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The Chemical-Physical and Quality Parameters of Woods Pellets Generated from Revegetation Reclamation of Post-Coal Mining Land

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ABSTRACT

It needs to become a source of renewable energy raw materials derived from biomass, through revegetation reclamation activities. Therefore, this study aims to analyze the differences in the quality of the wood pellets derived from distinguished raw materials and ages. It also aims to evaluate the relationship between raw material and wood pellet parameters. In this process, the method used emphasized the measurements of the chemical-physical and quality parameters of the materials and pellets, respectively. These analyses were subsequently carried out through a comparative test with the quality standards of SNI (Indonesian National Standard) 8021-2014 and SNI 01-6235-2000. To analyze the relationship between raw material and wood pellet quality parameters, a statistical test of Pearson correlation (product-moment) was conducted. Based on the results, the pellets produced from post-mining land revegetation reached SNI quality limits on the parameters of water content, density, fixed carbon, and heat. This proved that all the chemical-physical features of the raw materials had a relationship in improving the quality of wood pellets. Regarding the comparison between types, the *Acacia mangium* pellets relatively had the best quality.

Keywords: *Acacia mangium*; biomass; energy; post-mine reclamation; wood pellets.

INTRODUCTION

The world's energy needs are presently met mostly through non-renewable resources sourced from fossil fuels. Presently, coal is responsible for nearly one-third of the energy supply, and Indonesia being the fourth largest producer in the world and the highest exporter in 2014. It is predicted that the use of coal will more than double by 2030 (Gielen et al., 2017). The supply of fossil fuel is reportedly decreasing in nature, with the production process causing many social and environmental problems (Agustian, 2015). In post-coal mining areas, the problems encountered emphasize the following, (1) changes in the soil surface, (2) decreased soil productivity, (3) soil compaction, (4) erosion and sedimentation, (5) biodiversity decline, (6) disturbances in hydrology and hydrogeology, and (7) the atmospheric environment in the surrounding area (Subowo, 2015; Rande, 2016; Misbakhul & Setyowati, 2017; Lestari et al., 2019). For example, a 5-year revegetated post-mining land is often very acidic and only achieves a corrosive pH level after 10 years of revegetation (Yuningsih et al., 2022For the preservation of land functions as energy resources, post-coal mining areas are expected to remain a medium for raw power materials through revegetation reclamation activities. These activities are often prepared to become sources of renewable energy raw materials, which are derived from biomass. In this process, a solution is appropriately provided, indicating that coal reserves decreased by 11.8% in 2015. This result emphasized all coal materials, namely lignite, sub-bituminous, and bituminous. The reserves are also expected to be exhausted within 68 years (Yudiartono et al*.,* 2018). As an energy source, wood biomass is often used as fuel (Palipo et al*.,* 2015), due to being environmentally friendly and sustainable (Genissa et al., 2018; Nunes et al*.,* 2016). However, various problems are commonly observed when it is directly used into fuel, such as low energy and bulk density values, as well as high pollutant emissions. To improve the quality of this wood energy, biomass conversion needs to be carried out. Some appropriate applicable conversion techniques include bio-briquettes, gasification, pyrolysis, liquefaction, biochemistry, and carbonization (Arhamsyah, 2010). Biopelets can improve the quality of biomass as fuel, with some countries emphasizing it as one of the main energy sources (Goetzl, 2015). The European Union is the largest consumer of wood pellets (36%) of the need for wood pellets in the world, even reaching 50% in 2018 (Sgarbossa et al*.,* 2020).

For the benefit of commercialization, the production of wood pellets needs to comply with the physical and chemical requirements. This study aimed 1) Analyzing the difference in the wood pellet quality obtained from distinguished types of raw materials and ages; 2) Evaluating the relationship between raw material and wood pellet parameters. Out of the 25 cultivated and natural types of woody plants in South Sumatra, Indonesia, it was found that *Enterolobium cyclocarpum, Cassia siamea,* and *Acacia mangium* had the highest dominance value (Yuningsih et al*.,* 2021). This was derived from land revegetation activities, and met the SNI quality standards for all required parameters, including water and ash contents, volatile matter, fixed carbon, compressive strength, and calorific value.

