International Journal of Energy Production and Management
Vol. 8, No. 4, December, 2023, pp. 251-258
Journal homepage: http://iieta.org/journals/ijepm

Performance Evaluation of Wood Pellets Derived from Biomass Waste as a Sustainable Energy Source

Dino Rimantho[1*], Nur Yulianti Hidayah[1], Vector Anggit Pratomo[2]

[1] Industrial Engineering-Engineering Faculty, Pancasila University, DKI Jakarta 12640, Indonesia
[2] Electrical Engineering-Engineering Faculty, Pancasila University, DKI Jakarta 12640, Indonesia

Corresponding Author Email: dino.rimantho@univpancasila.ac.id

https://doi.org/10.18280/ijepm.080407

Received: 5 October 2023
Revised: 22 November 2023
Accepted: 8 December 2023
Available online: 29 December 2023

Keywords:
energy, natural resources, biomass waste, wood pellets, material, sustainability, renewable energy, energy crisis, global warming

ABSTRACT

Addressing pressing global challenges—such as energy crises, population growth, food scarcity, resource depletion, and global warming—requires innovative and sustainable solutions. Biomass-derived wood pellets present a promising eco-friendly energy alternative. This study investigates the conversion of agricultural residues into wood pellets, utilizing two distinct biomass compositions. Composition A comprises equal parts young coconut fiber, empty palm fruit bunches, and sawdust (1:1:1 ratio), while Composition B uses a 1:1:0.5 ratio of the same materials. Laboratory analyses were conducted in accordance with Indonesian National Standard (SNI) SNI 8021:2014 to determine the physical and chemical properties of the resulting wood pellets. It was found that the moisture content of Composition A ranged from 3.52% to 4.59% in Composition B, while ash content was significantly higher in Composition A at 10.09%, compared to 4.25% for Composition B. The energy content was measured to be approximately 4102 Kcal/Kg (17,173 MJ/Kg) for Composition A and 4613 Kcal/Kg (19,313 MJ/Kg) for Composition B. The results indicate that the moisture content and calorific value of the wood pellets are in compliance with several international standards, including SNI 8021:2014 (Indonesia), ONORM M7135 (Austria), and DIN 51731 (Germany). However, the ash content of Composition A exceeds these standards. The findings suggest that optimal composition ratios can yield biomass pellets that contribute to sustainable energy solutions in line with Indonesia's renewable energy goals and the broader Sustainable Development Goals (SDGs).

1. INTRODUCTION

The convergence of escalating energy demands, burgeoning population growth, diminishing food supplies, the depletion of natural resources, and the intensifying effects of global warming constitutes a spectrum of formidable global challenges [1-4]. In light of these multifaceted crises, the recovery of resources from waste emerges as a pivotal strategy to reduce the dependence on finite energy sources [2]. The shift from a linear consumption model to a circular economy (CE) is thus imperative, epitomized by resource reincorporation processes that aim to mitigate waste.

A growing body of research underscores the pivotal role of biomass in satisfying the burgeoning global energy demand [2, 5-7]. The transition to a Circular Resource-Based Economy (CRBE) is facilitated by the monetization of biomass, particularly through biofuel production, which offers a more sustainable and carbon-neutral alternative to fossil fuels [2, 8]. Concurrently, policy framework-s worldwide are increasingly aimed at curtailing the utilization of fossil fuels and reducing greenhouse gas (GHG) emissions [9]. Within this energy paradigm, wood pellets have been recognized for their numerous advantages, including transportability, low moisture content, and high calorific value, positioning them as a viable energy source [10]. Forecasts project that by 2025, wood pellet consumption will reach a significant 54 million tonnes globally [2].

Amidst a period of uncertainty and transition within the global forestry sector, there is a growing recognition among companies of the need to prioritize value-added forest products and enhance waste management practices. Sustainable energy sources, such as wood pellets, are garnering attention for their potential role in energy generation [10, 11], characterized by attributes such as high density, high heating value, and ease of storage and transport [12, 13]. The market for wood pellets has experienced global expansion, with certain countries becoming significant exporters [14]. This proliferation of wood pellet production facilities has precipitated heightened competition in the sector. The utilization of biomass as an alternative energy source confers notable environmental and socio-economic benefits, despite challenges related to its supply and carbon neutrality [15].

In numerous developing nations, substantial volumes of agricultural waste are generated, commonly underutilized and contributing to environmental degradation. A plethora of waste types, including rice husk, coffee husk, coir pith, bagasse, and sawdust, represent untapped biomass sources [15]. These residues, traditionally considered waste, present an economical feedstock for energy production. Recent initiatives have sought to capitalize on these materials through various thermal processes, addressing the inherent disadvantages of biomass, such as lower density and higher moisture content compared to conventional fuels. Densification is a process that mitigates these drawbacks by compressing biomass into a more energy-dense form, thereby enhancing handling qualities and calorific value, as delineated by Markson et al. [16]. Among the available methods, pelletizing stands out for its sophistication [17].

