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# Potential and Characteristic of Biomass Pellet from Tea Plantation Wastes as Renewable Energy Alternative

**Makbul Hajad[1]✉, Sugeng Harianto[2], Joko Nugroho Wahyu Karyadi[1], Adhi Irianto Mastur[2], Muhammad Khais Prayoga[2], Heri Syahrian Khomaen[2], Elaine Faustine[3], Ivander Nainggolan[4], Fahmi Aryo Majid[1], Muhammad Hafidz Syahputra[1], Ganesha Afnan Adipradana[1]**

[1] Departement of Agricultural Egineering and Biosystem, Fakulty of Agricultural Technology, Universitas Gadjah Mada, Yogyakarta, INDONESIA.
[2] Pusat Penelitian Teh dan Kina Gambung, Jawa Barat, INDONESIA.
[3] Departement of Food Technology, Fakulty of Biosciences, Indonesia International Institute for Life Sciences, Jakarta, INDONESIA.
[4] Departement of Agricultural product Technology, Fakulty of Agricultural Technology, Institut Pertanian Stiper, Yogyakarta, Indonesia.

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✉Corresponding Author:
makbul.hajad@ugm.ac.id

**ABSTRACT**

*Tea plantation biomass wastes, such as tea plantation pruning, shade trees, and woody weeds have not been utilized. The waste can be used as renewable energy in the form of wood pellets. The problem is the feasibility of biomass waste to be used as material for making wood pellets as energy. This paper aims to analyze the potential of tea plantation biomass waste as wood pellet material to meet energy needs. The research was conducted in a tea plantation owned by the Tea and Kina Research Center (PPTK). Quantification of biomass waste potential per unit area was conducted in the plantation using direct measurement method. Proximate analysis of each wood pellet variant of biomass waste was conducted to match the quality of Indonesian Wood Pellet Standard. The biomass waste potential in PPTK is 14,281 tons per year which can produce 8,186 tons of wood pellets per year. This potential can meet the needs of wood pellet consumption from the tea production process at PPTK which is around 1.8 tons / day for the tea processing process of 13 tons/day. Based on proximate analysis, the wood pellets produced have a calorific value of 4425 cal/ gram, density of 1.35 grams/cm3, fixed carbon content of 85.2%, and volatile matter of 3.72%. These results confirm that the wood pellets comply with the National Wood Pellet Standard (SNI 8021:2014). This can be a model for the application of the Green Circular Economy concept in the plantation sector.*

## 1. INTRODUCTION

One of the leading plantation commodities in Indonesia is tea. This is indicated by Indonesia being the 8$^{th}$ largest tea exporter in the world by exporting 70% of its tea production (FAO, 2022). The tea plant has a fast production rate compared to other plantation crops because it has advantages in the form of a hydrological function and a harvest rotation system managed at 28-30 days using a picking machine (Thoriq & Sita, 2021). Tea plants are generally cultivated at an altitude of 700 – 2000 m above sea level and the height of the tea plant is maintained at a size of 70 – 150 cm, and an ambient temperature between 11 – 25 °C (Ayu *et al*., 2012).

In the process of cultivating tea (*Camellia sinensis*) plants, plant maintenance in the form of pruning is carried out to improve branching, rejuvenate tissue life, and reduce picking areas. Pruning will initiate many lateral branches from the bottom of the stem (Anjarsari *et al*., 2021). In addition, pruning is also done to facilitate the picking process and maintain the growth of the tea so that it remains in the vegetative phase (Rohmah & Wachjiar, 2015). The pruning process will produce biomass waste in the form of tea plant leaves and stems. According to Wulandari *et al*. (2020), the biomass waste from the pruning process has the potential to be developed and used as a renewable energy source.