MATERIAL AND METHODS

The wood samples used emphasized the plants obtained from post-coal mining land revegetation activities, namely wide-leaf acacia (*A. mangium*), johar (*C. siamea*), and sengon buto (*E. cyclocarpum*). These plants were distinguished by the wood ages of 5, 8, 10, and 11 years. The development of wood pellets was carried out through the wood cutting, rough crushing (chipping), and fine-powder grinding processes, using a cleaver/saw, slicer, and hammer mill, respectively. This was accompanied by the compaction/printing of wood pellets through a pelletizer. Moreover, the quality test parameters of these pellets were aligned with Indonesian Product Standards, SNI8021-2014 and SNI 01-6235-2000, as shown in Table 1. Using a Pearson correlation analysis (product-moment), the relationship between the raw material and wood pellet quality parameters is also conducted. Additionally, data processing was carried out using SPSS software version 26.0, with the Pearson correlation formula shown as follows:

$$r = \frac{n\sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{n\sum X_i^2 - (\sum X_i)^2}\sqrt{n\sum Y_i^2 - (\sum Y_i)^2}} \quad (1)$$

where: r – correlation coefficient between variables x and y, n – number of samples, x_i – independent variable (i=1.2,..,n), y_i – dependent variable (i=1.2,...,n), x – parameters of chemical-physical. characteristics of raw materials, y – pellet quality parameters.

Water content of wood pellet was calculated using the formula as mentioned in Indonesian National Standard of wood charcoal (SNI 1683:2021). First, 1 g of sample must be accurately weighed in a known-weight weighing

Table 1. Parameters and quality standards of wood pellets based on SNI

No	Test parameters	Quality standard
1	Water content	Max 8% (SNI 01-6235-2000)
2	Density	Min 0.8 g/cm^3 (SNI 8021-2014)
3	Ash content	Max 1.5% (SNI 8021-2014)
4	Volatile matter	Max 80% (SNI 8021-2014)
5	Fixed carbon content	Min 14% (SNI 8021-2014)
6	Calorific value	Min 4.000 kal/g (SNI 8021-2014)

container. After flattening the sample, position it in the predetermined oven (115°C 5°C) for three hours. When heating, the weighing bottle's cap is removed. In a desiccator, cool the substance, and then weigh it until no moisture remains. Then the water content was determined using the equation:

$$Water\ content\ (\%) = \frac{w1}{w2} \times 100 \qquad (2)$$

where: $w1$ – loss of sample weight (g), and $w2$ – initial sample weight (g).

The analysis procedure for ash content, volatile content, and fixed carbon content is governed by Indonesian National Standard 06-3730-1995 for activated charcoal for technical applications. Ash content was determined as follows: one gram of sample was placed in a porcelain cup and heated at 105 °C until a constant mass was attained. The sample in the cup is then placed in the furnace and incubated for four hours at 650°C before being cooled in a desiccator. The resulting ash is weighed. For volatile content the procedure was employed as follows: the dried sample was heated for 15 minutes in a furnace at 900 °C, cooled in a desiccator, and then weighed. The fixed carbon content of a sample can be determined by subtracting the total percentage from the total percentages of water, ash, and volatile content**.** In addition, the calorific value is determined by referring to the Indonesian National Standard SNI 01-6235 concerning wood charcoal briquettes.

The compressive strength of wood pellets is measured based on the compressive strength parallel to the fibers by the formula

$$fc\ // = \frac{p}{b \times h2}\ (Mpa) \qquad (3)$$

and compressive strength perpendicular to the fiber with the formula

$$fc \perp = \frac{p}{b \times h2}\ (Mpa) \qquad (4)$$

where: $fc\ //$ – Parallel compressive strength, $fc \perp$ – compressive strength perpendicular to the grain, p – maximum test load, b – the width of the test object, h – test object height.