Indonesia is a tropical nation with vast forests, abundant arable land, and various biomass sources, including wood scraps, rice husks, corn leftovers, and wood plantations. Roughly 1.3 million hectares of the 74.4 million hectares of production forest are set aside for plantations connected to energy, and 32 companies have already committed to developing these. Sumatra has the most potential (15,588 MWe) for biomass supply to generate power, followed by Java and Bali (9,215 MWe), Kalimantan (5,062 MWe), Sulawesi (1,937 MWe), Nusa Tenggara (636 MWe), and Maluku and Papua (218 MWe). According to the Indonesian Directorate General of New, Renewable Energy and Energy Conservation, Ministry of Energy and Mineral Resources (DJ EBTKE), when biomass kinds are categorized, palm oil has the most potential at about 12,654 MWe, followed by rice husks (9,808 MWe), municipal garbage (2,066 MWe), rubber (2,781 MWe), corn (1,733 MWe), wood (1,335 MWe), sugar cane (1,295 MWe), and others (983 MWe)[18].

Moreover, agronomic crops like corn and wheat can yield roughly 70% more [19]. In comparison, industrial goods like cotton, flax, sesame seeds, and flowers have long been farmed in Indonesia. Soybeans and other fruit plants can be cultivated there in the Mediterranean region [19-21]. A range of agricultural wastes can be used in Indonesia as a biomass energy source. In addition, the residuals of farm yields, along with critical estimations of energy value. Amounts of dry residue, which total about 57 million tons, are used to compute the residue from agricultural products. It is comparable to 16 Mtoe of energy per year from agricultural residues. In Indonesia, agricultural leftovers such as wheat straw, grain dust, and hazelnuts are used as a source of biomass energy [22]. Indonesia can produce 3.4/109 tons of wheat straw annually [19]. This straw is occasionally tossed out to burn in the field. This straw can create high heat values during burning, equaling half of the coal, or about 28 MJ/kg [23]. Additional energy sources, like candlenut shells, offer enormous promise. This straw shell's estimated yearly energy output is 3.7/107 tons. The disadvantage value equals 1.9/108 kWh since the hazelnut's calorific value is 19.2 MJ/kg [23] [19]. Steam gasification technique can convert hydrogen-rich agricultural leftovers into gas fuel [24]. Conventional methods can produce classical biomass technology [25, 26]. Previous studies show the potential for fruit and fruit tree residues produced in Indonesia as raw material in renewable energy, for example, apricots (tree pruning), sour cherries (tree pruning), olives (cake), pistachios (shell), walnuts (cover), Almond (Shell), Hazelnut (Shell), Orange (tree pruning) [19]. Furthermore, residues available from fruit and trees include apricots (69,671 tons), sour cherries (17,120 tons), olives (746,843 tons), pistachios (4202 tons), walnuts (60,633 tons), almonds (23,205 tons), Hazelnuts (453,510 tons), Oranges (190,148 tons). In addition, the heating values are approximately apricots (19.3 MJ/kg), sour cherries (19.0 MJ/kg), olives (20.69/kg), pistachios (19.26 MJ/kg), walnuts (20.18 MJ/kg), almonds (19.38 MJ/kg), Hazelnuts (19.3 MJ/kg), Oranges (17.6 MJ/kg).

Furthermore, palm oil waste also has the potential to make wood pellets. The oil palm (*Elaeis guineensis Jacq.)* is the primary source of palm oil, produced in vast quantities in Indonesia, and has made up most of the nation's income in recent years. With around 8.5 million hectares of oil palm planted between 2014 and 2016, Indonesia is the world's largest palm oil producer. Forty-two countries cultivate 11 million hectares of palm oil crops overall [27]. Nevertheless, palm oil production is criticized worldwide because of its substantial and undeniable environmental harm. The most biologically varied terrestrial ecosystems on Earth are found in tropical and subtropical regions, destroyed by oil palm plantations [28].

Table 1. The requirements for quality parameters of wood pellets

Standards	Moisture Content (%)	Ash Content (%)	Caloric Value MJ/Kg
SNI 8021:2014	<12	<1.5	> 16.74
Austrian standard ONORM M7135	<10	<0.5	>17.99
German Standard DIN 51731	<12	<1.5	15.5 – 19.5
Swedish Standard SS 187120	<10	<1.5	16.89
Italian Standard CTI-R04/05	<10	<1.5	16.89
French ITEBE	<10	<10	>16.95

Wood pellets can potentially be derived from the waste from the above sources. The conversion of biomass can be classified into many processes, such as densification, carbonization, gasification, anaerobic digestion, and pyrolysis. Using pellets as a means of densification is a prevalent approach employed to enhance the worth of agricultural and biological substances. To ensure the production of high-quality wood pellets, the moisture content of the wood pellet must fall within the range of 6.85-7.45%, the ash content remains between 1.7-1.9%, and the calorific value is maintained at 3,814-4,724 Cal/g [29]. The quality characteristics of wood pellets are subject to regulation by several standards on a global scale, which are outlined in Table 1.

The accumulation of biomass waste, including empty oil palm fruit bunches, sawdust, and coconut waste, poses an emergent ecological challenge in Indonesia. The underutilization of such waste as a renewable energy source necessitates innovative approaches to convert this biomass into valuable commodities like wood pellets. This study aims to assess the potential of wood pellets derived from these sources and evaluates two wood pellet compositions against the SNI 8021:2014 standard. Moreover, this research will scrutinize the sustainability of wood pellet production from biomass waste.

