
- [3] J. G. Kaufman and E. L. Roy, *Aluminum Alloy Castings: Properties, Processes, and Applications*. 2004.
- [4] S. Khan, A. Ourdjini, Q. S. Named, M. A. Alam Najafabadi, and R. Elliott, "Hardness and mechanical property relationships in directionally solidified aluminium-silicon eutectic alloys with different silicon morphologies," *Journal of Materials Science*, vol. 28, no. 21, pp. 5957–5962, 1993, doi: 10.1007/BF00365208.
- [5] D. Masnur, Suyitno, and V. Malau, "The Influence of Mold Material on Cooling Curve, Solidification Parameters, and Micro-hardness of Al-6wt.% Si in Unidirectional

- Solidification,” *IOP Conf. Series: Materials Science and Engineering*, vol. 547, 2019, doi: 10.1088/1757-899X/547/1/012014.
- [6] M. Farkašová, E. Tillová, and M. Chalupová, “Modification of Al-Si-Cu cast alloy,” *FME Transactions*, vol. 41, no. 3, pp. 210–215, 2013.
- [7] G. Timelli, G. Camicia, and S. Ferraro, “Effect of grain refinement and cooling rate on the microstructure and mechanical properties of secondary Al-Si-Cu alloys,” *Journal of Materials Engineering and Performance*, vol. 23, no. 2, pp. 611–621, 2014, doi: 10.1007/s11665-013-0757-y.
- [8] L. Bolzoni, M. Xia, and N. H. Babu, “Formation of equiaxed crystal structures in directionally solidified Al-Si alloys using Nb-based heterogeneous nuclei,” *Nature Publishing Group*, no. December, pp. 1–10, 2016, doi: 10.1038/srep39554.
- [9] M. Nowak, L. Bolzoni, and N. Hari Babu, “Grain refinement of Al-Si alloys by Nb-B inoculation. Part I: Concept development and effect on binary alloys,” *Materials and Design*, vol. 66, no. PA, pp. 366–375, 2015, doi: 10.1016/j.matdes.2014.08.066.
- [10] M. Okayasu, S. Takeuchi, S. Wu, and T. Ochi, “Effects of Sb, Sr, and Bi on the material properties of cast Al-Si-Cu alloys produced through heated mold continuous casting,” *Journal of Mechanical Science and Technology*, vol. 30, no. 3, pp. 1139–1147, 2016, doi: 10.1007/s12206-016-0218-2.
- [11] Q. Wang, Y. X. Li, and X. C. Li, “Grain Refinement of Al – 7Si Alloys and the Efficiency Assessment by Recognition of Cooling Curves,” *Metallurgical and Materials Transactions A*, vol. 34, no. May, pp. 1175–1182, 2003.
- [12] G. K. Sigworth and T. A. Kuhn, “Grain refinement of aluminum casting alloys,” *International Journal of Metalcasting*, vol. 1, no. 1, pp. 31–40, 2007, doi: 10.1361/asmhba0005302.
- [13] Z. Fan *et al.*, “Grain refining mechanism in the Al / Al – Ti – B system,” *ACTA MATERIALIA*, vol. 84, pp. 292–304, 2015, doi: 10.1016/j.actamat.2014.10.055.
- [14] K. Kashyap and T. Chandrashekar, “Effects and mechanisms of grain refinement in aluminium alloys,” *Bulletin of Materials Science*, vol. 24, no. 4, pp. 345–353, 2001, doi: 10.1007/BF02708630.
- [15] M. Easton and D. StJohn, “Grain Refinement of Aluminum Alloys : Part I . The Nucleant and Solute Paradigms — A Review of the Literature,” *Metallurgical and Materials Transactions A*, vol. 30, no. June, pp. 1613–1623, 1999, doi: 10.1007/s11661-999-0098-5.
- [16] M. Easton and D. StJohn, “Grain refinement of aluminum alloys: Part II. Confirmation of, and a mechanism for, the solute paradigm,” *Metallurgical and Materials Transactions A*, vol. 30, no. June, pp. 1625–1633, 1999, doi: 10.1007/s11661-999-0099-4.
- [17] M. Riestra, E. Ghassemali, T. Bogdanoff, and S. Seifeddine, “Interactive effects of grain refinement, eutectic modification and solidification rate on tensile properties of Al-10Si alloy,” *Materials Science and Engineering A*, vol. 703, no. July, pp. 270–279, 2017, doi: 10.1016/j.msea.2017.07.074.
- [18] D. Masnur, V. Malau, and S. Suyitno, “Composition Profile and Microstructure Formation of Unidirectionally Solidified Al-4.5 wt% Cu,” *Inter Metalcast*, vol. 16, no. 1, pp. 349–358, Jan. 2022, doi: 10.1007/s40962-021-00598-4.