RESULTS AND DISCUSSION

Wood pellet quality

Type of pelletizer and the compacting parameters

To prepare wood pellets, we used only lignin as glue to compact word pellets. The WPQ (wood pellet quality) of the *E. cyclocarpum*, *C. siamea*, and *A. mangium* aged 5, 8, 10, and 11 years old, were analyzed in this study, as presented in Table 2. Based on Table 2, the moisture content value varied between 2.93–7.74%. This indicated that all the samples met the appropriate quality requirements of SNI 01-6235-2000, where the value of a maximum charcoal briquette quality was 8%, as shown in Figure 1a. The moisture content of these pellets was significantly lower than that of other biomass types, with a resistance rate of more than 90% (Carroll & Finnan, 2012).

The ash content value also ranged from 0.91–2.08%, proving that some wood pellets met the

Table 2. The chemical-physical characteristics of wood pellets regarding the *E. cyclocarpum*, *C. siamea*, and *A. mangium* aged 5, 8, 10, and 11 years old

Pellet type/age	Water content (%)	Density (%)	Ash content (%)	Volatile matter (g/cm^3)	Fixed carbon content (%)	Calorific value (kal/g)	Compressive strength (kg/cm^3)
E. cyclocarpum U-5	5.57	2.08	81.03	1.11	16.89	4.31	21.60
E cyclocarpum U-8	5.49	1.39	80.92	1.15	17.69	4.38	26.20
E. cyclocarpum U-10	4.38	1.40	82.72	1.10	15.88	4.29	14.00
E. cyclocarpum U-11	7.02	1.62	80.28	1.04	18.10	4.44	11.60
C. siamea U-5	3.20	1.55	79.98	1.13	18.47	4.41	16.40
C. siamea U-8	5.20	1.66	79.42	1.15	18.92	4.42	40.00
C. siamea U-10	2.93	1.88	80.16	1.32	17.96	4.37	40.00
C. siamea U-11	5.10	0.94	80.72	1.11	18.34	4.42	15.60
A. mangium U-5	6.24	0.91	80.41	1.18	18.68	4.44	15.50
A. mangium U-8	7.16	1.08	79.09	1.19	19.83	4.49	28.80
A. mangium U-10	7.74	1.99	77.76	1.14	20.25	4.48	32.80
A. mangium U-11	5.98	1.39	79.07	1.18	19.54	4.46	12.00

maximum standard SNI requirement of 1.5%. These pellets included the *A. mangium* of 5, 8 and 11 years, *E. cyclocarpum* with 8 and 10 years, and *C.siamea* with 11 years, as shown in Figure 1. Ash was formed from the mineral materials fixed in the carbon structure of biomass during combustion, such as potassium, calcium, magnesium, and silica (Sukarta & Ayuni, 2016). Meanwhile, no calorific value and carbon elements were found after the combustion process. In this case, the higher silica content of biomass led to the greater production of ash (Fatriani et al*.,* 2018). The higher ash content produced also led to the lower quality of wood pellets. These conditions confirmed that high ash content caused decreased heat generation, due to the great accumulation of ash during combustion. It also negatively affected the calorific value because minerals did not produce heat during the combustion process. Additionally, high ash content caused decreased organic matter, proving that the calorific value of combustion was lower for similar total weight (Brayen et al., 2022).

Based on Table 2, the volatile matter values ranged from 77.76–82.72%, indicating that some wood pellets maximum standard SNI requirement of 80% (SNI 8021-2014). These pellets included *A. mangium* of 8, 10, and 11 years and *C. siamea* with 5 and 8 years, as indicated in Figure 2a) This showed that the multiplicity of volatile substances was developed due to the decomposition of the compounds consisting of methane, hydrocarbons, hydrogen, and nitrogen.