2. METHOD

The equipment used in this research includes machetes/cutting scissors, mixers, hammer mills, bio-pellet presses (palletizers), scales, ovens, and calipers. Making wood pellets can be divided into five stages: providing raw materials containing cellulose lignin from agricultural waste (sawdust, empty oil palm fruit bunches, young coconut fiber), drying the raw materials, refining the raw materials, and conditioning and pelletizing.

The raw materials include sawdust waste, empty palm fruit bunches, and young coconut husks. The initial process of all raw materials is drying to obtain the dryness required for making wood pellets. All raw materials are dried naturally in the sun for 15 days to obtain the dryness level of the material, then stored in a cold room, and the water content is ensured to be <12%. This natural drying process takes quite a long time due to limited equipment. Next, the empty oil palm bunch material and young coconut fibers are cut to a size of around 1 cm using a knife/cutting scissors to facilitate the crushing process into powder, which has a size of 40 mesh.

The next stage in making wood pellets is that the raw material is ground into powder form using a hammer mill machine so that the particle size of the raw material makes it possible to make wood pellets according to the available wood pellet printing equipment. The resulting particle size is ≤40 mesh. To maintain its water content, the raw material in powder form remains stored in the conditioning room until wood pellets are characterized and molded.

Wood pellets are produced from a mixture of raw materials that have undergone the abovementioned treatment: sawdust, empty palm fruit bunches, young coconut fiber, and tapioca flour adhesive. The combination of raw materials in this research is young coconut fiber, sawdust, and empty palm oil bunches. The variety of raw materials used in making wood pellets can be seen in Table 2.

Table 2. Material Composition

No.	Material	Composition (Kg)
1	Young coconut fiber, empty palm fruit bunches, sawdust	1: 1: 1
2	Young coconut fiber, empty palm fruit bunches, sawdust	1: 1: 0.5

All ingredients based on each ratio are mixed in a low-speed mixer and then pelletized using a wood pellet pelletizer. Pellet molding pressure uses a size of 40 kg/cm^2. The finished wood pellets are immediately placed in the oven at a temperature of 102 ± 3°C for 24 hours to maintain dimensional stability. After drying, it is stored in a conditioning room, and its characteristics are tested to determine its quality.

Testing for each parameter was carried out ten times. Then, the data is processed, compared with existing data from similar research results, and compared with applicable quality standards to determine whether the research data meets the relevant quality requirements. Analysis of wood pellet parameters was carried out using Sucofindo laboratory services. From observations of the characterization results of wood pellets based on SNI 8021:2014, the results were analyzed in the form of water content, ash content, volatile substance content, bound carbon content, compressive strength, density, and heating value. The laboratory test results were then analyzed using one-way ANOVA with a confidence level of 95% to determine whether there were differences in sample means.

The form of the hypothesis in one-way ANOVA generally follows the following two statements:

Reject H0 (accept H1) if the P-value < significance level α (1)

Reject H1 (accept H0) if the P-value > Significance level α (2)

where,

H0: Composition A has no significant difference from Composition B.

H1: Composition A has a significant difference from Composition B.

3. RESULT AND DISCUSSION

3.1 Results

Based on the laboratory test results, the results shown in Table 3 are as follows:

Table 3 provides information related to test results on two wood pellet specimen compositions using the SNI 8021:2014 standard on several parameters such as moisture, ash content, volatile matter, fixed carbon, total Sulfur, and gross caloric value. Furthermore, from these results, the highest moisture value for Composition A was around 3.52% and 4.59% for Composition B. Testing the ash content for Composition A obtained the highest value of approximately 10.09% and 4.25% for Composition B. Moreover, the caloric value assessment for composition A is around 4102 Kcal/Kg or equivalent to 17,173 MJ/Kg. Composition B's highest value is about 4613 Kcal/Kg or 19,313 MJ/Kg. The results of the test show that the results of moisture content and caloric value tests follow existing standards for both SNI 8021:2014 (Indonesia), Austrian standard ONORM M7135 (Austria), and German Standard DIN 51731 (Germany). However, Ash's content still does not meet all existing standards.

Based on the test results, statistical tests were then carried out to test the level of difference between compositions A and B, the results of which are shown in Table 4.

The results of this research with the Gross Caloric Value parameter use wood pellets made from biomass waste with different compositions. The test was carried out ten times in repetition. Test result data is presented in Kcal/Kg units. The results obtained can be seen in Table 3.

Based on the results obtained from the ANOVA test on Gross Caloric Value, it can be seen that F count = > F crit= 4.413, which means Ho is rejected and Ha is accepted. Additionally, for the probability value, it can be seen that the probability value is 0.000 < 0.05. Thus, the null hypothesis (Ho) is rejected. This shows a difference in the average GCV value using different types of Composition in biomass waste. Composition B produces a higher GCV value than composition A; this means that composition B can be an environmentally friendly fuel. Therefore, there are different values with different composition concentrations in biomass waste.