Biomass is a type of organic material derived from plants that converts sunlight with water, carbon dioxide and other minerals into organic matter through the process of photosynthesis (Papilo *et al*., 2015). Biomass can be used as an energy source that comes from natural sources so it can be renewed (Wulandari *et al*., 2020). The potential of biomass in tea plantations has great value. The biomass potential is based on the number of biomass sources produced by each region (Papilo *et al*., 2015). Tea plantations have large biomass potential from cover crops used in tea plantations such as silver oak (*Grevillia robusta*) which can produce annual leaf waste of 6-8 ton/ha (Widayat & Rayati, 2011). Other biomass in tea plantations comes from weeds. These biomasses can be used as wood pellets which are renewable fuels that are environmentally friendly. According to Petlickaitė *et al*. (2022) pellets derived from non -timber plants such as weeds have lower quality than pellets made from wood. However, this can be improved by mixing with other ingredients to produce better quality wood pellets.

In the green tea processing, heat energy is required for the withering and drying of the tea (Bardant *et al*., 2019). At the tea processing factory in PPTK Gambung, the drying station currently still utilizes LPG gas as a processing fuel. The high price of LPG and the environmental emissions resulting from the combustion process have put pressure on the tea processing sector to seek alternative renewable energy. The use of wood pellets as an energy source for processing has been widely recommended compared to using firewood. The heat temperature in the heat exchanger using wood pellets is more constant compared to using firewood because the combustion process using wood pellet fuel is assisted by a burner engine (Ramanda *et al*., 2021). Utilization of tea plantation biomass waste as an alternative raw material for wood pellet production has high potential from environmental and economic aspects, for example biomass from remaining tea pruning waste (Harianto *et al*., 2019). This potential needs to be explored specifically on tea plantation biomass as a raw material for wood pellets. This aims to increase the added value of tea plantation biomass waste, reduce tea production costs, and reduce the use of fossil energy. Exploration of this potential is necessary both for the potential quantity and quality potential of wood pellets as fuel for tea processing. The main contribution of this study is to provide an overview regarding the potential of tea plantation biomass waste in terms of quantity to be used as raw material for wood pellets and its quality as an alternative fuel for tea processing. Based on the literature review that the author has conducted, there are limitations to aspects of the study related to the overall potential of biomass in tea plantations and the study of the characteristics of each existing type of biomass as an energy raw material. This is certainly interesting as material for studying the application of the concept of green circular economy in the tea plantation sector and other sectors in the future. Therefore, this study aims to analyze the quantitative potential of tea plantation biomass waste as wood pellet material and its physical characteristics to meet the energy needs of green tea processing in the PPTK Gambung tea processing factory.

## 2. MATERIALS AND METHODS

This research was conducted at the Gambung Tea and Quinine Research Center (PPTK Gambung) with a daily production capacity of 13-15 tons of wet shoots. The PPTK Gambung was located at the foot of Mount Tilu, Mekarsari Village, Pasir Jambu District, Bandung Regency, West Java. This research was conducted from September to November 2022.

### 2.1. Biomass Waste Measurement

Tea plantation biomass waste can come from white calliandra (*Calliandra tetragona*), saliara (*Lantana camara* LINN.), kirinyuh (*Chromolaena odorata*), malakatika or akasia (*Acacia mangium*), silver oak (*Grevillea robusta*), lamtoro (*Leucaena leucocephala*), and tea pruning. Sampling was conducted at 3 points in 3 different locations. The size of each sampling point was 2 m x 2 m. Plant stems in tea plantations are trimmed and then reduced in size or chopped using a chopper or crusher with a mesh size of 7 (2.83 mm). The pruning results were then weighed and the water content was measured. Prior to pelletizing, the material was first dried in the sun into a final moisture content of 13% to 15%.

### 2.2. Wood Pellet Processing

The process of making pellets was carried out by sorting raw materials from unwanted materials such as stone, metal, plastics, glass, and other hard materials that can hinder machine work. Then, the material was fed into the pellet machine with a disk diameter of 97 cm and a thickness of 13 cm having 104 die holes with a diameter of 8 mm for each hole as shown in Figure 1. In the pellet machine, the material is heated to a temperature of 90-110°C to deform the lignin content, which can be a natural adhesive material from the biomass itself (Holubcik *et al*., 2012).