Regarding Table 2, the density, carbon, and calorific values of the wood pellets met the standard quality requirements (SNI 8021-2014), as shown in Figure 2b, 3a, and 3b, respectively. In this process, the density values ranged from 1.04–1.32g/

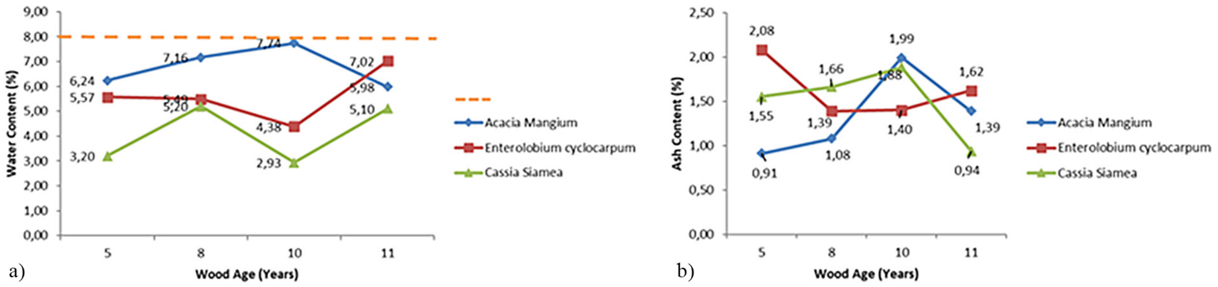

Figure 1. Comparison of (a) moisture content and (b) ash content of wood pellets

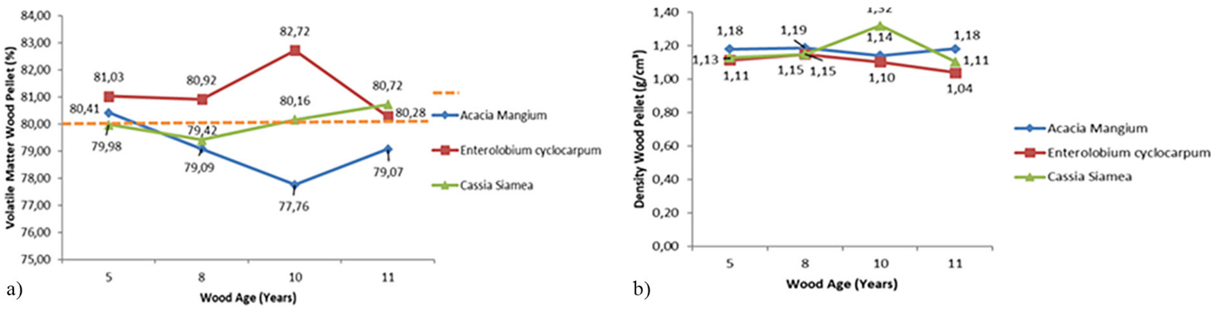

Figure 2. Comparison of (a) the value of volatile matter and (b) the density of wood pellets

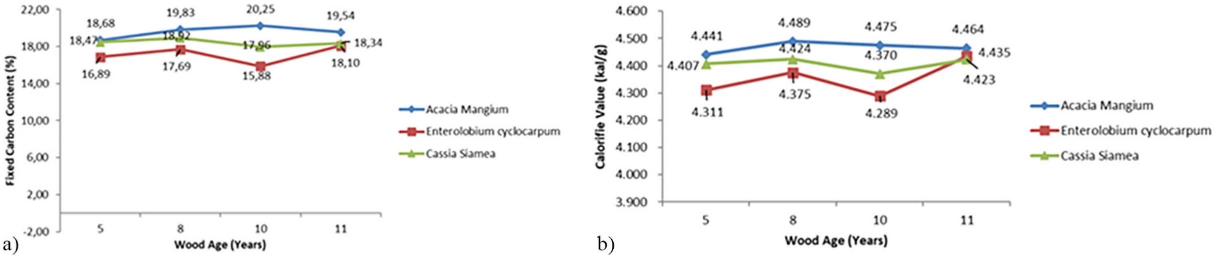

Figure 3. Comparison of (a) the value of fixed carbon and (b) calorific of wood pellets against the SNI value