Table 3. Test results on wood pellet specimens

No.	Moisture (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Total Sulfur (%)	Gross Caloric Value (Kcal/Kg)
	Composition A					
1	3.42	8.59	73.73	13.32	0.03	4014
2	3.45	8.70	7673	13.26	0.03	4069
3	3.41	8.75	76.83	13.79	0.03	3993
4	3.52	9.53	76.24	13.23	0.04	4072
5	3.43	10.04	73.40	13.10	0.03	3988
6	3.35	9.10	74.66	13.39	0.03	4038
7	3.44	10.09	75.19	12.71	0.03	3993
8	3.52	9.71	73.05	12.58	0.04	4102
9	3.48	9.32	75.65	13.60	0.03	4007
10	3.52	10.06	72.82	13.64	0.04	4007
	Composition B					
1	4.29	4.25	77.92	13.40	0.05	4432
2	4.20	4.21	76.80	13.44	0.04	4565
3	4.48	4.09	78.63	13.10	0.04	4262
4	4.35	3.60	77.38	14.13	0.03	4346
5	4.17	3.95	78.09	14.31	0.05	4306
6	3.93	3.55	78.16	13.89	0.04	4613
7	4.49	4.11	77.22	12.75	0.05	4322
8	4.25	3.73	78.69	14.09	0.05	4502
9	3.91	3.52	77.94	14.34	0.03	4417
10	4.59	3.71	77.22	13.84	0.03	4505

Table 4. Results of one-way ANOVA

Groups	Count	Sum	Average	Variance	Source of Variation	SS	df	MS	F	P-value	F crit
Composition A	10	44271.18	4427.118	13877.46	Between Groups	795407.4	1	79540.,4	102.8081	7.21E-09	4.413
Composition B	10	40282.68	4028.268	1596.182	Within Groups	139262.7	18	7736.819			
Total						934670.1	19				

3.2 Discussion

The obtained moisture results are deemed acceptable; further explanation is necessary. The reduced humidity observed in carbonized biomass waste can be attributed to removing inherent moisture (bound water) during the carbonization process. The remaining moisture content is primarily extrinsic, influenced by weather conditions and storage practices. Non-carbonized biomass waste, which contains both types of moisture, does not exhibit this phenomenon.

According to prior studies, humidity has been found to constrain the local temperature within biomass. Consequently, further energy will be necessary to raise the fuel's temperature [30]. The energy required for the evaporation of water present in biomass waste will decrease the temperature within the combustion chamber, thereby decelerating the combustion rate. The presence of moisture within the biomass will have the effect of reducing the adiabatic flame temperature and necessitating a greater quantity of air for achieving complete burning. A significant amount of water in biomass waste has been observed to have a mitigating effect on generating volatile compounds during the pyrolysis process while simultaneously promoting char development [31].

The ash content obtained from the findings of this investigation has been found to comply with the parameters indicated in Table 1. Moreover, this study's findings demonstrate notable benefits compared to prior research conducted by Pierre Delot, who utilized rice husks with an ash content of approximately 22.9% [32]. The elevated ash content in the biomass samples, specifically bioterror (55.27%) and typha biochar (43.22%), can be attributed to including clay particles. Clay is classified as a mineral substance and does not undergo carbonization. The residue obtained when determining ash content comprises ash particles and clay constituents. Using biomass for cooking or heating offers several benefits, including mitigating corrosion resulting from excessive ash accumulation, simplified maintenance procedures, convenient fire accessibility, and the absence of a ventilation cover on the stove. The energy yield of specific biomass sources is greatly diminished by a high ash concentration [30, 33], which in turn negatively impacts the efficiency of the stove [34].

The term "volatile material" pertains to the fraction of biomass material that undergoes conversion into gaseous form with exposure to temperatures ranging from 400℃ to 500℃. Biomass typically exhibits a substantial proportion of volatile matter, ranging from approximately 70% to 86%, while its charcoal concentration remains relatively modest. A significant concentration of volatile chemicals in a biomass material suggests that, when subjected to combustion, most of the material will undergo evaporation and then burn as gas within the boiler [34]. In addition, research conducted by Mitchual et al. [34] revealed that the volatile chemical composition of the six different wood species examined ranged from 75.23% (*Robusta*) to 83.70% (*Mildbreadii*), except for A. Robusta, the volatile matter content of all the species examined in the study exceeded 78% [34]. Furthermore, it has been shown that biomass materials containing a volatile content of up to 78% exhibit an ignition temperature ranging from 236°C to 270°C. In contrast, lignite, which has a volatile content of 53%, ignites at a temperature of 274°C [35].

The findings of this investigation indicate that the volatile matter value falls within the range of 73% - 78% for both compositions. The carbonization process is responsible for the degree of volatility wood pellets exhibit. During this chemical transformation, a significant quantity of volatile substances is released from the biomass waste, resulting in carbon retention as the residual component. In contrast, pelletizing or briquette is a physical procedure that does not alter the characteristics of the biomass but rather enhances its density. During this particular procedure, it is observed that there is an absence of volatiles being lost. However, it is noted that the denser biomass tends to undergo combustion over an extended duration [34].

The elevated volatile matter concentration of coal renders it more fragile than charcoal, resulting in reduced dust generation during transportation and handling. However, it is essential to note that coal combustion yields a smokey flame. Efficient combustion necessitates the utilization of substantial quantities of secondary air and the application of high pressure [36]. Biomass possessing a significant volatile matter concentration exhibits greater ease of gasification; nonetheless, it concurrently yields a considerable tar content [30].