### 2.3. Characteristic Measurement of Wood Pellets

a. Water content (SNI 06-3730-1995)

Measurement of the water content was carried out by taking a sample of 5 around g ($W_0$) in a cup of known weight and then drying it in a Memmert brand electric oven with a temperature of 105 °C for 6 hours. Sampling was carried out in triplicate for each waste type. After that, the cup was removed and cooled in a desiccator which was then weighed to obtain the final weight ($W_1$). The treatment was repeated until the weight obtained was constant. Moisture content (*Ka*) can be obtained by Equation 1 (BSN, 1992).

$$Ka\ (\%) = \frac{W_0 - W_1}{W_0} \times 100\% \tag{1}$$

b. Pellet Density (SNI 8021:2014)

Sample density testing was carried out by taking ten samples of wood pellets randomly in each material. Then the length and diameter dimensions of each sample were measured using a caliper with an accuracy of 0.1 mm to obtain the sample volume (V). The volume of the wood pellet was divided by the mass of the wood pellet (W) which was weighed using an analytical balance with an accuracy of 0.0001 g (BSN, 2014). The density ($K$, in g/cm$^3$) value was obtained using Equation 2.

$$K = \frac{W}{V} \tag{2}$$

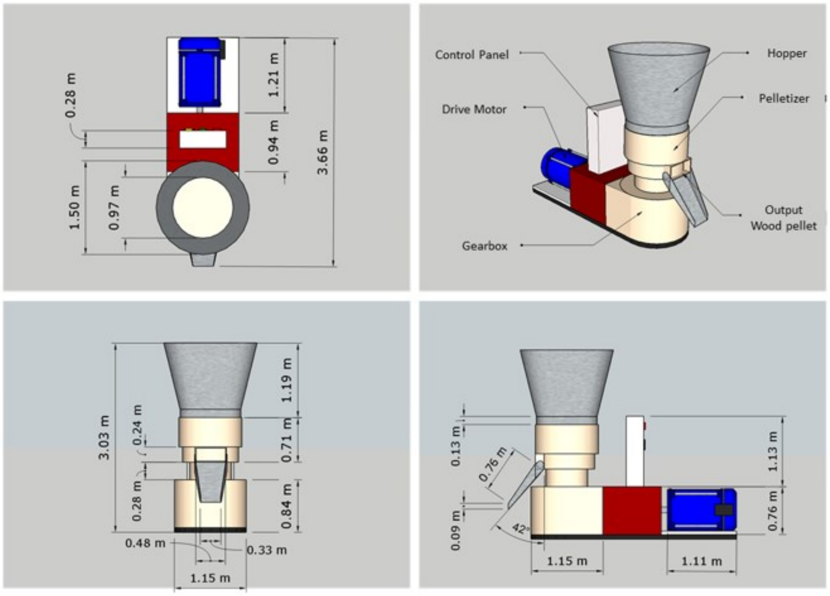


**Figure 1.** Wood pelletizer used in the experiment

c. Ash Content (SNI 14-1031-1989)

Testing the ash content was carried out by treating the sample with a mass of around 5 g ($W_i$) for each treatment and heating it using an electric muffle furnace at 600 °C for a minimum of 4 h. After that, the cup was removed and cooled for 15 minutes in a desiccator which was then weighed using an analytical balance with an accuracy of 0.0001 g to obtain the final weight ($W_f$). Ash content was obtained by equation 3 (BSN, 1989).