cm^3, subsequently meeting the minimum standard quality requirements of 0.8g/cm^3 (SNI 8021-2014). This indicated that all the wood pellets of different types and ages were included in the SNI, due to having a density value >0.8g/cm^3. According to (Fatriani et al., 2018), higher density value led to better WPQ (wood pellet quality). It also facilitated solution, storage, and transportation, to reduce the costs needed. Basically, the manufacture of wood pellets is a process of densification of biomass to increase the energy content of biomass per unit. For the fixed carbon contained in the pellets, the values ranged from 15.88–20.25%, subsequently meeting the minimum standard quality requirements of 14%. This confirmed that all the wood plants of different types and ages were included in the SNI quality standard because they had indigo >14%.

Based on the calorific value of wood pellets, the values ranged from 4,289–4,489kal/g, meeting the minimum quality standard of 4,000 cal/g (SNI 8021-2014). This showed that all the wood pellets of different types and ages were included in the SNI standard due to having calorific values >4,000 cal/g. Calorific value is the maximum amount of heat energy released during the combustion process (Almu et al., 2014). The calorific value of wood pellets in this study when compared to wood pellets from jabon and ketapang wood has a relatively high value above 16,000 J/kg (Lestari et al., 2019). This shows that a higher calorific value leads to increased heat energy produced by bioenergy (Sulistio et., 2020).

The compressive strength of wood pellets ranges from 11.60–40.00 kg/cm^2. The compressive strength value of wood pellets has a relation to the calorific value contained in the pellets. With an increase in the value of the compressive strength of the pellets it will increase the heating value, but it is very weak and not significant, as indicated by the correlation value (r) 0.081 and the significant value with the significance value (p) 0.803.

Relationship of raw material and wood pellet characteristics

To determine the relationship between raw material and wood pellet parameters, a statistical test was carried out through Pearson correlation analysis (product-moment). This emphasizes the assessment of positive/negative and significant/insignificant relationships, using a 5-point scale containing "very weak", "weak", "sufficient", "strong", and "very strong" correlation levels (Sugiyono, 2022). The analyzed parameters were then connected with the quality features of wood pellets, namely moisture and ash contents, volatile matter, fixed carbon, density, and heat. Figure 4 shows the relationship between the parameters of raw materials and wood pellets.

Based on Figure 4, the increasing age of raw materials improved the quality of pellets through a decrease in the ash content and volatile matter, as well as an increase in the fixed carbon, density, and calorific value. This is in line with the results of research (Latterini et al., 2022) which states that there is a relationship between cycle duration and pellet quality, with increasing age of the culm will increase the characteristic quality of wood pellets. By decreasing the moisture content within the materials, the values of fixed carbon, density