Ignition of fuels containing volatile chemicals poses challenges, yet if ignited, these fuels exhibit a distinct and transparent flame [30]. The Volatile Matter (VM) rate is directly related to the constant carbon rate (CF). It is a well-established observation that an increase in the biomass's VM level is accompanied by a decrease in the FC (fixed carbon) level. A biomass with a lower selected carbon content is considered to possess higher quality due to its significant concentration of volatile elements. When combusted using an appropriate stove, it will generate higher heat levels and facilitate the pyrolysis of flammable substances.

The study analyzed the properties of wood and bark fuels and the various elements that impact heat recovery efficiency. The study's findings indicated that woody biomass exhibits an average heating density of 19.8 MJ/kg [34]. The particular heating value under investigation has a higher magnitude compared to other forms of wood biomass, as well as surpassing the heating values of alternative biomass fuels such as wheat straw (17.51 MJ/kg), rice straw (14.56 MJ/kg), corn straw (17.70 MJ/kg) and sugarcane bagasse (17.33 MJ/kg) [37, 38]. Even though the species under investigation exhibit a somewhat elevated calorific value, it remains lower in comparison to fossil fuels such as kerosene (46.5 MJ/kg), natural gas (37.3 MJ/kg), and coal (31.80 MJ/kg) [34]. Despite the relatively lower calorific value of the biomass fuels examined than fossil fuels, their significance as an energy source remains substantial owing to their long-term sustainability and extensive social and environmental advantages.

Among the various categories of biomass resources, agricultural residues, such as sawdust, coconut fiber, rice husks, corn stover, empty fruit bunches of palm oil, cotton stems, and peanut husks, have emerged as up-and-coming alternatives for cooking fuel. This is primarily attributed to their abundant availability as waste annually. Nevertheless, using biomass residue in its unprocessed state as a fuel presents considerable challenges due to its low density, limited heat release, and excessive smoke emission [35, 37]. The attributes above provide challenges in managing, storing, transporting, and using biomass leftovers in their unprocessed state. One approach to enhance biomass waste's thermal efficiency is briquette technology [38-40]. The process entails compressing loose biomass waste to generate a fuel with improved handling properties and a higher volumetric calorific value than biomass in its original form. One crucial technological advancement that can enhance biomass's use in generating electricity and heat has been identified [41, 42].

3.3 Sustainability in the production of wood pellets made from biomass waste

The Sustainable Development Goals (SDGs) are designed to be achieved by 2030, with each goal accompanied by a different set of targets. The goals and benchmarks outlined were formulated to recognize the importance of addressing poverty and other disadvantages through implementing initiatives to improve health and education, reduce inequality, encourage economic growth, and simultaneously manage climate change while safeguarding our oceans and forests. Therefore, assessing the impact of manufacturing wood pellets derived from biomass waste on the Sustainable Development Goals (SDGs) offers a valuable perspective in achieving global goals for social, environmental and economic progress [41]. Utilization of biomass waste for bioenergy is recommended as an effort to overcome climate change by replacing fossil fuels and increasing the resilience of forest ecosystems while facilitating carbon sequestration through improved natural resource management [43]. However, the efficacy of bioenergy in mitigating climate change and its impact on other Sustainable Development Goals (SDGs) depends on various factors, including local circumstances [44], as well as the size and intensity of production for various categories of raw materials and energy. The supply chain is related to the production process and availability of raw materials [45]. From the seventeen Sustainable Development Goals (SDGs), it was determined that five of them have significant relevance and are directly influenced by the manufacture of wood pellets from biomass waste.

Sustainable Development Goal 7.2 aims to increase the proportion of renewable energy sources. In achieving SDGs target 7 (Affordable and clean energy), the share of renewable energy is increasing due to the shift from fossil fuel energy to heating energy with district heat biomass in Marum, the Netherlands, Europe. This increase is proven by a bioheater of 7000 GJ/year, which eliminates 250,000 m^3 of natural gas consumption in the Netherlands [46].

The goal of SDG 8.4 is to increase efficiency and sustainability by decoupling economic growth from environmental degradation. To achieve SDG goal 8 (Decent work and economic growth), the Dutch government is offering incentives to employers who employ members of marginalized communities to oversee the heating network supply chain. About ten residents from disadvantaged backgrounds were employed in the supply chain [46].

Sustainable Development Goal 12.2 relates to the sustainable management of natural resources. Harvesting forests produces raw materials. Furthermore, the Rwandan government uses the remaining wood from eucalyptus trees to produce wood pellets. Additionally, by replacing carbon-intensive heating fuels with agricultural waste streams, the Danish government reduced waste and increased the efficiency of material use [47]. Meanwhile, tree intercropping is used by the state government of Victoria in Australia to increase biodiversity and restore degraded land [47].

Various problems arise when assessing the suitability of biomass waste-based wood pellet production with the Sustainable Development Goals (SDGs). A common problem encountered in IEA Bioenergy Inter-Task project evaluations is the mismatch between Sustainable Development Goal (SDG) indicators and more specific metrics relating to particular biomass supply chain scenarios [48, 49]. The complexity of these challenges is magnified when considering the interplay between dynamic human economies and biological systems in a landscape influenced by multiple drivers of change simultaneously [50]. Accurate and comprehensive knowledge of forest landowners and reliable data on forest conditions over recent decades is essential for understanding and assessing the impacts of policies, management strategies, climate change and other phenomena [51]. The use of reliable historical and contemporary data sets, such as the Forest Inventory and Analysis, can provide substantial evidence to assess the feasibility of achieving the desired goals by utilizing bioenergy derived from wood pellets produced from biomass waste. Therefore, it is essential to adhere to systematic procedures for establishing indicators that are aligned with the requirements and preferences of local stakeholders [52].