$$Ash = \frac{W_f}{W_i} \times 100\% \tag{3}$$

d. Volatile Matter **(BSN, 1995)**

Volatile matter content was measured by burning the material in an electric muffle furnace at 950 °C in a covered porcelain cup. This measurement was conducted by weighing 1-2 g of sample ($W_i$) in a porcelain cup of known weight and placing another cup or lid with a known weight on it. Then the sample and cup were heated in a furnace at 950 °C for 7 min. After that, the cup was removed and cooled in a desiccator which was then weighed using an analytical balance with an accuracy of 0.0001 g to obtain the final weight ($W_f$). Volatile matter ($Vm$) content was calculated as the following:

$$Vm\ (\%) = \frac{(W_i - W_f)}{W_i} \times 100\% \tag{4}$$

e. Fixed Carbon Content (BSN, 1995)

The fixed carbon content was calculated by calculating the difference between the initial mass (100%) and the total percentage of moisture content, ash content, and volatile matter content. The calculation of the fixed carbon (*FC*) content was carried out using Equation 5.

$$FC\ (\%) = 100\% - (Ka + Ash + Vm)\% \tag{5}$$

f. Burn Rate (BSN, 1995)

The ability of the biopellets to burn as fuel was tested to determine the burning rate of the biopellets. The combustion rate was measured using a bomb calorimeter type Cal3k DDScalorimeters with a resolution of 0.0001 MJ/kg to 99 MJ/kg. The burning rate was calculated by dividing the wood pellet burning time by the mass of the wood pellet sample used. Measurement of the wood pellet burning rate (*BR*) was carried out using equation 6.

$$BR\ (g/min) = \frac{Mass\ burnt\ biopellet\ (g)}{Burning\ time\ (min)} \tag{6}$$

g. Calorific Value (BSN, 2000)

Calorific value testing was carried out using a bomb calorimeter type Cal3k DDScalorimeters with a resolution of 0.0001 MJ/kg to 99 MJ/kg. The test was carried out by weighing around 1 gram of the sample which has been mashed and then compacted. Ten cm fuse wire was connected to each electrode and pellet in the vessel. Gas was filled with oxygen at a maximum pressure of 30 atm in the vessel then the gas flow control was closed, wait a few moments and remove the remaining oxygen in the hose until the regulator shows zero. The bucket was filled with 1.5 L of distilled water and place it on the calorimeter. The vessel was then inserted into the bucket and then the cable terminal was connected to the vessel. The calorimeter was closed, then the stir bar was connected and allowed to stand for 5 min until the temperature of the distilled water did not change, and the initial temperature was recorded. The ignition button was pressed until the indicator light turned off and then pressed for approximately 5 min. The temperature rise was then recorded. The temperature change was recorded for about 3 min to the final temperature on the thermometer. After that, the calorimeter was opened, the vessel was removed, and the remaining oxygen gas was released completely. After opening, the vessel was rinsed and the water in the bucket is transferred to an Erlenmeyer and titrated with a $Na_2CO_3$ solution using a methyl sindur indicator or methyl red. The remaining unburned fuse wire was measure. The calorific value (*Hg*) was calculated by Equation 7 (BSN, 2000).

$$Hg\ (cal/g) = \frac{(t \times w) - l_1 - l_2 - l_3}{M} \tag{7}$$

where $t$ is the temperature rise on the thermometer (°C), $w$ is the fuse wire constant (2426 cal/°C), $\ell_1$ is the volume of $Na_2CO_3$ used for titration (grams), $\ell_2$ is 13.7×1.02×mass of sample (g), $\ell_3$ is 2.3 g×length of burnt fuse wire (grams) and $M$ is mass of sample (g).