- [19] D. Masnur, V. Malau, and S. Suyitno, “The dependency of the microhardnes on microstructure and solidification parameters of directionally solidified Al-4.5wt.%Cu in clay mold,” *JMES*, vol. 14, no. 3, pp. 7125–7131, Sep. 2020, doi: 10.15282/jmes.14.3.2020.13.0558.
- [20] V. Raghavan, “Al-Cu-Si (aluminum-copper-silicon),” *Journal of Phase Equilibria and Diffusion*, vol. 33, no. 1, pp. 59–61, 2012, doi: 10.1007/s11669-012-9982-6.
- [21] D. G. Eskin, Q. Du, D. Ruvalcaba, and L. Katgerman, “Experimental study of structure formation in binary Al-Cu alloys at different cooling rates,” *Materials Science and Engineering A*, vol. 405, no. 1–2, pp. 1–10, 2005, doi: 10.1016/j.msea.2005.05.105.
- [22] W. Desrosin, L. Boycho, V. Scheiber, C. M. Méndez, C. E. Schvezov, and A. E. Ares, “Evolution of Metallographic Parameters during Horizontal Unidirectional Solidification of Zn-Sn Alloys,” *Procedia Materials Science*, vol. 8, pp. 968–977, 2015, doi: 10.1016/j.mspro.2015.04.158.
- [23] H. Kaya, U. Böyük, E. Çadirlı, and N. Maraşlı, “Influence of growth rate on microstructure, microhardness, and electrical resistivity of directionally solidified Al-7 wt% Ni hypoeutectic alloy,” *Metals and Materials International*, vol. 19, no. 1, pp. 39–44, 2013, doi: 10.1007/s12540-013-1007-4.
- [24] E. Çadirlı, “Effect of solidification parameters on mechanical properties of directionally solidified Al-Rich Al-Cu alloys,” *Metals and Materials International*, vol. 19, no. 3, pp. 411–422, 2013, doi: 10.1007/s12540-013-3006-x.
- [25] S. Farahany, Mohd. H. Idris, A. Ourdjini, F. Faris, and H. Ghandvar, “Evaluation of the effect of grain refiners on the solidification characteristics of an Sr-modified ADC12 die-casting alloy by cooling curve thermal analysis,” *J Therm Anal Calorim*, vol. 119, no. 3, pp. 1593–1601, Mar. 2015, doi: 10.1007/s10973-014-4367-1.
- [26] M. Johnsson, L. Backerud, and G. K. Sigworth, “Study of the mechanism of grain refinement of aluminum after additions of Ti- and B-containing master alloys,” *Metallurgical Transactions A*, vol. 24, no. 2, pp. 481–491, 1993, doi: 10.1007/BF02657335.
- [27] M. Vončina, J. Medved, L. Jerina, I. Paulin, P. Cvahte, and M. Steinacher, “The Impact of AL-TI-B Grain-Refiners from Different Manufacturers on Wrought AL-alloy,” *Archives of Metallurgy and Materials*, pp. 739–746, Mar. 2019, doi: 10.24425/amm.2019.127607.
- [28] M. Buchmann and M. Rettenmayr, “Microstructure evolution during melting and resolidification in a temperature gradient,” *Journal of Crystal Growth*, vol. 284, no. 3–4, pp. 544–553, 2005, doi: 10.1016/j.jcrysgro.2005.06.044.
- [29] A. Kolahdooz, S. Nourouzi, M. Bakhshi, and S. J. Hosseinipour, “Investigation of the controlled atmosphere of semisolid metal processing of A356 aluminium alloy,” *Journal of Mechanical Science and Technology*, vol. 28, no. 10, pp. 4267–4274, 2014, doi: 10.1007/s12206-014-0940-6.
- [30] O. L. Rocha, C. A. Siqueira, and A. Garcia, “Heat flow parameters affecting dendrite spacings during unsteady-state solidification of Sn-Pb and Al-Cu alloys,” *Metallurgical and Materials Transactions A*, vol. 34, no. 4, pp. 995–1006, 2003, doi: 10.1007/s11661-003-0229-3.
- [31] M. Gündüz, H. Kaya, E. Çadirlı, N. Maraşlı, K. Keşlioğlu, and B. Saatçi, “Effect of solidification processing parameters on the cellular spacings in the Al-0.1wt% Ti and Al-0.5wt% Ti alloys,” *Journal of Alloys and Compounds*, vol. 439, no. 1–2, pp. 114–127, Jul. 2007, doi: 10.1016/j.jallcom.2006.08.246.
- [32] A. J. Vasconcelos, R. H. Kikuchi, A. S. Barros, and T. A. Costa, “Interconnection between microstructure and microhardness of directionally solidified binary Al-6wt.% Cu and multicomponent Al-6wt.% Cu-8wt.% Si alloys,” *Annals of the Brazilian Academy of Sciences*, vol. 88, no. 2, pp. 1099–1111, 2016, doi: 10.1590/0001-3765201620150172.