4. CONCLUSION

The findings of this study indicate that wood pellets produced from a mixture of biomass waste composition meet the recommended standard characteristics of wood pellets. The characteristics of wood pellets assessed in this study indicate that wood pellets made from a mixture of biomass waste composition have the highest water content value at composition A, around 3.52% and 4.59% for Composition B. Testing the ash content for Composition A obtained the highest value of around 10.09% and 4.25% for composition B. In addition, the calorific value for Composition A was around 4102 Kcal/ Kg or equivalent to 17,173 MJ/Kg. The highest value for Composition B is 4613 Kcal/Kg or 19,313 MJ/Kg. The test results show that the water content and calorific value test results follow existing standards, both SNI 8021:2014 (Indonesia), Austrian standard ONORM M7135 (Austria), and German standard DIN 51731 (Germany). The results also show that the wood pellets produced from the two compositions are not significantly different from previous studies that used biomass as the raw material. However, this research can still be developed on various types of Composition to get better values. This research can be a reference for developing new renewable energy from biomass waste. Furthermore, the results of this research also show that wood pellet production can be an alternative for achieving SDG targets. This article can also guide policymakers, especially regarding the obstacles and challenges in achieving SDGS related to renewable energy. This research has limitations, such as the material composition, which only consists of two compositions, and has not discussed the life cycle analysis in detail. Therefore, further research is still needed, especially life cycle analysis, to learn more about the environmental impact of using biomass-based wood pellets, especially from the Composition of coconut fiber waste, sawdust, and empty oil palm fruit bunch waste.

ACKNOWLEDGMENT

This research is supported by the Institute for Research and Community Service (LPPM) Pancasila University, Indonesia, with contract number 0040/LPPM/UP/V/2023.

REFERENCES

[1] Habib, M.S., Tayyab, M., Zahoor, S., Sarkar, B. (2020). Management of animal fat-based biodiesel supply chain under the paradigm of sustainability. Energy Conversion and Management, 225: 113345. https://doi.org/10.1016/j.enconman.2020.113345.

[2] Abusaq, Z., Habib, M.S., Shehzad, A., Kanan, M., Assaf, R. (2022). A flexible robust possibilistic programming approach toward wood pellets supply chain network design. Mathematics, 10(19): 3657. https://doi.org/10.3390/math10193657

[3] Sarfraz, M., Khawaja, K.F., Han, H., Ariza-Montes, A., Arjona-Fuentes, J.M. (2023). Sustainable supply chain, digital transformation, and blockchain technology adoption in the tourism sector. Humanities and Social Sciences Communications, 10: 1-13. https://doi.org/10.1057/s41599-023-02051-9

[4] Rimantho, D., Putra, W.A., Hidayah, N.Y. (2018). Determining the key criteria development of renewable energy in Indonesia using a combination ISM and AHP methods. Journal of Sustainability Science and Management, 13(2): 117-128.

[5] Kanan, M., Habib, M.S., Habib, T., Zahoor, S., Gulzar, A., Raza, H., Abusaq, Z. (2022). A flexible robust possibilistic programming approach for sustainable second-generation biogas supply chain design under multiple uncertainties. Sustainability, 14(18): 11597. https://doi.org/10.3390/su141811597

[6] Yun, H., Wang, H., Clift, R., Bi, X. (2022). The role of torrefied wood pellets in the bio-economy: A case study from Western Canada. Biomass and Bioenergy, 163: 106523. https://doi.org/10.1016/j.biombioe.2022.106523

[7] Rimantho, D., Hidayah, N.Y., Pratomo, V.A., Saputra, A., Akbar, I., Sundari, A.S. (2023). The strategy for developing wood pellets as sustainable renewable energy in Indonesia. Heliyon, 9(3): e14217. https://doi.org/10.1016/J.HELIYON.2023.E14217

[8] Kanan, M., Habib, M.S., Shahbaz, A., Hussain, A., Habib, T., Raza, H., Abusaq, Z., Assaf, R. (2022). A grey-fuzzy programming approach towards socio-economic optimization of second-generation biodiesel supply chains. Sustainability, 14(16): 10169. https://doi.org/10.3390/su141610169

[9] Boukherroub, T., LeBel, L., Lemieux, S. (2017). An integrated wood pellet supply chain development: Selecting among feedstock sources and a range of operating scales. Applied Energy, 198: 385-400. https://doi.org/10.1016/j.apenergy.2016.12.013