**3. RESULTS AND DISCUSSION**

**3.1. Quantitative Potential of Tea Plantation Biomass**

Wood biomass in tea plantations comes from permanent shade trees, silver oak

(*Grevilia robusta*) and residue from tea pruning. Biomass in tea plantations is mainly in young tea plants which are divided into 2 namely weeds and grasses. Weeds in the PPTK Gambung includes Jukut Pakit (P*aspalum conjugatum* Berg), Lalayampuyangan (*Panicum repens* Linn), Jukut Kakawatan (*Cynodon dactylon* Linn. Pers), Papaitan (*Axonopus compressus* (Swartz), Beauv), Jukut Kuda (*Paspalum distichum*), Jukut Paparean (*Phalaris arundinaceae* Linn), Sauheun (*Setaria plicata* (Lamk), T. Cooke), Jukut Jampang (*Elusine indicana* Linn), Jampang Pilit (*Digitaria adscendens* (HB. K) Henr.), and Jampang Karincing (*Hoplismenus compositus* P. Beauv) (Sanusi, 1990). Whereas, the types of grass that can be found include Babadotan (*Ageratum spp* Linn), Sintrong (*Crassocephalum crepidioides* Benth Moors), Goletrak (*Borrera alata* Aubl.D.C.), Jukut Haseum (*Polygonum nepalens* Meissn), Lokatmala (*Artehmisia vulgaris* Linn), Tali Said (*Commelia nodiflora* Linn), Jonge (*Emilia sonchifolia* (Linn) D.C.ex.weight), and Jukut Rikut (*Mimosa pudica* Linn) (Sanusi, 1990).

From the results of field observations and based on reference sources, it was found that some potential biomass in the tea plantation of the PPTK Gambung. The overall potential of plantation biomass in an area of 154 ha of idle land and 462 ha of tea plantation has the potential to produce 14,281 ton of biomass per year with a potential yield of wood pellets of 8,186 ton per year. This number was calculated based on the potential of shade trees those need to be trimmed or thinned in tea cultivation. Then on idle land which consists of vacant land and reserve land which consists of forests, ravines and watersheds where there are many potential woody weeds. The greatest potential for biomass is found in biomass from tea pruning waste with annual potential of 18.3 ton/ha, while for the smallest potential is in lamtoro biomass with annual production of 1.38 ton/ha. However, the overall potential depends on the number of planted tree populations. The overall potential of biomass wastes can be seen in Table 1.

**Table 1.** Biomass potential of tea plantations in the Gambung PPTK experimental garden

| Jenis Biomassa | Biomass production (ton/ha/y) | Area (ha) | Biomass potential (ton/year) | Moisture content (%) | | Pellet potential (ton/year) | Remark |
|---|---|---|---|---|---|---|---|
| | | | | Feedstock | Pellet | | |
| Silver oak (*Grevillia robusta*) | 6.00 | 462 | 2,772 | 47.02 | 7.91 | 1,612 | Tea shading |
| Malakatika (*Acacia Magium*) | 1.93 | 462 | 891 | 35.18 | 6.42 | 624 | Tea shading |
| Tea pruning (*Camellia sinensis*) | 18.30 | 462 | 8,455 | 46.11 | 7.39 | 4,944 | Tea plants |
| Lamtoro (*Leucaena leucocephala*) | 1.38 | 462 | 635 | 50.35 | 7.98 | 343 | Tea shading |
| White Caliandra (*Calliandra tetragona*) | 10.50 | 94 | 986 | 56.49 | 7.00 | 461 | Weed |
| Lantana (*Lantana camara* LINN) | 5.79 | 30 | 175 | 52.85 | 6.53 | 88 | Weed |
| Kirinyuh (*Chromolaena* | 12.12 | 30 | 366 | 71.19 | 6.45 | 114 | Weed |
| Total potential | | | 14,281 | | | 8,186 | |

### 3.2. Characteristics of Wood Pellets

The characteristics of the wood pellets produced for each plantation biomass waste are tested according to predetermined standards. The characteristics tested involved water content, ash content, density, volatile matter content, fixed carbon content, as well as the heating value and burning rate of the wood pellets. Biomass wastes are grouped into two, namely biomass wastes derived from shade trees and from woody weeds. The characteristics of the wood pellets produced can be seen in Table 2 and Table 3.