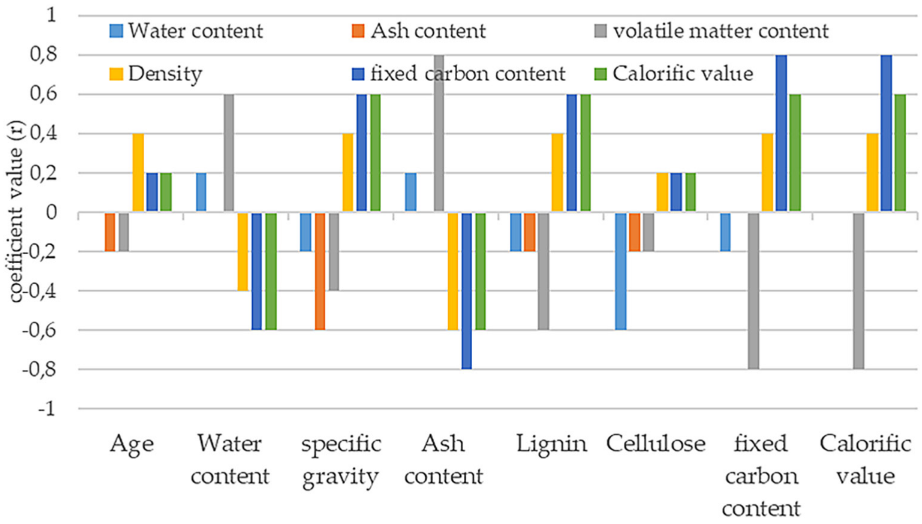

Figure 4. The relationship of wood raw material characteristics to the quality parameters of wood pellets

and heat in the pellets were increased, accompanied by a decrease in their mosture content and volatile matter levels. The lower moisture content in the fuel caused higher calorific value production. These conditions emphasized the need for sufficient energy during the conversion process, to remove water from the wood into steam. This subsequently caused a smaller quantity of energy in the fuel (Vitriandhani, 2019). Meanwhile, high moisture content caused a low calorific value. This was because the moisture content level in the wood pellets absorbed heat for the evaporation process during combustion, leading to the reduction of the calorific value contained. The presence of high moisture content also caused the incomplete combustion of volatile materials and affected the internal fuel temperature changes (Sukarta & Ayuni, 2016). These thermal changes were due to the endothermic evaporation process and the total energy required to achieve combustion. Moisture content is known to also affect the quality of wood pellets in the form of density and wear resistance (Lestari et al., 2019).

The specific gravity contained in the raw materials improved the quality of wood pellets, by reducing the values of moisture and ash contents, as well as volatile matter. This improvement subsequently prioritized the increase of the pellets' fixed carbon, density and calorific values. In this condition, the relationship between specific gravity and calorific value led to the production of the energy content per volume, which often increased with higher specific gravity (Satmoko et al., 2013). Regarding the decreased level of volatile matter in the raw materials, a reduction was observed in the moisture content and volatile matter of wood pellets, accompanied by increased fixed carbon, density and calorific value. This was because volatile matter were the thermal degradation products of the wood's chemical components (Satmoko et al., 2013). In this analysis, the decreased levels of these substances in the raw materials significantly reduced those of the pellets, as shown in Figure 5 (significance value (p) of 0.017).

This showed that a 1% decrease in wood volatile matter reduced the volatile material of the pellets by 0.4%. Similarly, a decrease in the value of this characteristic in raw materials significantly increased the estimations of pellet- fixed carbon at a significance (p) of 0.037 as indicated in Figure 5b. This confirmed that a 1% decrease in wood volatile matter increased the fixed carbon of the pellets by 0.36%. The level of volatile matter in wood pellets determines the combustion ability of a fuel (Brayen et al., 2022). This shows that most of the calorific values possessed are commonly released as combustion vapours when using high-level volatile matter fuels (Sukarta & Ayuni, 2016). In addition, higher fuel volatile matter leads to decreased combustion efficiency, causing the generation of more smoke (Hasna et al., 2019). When reduced volatile matter levels increased the fixed carbon values affecting the elevation of calorific value (Satmoko et al., 2013).