[10] Hughes, N.M., Shahi, C., Pulkki, R. (2014). A review of the wood pellet value chain, modern value/supply chain

management approaches, and value/supply chain models. Journal of Renewable Energy, 2014: 654158. https://doi.org/10.1155/2014/654158
[11] Smith, T., Lattimore, B., Atkin, E. (2015). Mobilizing sustainable bioenergy supply chains: Strategic inter-task study. IEA Bioenergy's Inter-Task Project Synthesis Report.
[12] Yoshida, T., Nomura, T., Gensai, H., Watada, H., Sano, T., Ohara, S. (2015). Upgraded pellet making by torrefaction—Torrefaction of Japanese wood pellets. Journal of Sustainable Bioenergy Systems, 5(3): 82-88. https://doi.org/10.4236/jsbs.2015.53008
[13] Nabavi, V., Azizi, M., Tarmian, A. (2016). Costs of wood pellet production in Iran. iBusiness, 8(3): 37-47. https://doi.org/10.4236/ib.2016.83005
[14] Peng, H.T., Bi, H.S., Sokhansanj, S., Lim, J.C., Melin, S. (2010). An economical and market analysis of Canadian wood pellets. International Journal of Green Energy, 7(2): 128-142. https://doi.org/10.1080/1543507100367351
[15] Japhet, J.A., Tokan, A., Kyauta, E.E. (2019). A review of pellet production from biomass residues as domestic fuel. International Journal of Environmental & Agriculture Biotechnology, 4(3): 835-842. https://doi.org/10.22161/ijeab/4.3.34
[16] Markson, I.E., Akpan, W.A., Ufot, E. (2013). Determination of combustion characteristics of compressed pulverized coal-rice husk briquettes. International Journal of Applied Science and Technology, 3(2): 61-64.
[17] Poddar, S., Kamruzzaman, M., Sujan, S.M.A., Hossain, M., Jamal, M.S., Gafur, M.A., Khanam, M. (2014). Effect of compression pressure on lignocellulosic biomass pellet to improve fuel properties: Higher heating value. Fuel, 131: 43-48. https://doi.org/10.1016/j.fuel.2014.04.061
[18] Forecast of biomass demand potential in Indonesia: Seeking a business model for wood pellets. Economic Research Institute for ASEAN and East Asia. https://policycommons.net/artifacts/2458191/forecast-of-biomass-demand-potential-in-indonesia-seeking-a-business-model-for-wood-pellets/3479988/.
[19] Mahidin, M., Zaki, M., Mamat, R., Susanto, H. (2020). Potential and utilization of biomass for heat energy in Indonesia: A review. International Journal of Science and Technology Research, 9(10): 331-344.
[20] Erahman, Q.F., Purwanto, W.W., Sudibandriyo, M., Hidayatno, A. (2016). An assessment of Indonesia's energy security index and comparison with seventy countries. Energy, 111: 364-376. https://doi.org/10.1016/j.energy.2016.05.100
[21] Chen, J.J., Pitt, M.M. (2017). Sources of change in the demand for energy by Indonesian households: 1980–2002. Energy Economics, 61: 147-161. https://doi.org/10.1016/j.eneco.2016.10.025
[22] Singh, R., Setiawan, A.D. (2013). Biomass energy policies and strategies: Harvesting potential in India and Indonesia. Renewable and Sustainable Energy Reviews, 22: 332-345. https://doi.org/10.1016/j.rser.2013.01.043
[23] Khalil, M., Berawi, M.A., Heryanto, R., Rizali, A. (2019). Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. Renewable and Sustainable Energy Reviews, 103: 323-331.
[24] Inayat, A., Raza, M. (2019). District cooling system via renewable energy sources: A review. Renewable and Sustainable Energy Reviews, 107: 360-373. https://doi.org/10.1016/j.rser.2019.03.023
[25] Dominković, D.F., Bačeković, I., Pedersen, A.S., Krajačić, G. (2018). The future of transportation in sustainable energy systems: Opportunities and barriers in a clean energy transition. Renewable and Sustainable Energy Reviews, 82: 1823-1838. https://doi.org/10.1016/j.rser.2017.06.117
[26] Batinge, B., Musango, J.K., Brent, A.C. (2019). Sustainable energy transition framework for unmet electricity markets. Energy Policy, 129: 1090-1099. https://doi.org/10.1016/j.enpol.2019.03.016
[27] Abdul Khalil, H.A., Siti Alwani, M., Ridzuan, R., Kamarudin, H., Khairul, A. (2008). Chemical composition, morphological characteristics, and cell wall structure of Malaysian oil palm fibers. Polymer-Plastics Technology and Engineering, 47(3): 273-280. https://doi.org/10.1080/03602550701866840
[28] Brunerová, A., Müller, M., Šleger, V., Ambarita, H., Valášek, P. (2018). Bio-pellet fuel from oil palm empty fruit bunches (EFB): Using European standards for quality testing. Sustainability, 10(12): 4443. https://doi.org/10.3390/su10124443
[29] Munawar, S.S., Subiyanto, B. (2014). Characterization of biomass pellet made from solid waste oil palm industry. Procedia Environmental Sciences, 20: 336-341. https://doi.org/10.1016/j.proenv.2014.03.042
[30] Ndecky, A., Tavares, P.W., Senghor, A., Kane, M., Ndiath, H., Youm, I. (2022). Proximate analysis of alternatives cooking solides fuels in Sub Saharan by using Astm standards. International Journal of Clean Coal and Energy, 11(1), 1-12. https://doi.org/10.4236/ijcce.2022.111001
[31] L'Orange, C., DeFoort, M., Willson, B. (2012). Influence of testing parameters on biomass stove performance and development of an improved testing protocol. Energy for Sustainable Development, 16(1): 3-12. https://doi.org/10.1016/j.esd.2011.10.008
[32] Delot, P. (2014). Balle de riz, Les cendres. https://www.associationlevillage.fr/, accessed on Dec. 1, 2023.
[33] James, A.K., Thring, R.W., Helle, S., Ghuman, H.S. (2012). Ash management review-applications of biomass bottom ash. Energies, 5(10): 3856-3873. https://doi.org/10.3390/en5103856
[34] Mitchual, S.J., Frimpong-Mensah, K., Darkwa, N.A. (2014). Evaluation of fuel properties of six tropical hardwood timber species for briquettes. Journal of Sustainable Bioenergy Systems, 4(1): 1-9. https://doi.org/10.4236/jsbs.2014.41001
[35] Akowuah, J.O., Kemausuor, F., Mitchual, S.J. (2012). Physico-chemical characteristics and market. International Journal of Energy and Environmental Engineering, 3(20): 1-6.
[36] Patel, B., Gami, B. (2012). Biomass characterization and its use as solid fuel for combustion. Iranian Journal of Energy and Environment, 3(2): 123-128. https://doi.org/10.5829/idosi.ijee.2012.03.02.0071
[37] Amaya, A., Medero, N., Tancredi, N., Silva, H., Deiana, C. (2007). Activated carbon briquettes from biomass materials. Bioresource Technology, 98(8): 1635-1641. https://doi.org/10.1016/j.biortech.2006.05.049