By increasing the fixed carbon level of raw materials, a decrease was found in the moisture content and volatile matter of the pellets. In this process, the fixed carbon, density, and calorific values of the pellets were also increased. The ultimate carbon content (C) of a fuel affects its energy level (Sukarta & Ayuni, 2016), with elements C, H, and O often the main components of biomass power (Hasna et al., 2019). Generally, this biomass subsequently has a carbon content of about 53% (Haryanto et al., 2021). Sawdust had C, H, O, S, N, and ash contents of 51.6%, 6.3%, 41.5%, 0.1%, 0%, and 1%, respectively (McKendry, 2002). Based on the results, a positive correlation was observed between the calorific value and the ultimate properties containing carbon, hydrogen,

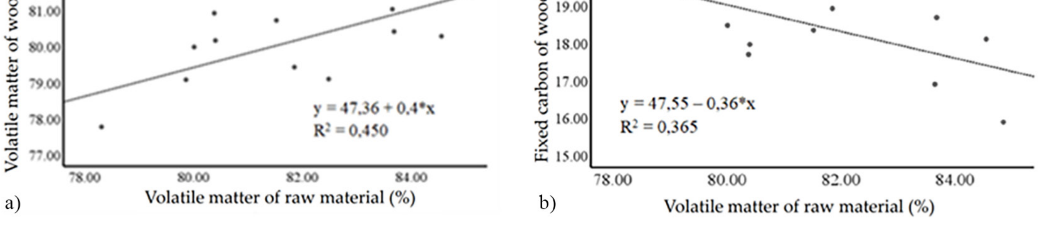

Figure 5. Correlation between raw material volatile matter levels to (a) volatile matter and (b) wood pellet- fixed carbon

and oxygen, indicating that a higher carbon percentage led to greater high heating value (Miranda et al., 2015; Liu et al., 2014). This was because carbon (C) and hydrogen (H) contributed to the energy content in biomass fuels, regarding an exothermal reaction occurring with O_2 during combustion. In this process, each element produced CO_2 and H_2O (Obernberger & Thek, 2010).

The more the value of fixed carbon, the higher the pellet quality. This significantly decreased the level of volatile matter at a significance value (p) of 0.008, as indicated in Figure 6a. From this result, a 1% increase in wood-fixed carbon, as raw material, reduced the volatile matter of pellets by 0.51%. Regarding the fixed carbon contents of the raw materials and the wood pellets, a significant positive relationship of 5% was observed with an *r*-value of 0.658*. This explained that the increasing value of fixed carbon in the raw material significantly produced higher fixed carbon values on the pellets, at a significance (p) of 0.02, as illustrated in Figure 6b. Therefore, a 1% increase in wood fixed carbon increased the pellet- fixed carbon by 0.46%. This was because the heating process (pyrolysis) increased the carbon value, with the hydrogen and oxygen contents easily lost. The results obtained subsequently led to the production of a pure carbon element (Chew & Doshi, 2011).

The lignin content contained in the raw materials improved the quality of the wood pellets, regarding the reduction of moisture and ash contents, as well as volatile matter. It also increased the fixed carbon, density and calorific values. High levels of lignin contributed to increased content of fixed carbon. It was used as a source of natural adhesive materials. Based on the cellulose content of the raw materials, an increase was observed in the calorific value of pellets. This indicated that increased cellulose led to the improvement of pellet quality, regarding the decreased values of moisture and ash contents, as well as volatile matter. It also led to an increase in the contents of fixed carbon, density, and calorific values.

Based upon the results, the heat content contained in the raw materials had a relationship in improving the quality of pellets. By increasing the calorific value of these materials, a reduction was observed in the volatile matter level of the pellets, accompanied by an elevation in the carbon, density and calorific values. Based on the 1% correlation level between the raw material calorific value and the volatile matter of the pellets, a significantly strong and negative relationship was observed with the *r*-value of -0.797**. This proved that the increasing calorific value improved the quality of the pellets, indicating a