[38] Ofori, P., Akoto, O. (2020). Production and characterisation of briquettes from carbonised cocoa pod husk and sawdust. OALib, 7(2): 1-20. https://doi.org/10.4236/oalib.1106029
[39] Wilaipon, P. (2007). Physical characteristics of maize cob briquette under moderate die pressure. American Journal of Applied Sciences, 4(12): 995-998. https://doi.org/10.3844/ajassp.2007.995.998
[40] Jiri, R., Jiri, H., Lenka, K., Miroslav, J., Frantisek, H., Kamil, K., Petr, K. (2021), Beech leaves briquettes and standard briquettes combustion: Comparison of flue gas composition. International Journal of Energy Production and Management, 6(1): 32-44. https://doi.org/10.2495/EQ-V6-N1-32-44
[41] Aribo, S. (2011). Effect of varying corn cob and rice husk ashes on properties of moulding sand. Journal of Minerals and Materials Characterization and Engineering, 10(15): 1449-1455. https://doi.org/10.4236/jmmce.2011.1015112
[42] Hussain H.A., Elena M. Hasanain A.A.W. (2021). Experimental characterization of biomass–Coal fuel mixtures. International Journal of Energy Production and Management, 6(1): 45-55. https://doi.org/10.2495/EQ-V6-N1-45-55
[43] Eggers, J., Melin, Y., Lundström, J., Bergström, D., Öhman, K. (2020). Management strategies for wood fuel harvesting-trade-offs with biodiversity and forest ecosystem services. Sustainability, 12(10): 4089. https://doi.org/10.3390/su12104089
[44] Efroymson, R.A., Dale, V.H., Kline, K.L., McBride, A.C., Bielicki, J.M., Smith, R.L., Parish, E.S., Schweizer, P.E., Shaw, D.M. (2013). Environmental indicators of biofuel sustainability: What about context?. Environmental Management, 51(2): 291-306. https://doi.org/10.1007/s00267-012-9907-5
[45] Creutzig, F., Ravindranath, N.H., Berndes, G., et al. (2015). Bioenergy and climate change mitigation: An assessment. GCB Bioenergy, 7(5): 916-944. https://doi.org/10.1111/gcbb.12205
[46] Blair, M.J., Gagnon, B., Klain, A., Kulišić, B. (2021). Contribution of biomass supply chains for bioenergy to sustainable development goals. Land, 10(2): 1-28. https://doi.org/10.3390/land10020181
[47] Blair, J., Gagnon, B., Klain, A. (2021). Biomass supply and the sustainable development goals. International Case Studies.
[48] Kline, K.L., Dale, V.H., Rose, E., Tonn, B. (2021). Effects of production of woody pellets in the southeastern United States on the sustainable development goals. Sustainability, 13(2): 821. https://doi.org/10.3390/su13020821
[49] Zahir B., Marianne S.E. (2022). Assessing and prioritizing challenges facing bioenergy supply chain in Norway: A Delphi-AHP method. International Journal of Energy Production and Management, 7(4): 310-330. https://doi.org/10.2495/EQ-V7-N4-310-330
[50] Brandão, M., Kirschbaum, M.U., Cowie, A.L., Hjuler, S.V. (2018). Quantifying the climate change effects of bioenergy systems: Comparison of 15 impact assessment methods. GCB Bioenergy, 11(5): 727-743. https://doi.org/10.1111/gcbb.12593
[51] Dale, V.H., Parish, E., Kline, K.L., Tobin, E. (2017). How is wood-based pellet production affecting forest conditions in the southeastern United States? Forest Ecology and Management, 396: 143-149. https://doi.org/10.1016/j.foreco.2017.03.022
[52] Dale, V.H., Kline, K.L., Parish, E.S., Eichler, S.E. (2019). Engaging stakeholders to assess landscape sustainability. Landscape Ecology, 34: 1199-1218. https://doi.org/10.1007/s10980-019-00848-1

NOMENCLATURE

SS	Sum of Square
Df	Degree of freedom
MS	Mean Square
MJ	Megajoule
Kg	Kilogram