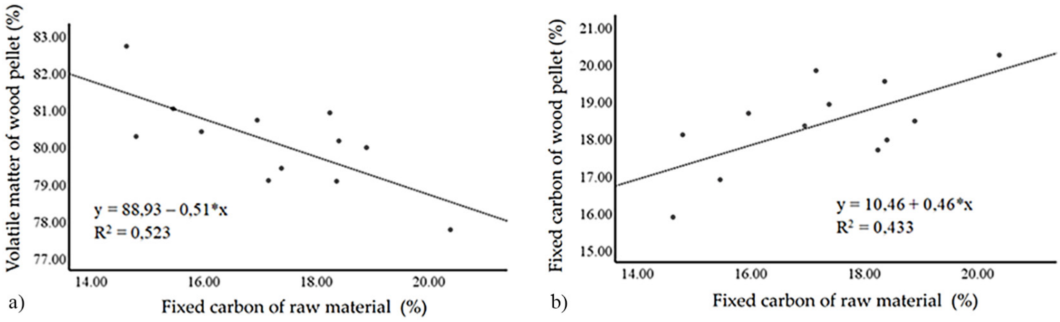

Figure 6. Correlation between carbon- fixed raw materials to (a) volatile matter and (b) wood pellet- fixed carbon

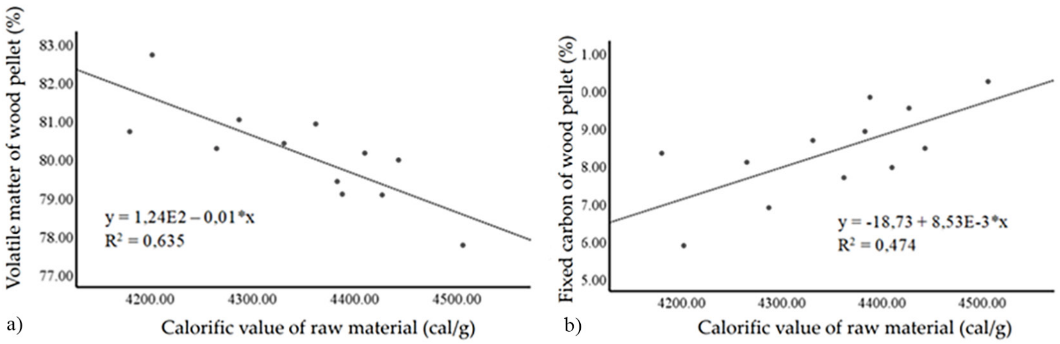

Figure 7. Correlation between the heat of raw materials to (a) volatile matter and (b) carbon- fixed wood pellets

relevant decrease in the level of volatile matter at a significance (*p*) of 0.002, as shown in Figure 7a. From these results, every 1 kal/g increase in the calorific value of wood reduced the volatile matter of the pellets by 0.01%. The calorific value contained in the raw material also improved the fixed carbon of the pellets, emphasizing a strong positive relationship with a correlation value (*r*) of 0.688*. This was subsequently significant at a level of 5% with a significance value (*p*) of 0.013, as indicated in Figure 7b. In this case, each increase of 1kal/g wood calorific value increased the fixed carbon of the pellets by 8.53×10^{-3}%, the increased fixed carbon automatically elevated the calorific value of the wood pellets. The calorific value of wood pellets is also influenced by the physical and chemical properties of wood pellets, where an increase in the density of wood pellets will increase the calorific value and the pre-treatment process can also affect the calorific value of wood pellets (Abdoli et al., 2018). On the other hand, wood pellets made from biomass carbon through carbonization are known to have a high calorific value.

CONCLUSIONS

The quality of the pellets produced met the SNI quality standards for moisture and ash contents, density, fixed carbon, and calorific value. Meanwhile, the ash content parameters provided varying values. Regarding the results, the types of *A. mangium* relatively showed the best quality, with the distinguished ages emphasising insignificant differences. All the chemical-physical parameters of the raw materials also had a relationship in improving the quality of wood pellets. This emphasized the reduction of the moisture, ash, and volatile matter contents, as well as the elevation of the fixed carbon, density and calorific values. The findings revealed that the species established via revegetation on Post-Coal Mining Land possessed physical and chemical properties that might be exploited as biomass-based energy supplies.

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