**Table 2.** Characteristic of wood biopellet from trimming

| Measurement | Tea pruning | Malakatika | Silver Oak | Lamtoro |
|---|---|---|---|---|
| Moisture content (%) | 7.39 | 6.42 | 7.91 | 7.98 |
| Density (g/cm$^3$) | 1.35 | 1.32 | 1.22 | 1.27 |
| Volatile matter (%) | 73.3 | 71.8 | 73.5 | 71.3 |
| Ash (%) | 0.57 | 0.83 | 0.73 | 0.78 |
| Fixed carbon (%) | 18.77 | 20.95 | 17.86 | 19.94 |
| Burning rate (g/h) | 3.44 | 2.76 | 3.56 | 3.03 |
| Heating value (MJ/kg) | 18.52 | 18.05 | 18.44 | 18.31 |

**Table 3.** Characteristic of wood biopellet from woody weeds

| Measurement | White caliandra | Lantana | Kirinyuh |
|---|---|---|---|
| Moisture content (%) | 7.00 | 6.53 | 6.45 |
| Density (g/cm$^3$) | 1.36 | 1.32 | 1.34 |
| Volatile matter (%) | 73.5 | 73.9 | 74.4 |
| Ash (%) | 0.58 | 0.64 | 0.48 |
| Fixed carbon (%) | 18.92 | 18.93 | 18.67 |
| Burning rate (g/h) | 3.39 | 3.20 | 2.92 |
| Heating value (MJ/kg) | 17.88 | 17.80 | 17.60 |

### 3.3. Water Content

The moisture content of wood pellets is influenced by several factors such as the processing stages and water content of the input material. Moisture content is an important factor in the manufacture of wood pellets because it can affect the quality of wood pellets. Water content is inversely proportional to the calorific value, the lower the water content, the higher the calorific value. Not only that, the moisture content factor makes the pellets susceptible to attack by microorganisms and fungi (Samuelsson *et al.,* 2012).

In general, the water content in wood pellets ranges from 10-12% (Garcia-Maraver *et al.* 2015). The decrease in water content that occurs in pellets can be influenced by the pelletization process, where the material will get high pressure which causes each particle to fill each other's pores of the material resulting in reduced water content in the pellet. An increase in temperature of around 80-90 °C can occur in the wood pellet during pelletization process. The increase in temperature in the pelleting mechine occurs due to the frictional force between the rotating gear and the pellet material and the disk as well. Some experts suggesting the high pressure exerted and when the particles are compacted will force the particles to experience elastic and plastic deformation which will increase the contact area between the particles. The plasticity of these particles can also be caused by temperature and moisture content (Garcia-Maraver *et al.* 2015).

The water content values of the four types of pelleted woody biomass wastes were obtained 7.39% for tea prunings, 6.42% for malakatika, 7.91% for silver oak, and 7.98% for lamtoro, 7.00% for white caliandra, 6.53% for Lantana, and 6.45% for Kirinyuh. The pelletization process was carried out consistently for each ingredient, the lowest water content was found in tea prunings while the highest was found in silver oak wood. The potential for tea pruning is quite large. It is estimated that 23,750 kg/ha or equivalent to 30% of the total area of the tea plant which consists of branches, twigs, and leaves is obtained annually. When compared with the applicable standards, the wood pellet moisture content of the four types of wood above meets standards such as SNI standards with a max value of 12% and for international standards, such as Germany (DIN 51731), Europe (CEN/TC 335), French (ITEBE, 2009), and Austria (Ö-Norm 7135) (Garcia-Maraver & Carpio, 2015). The range of wood pellet moisture content from tea plantation biomass waste is smaller than the water content value obtained from wood pellets made from olive plant biomass waste as reported in a study by (Garcia-Maraver *et al.* 2015) that is in the range of 9%.

### 3.4. Density

Density describes a ratio between weight and volume of wood pellets. The density tested in this study is particle density. Density has an influence on the calorific value of the material. The high density of the material can increase the high heating value. The value of pellet density is influenced by the size and the composition of the feedstock. The density of wood pellets will affect the level of holding time or the length of time it takes to produce blazing fire from wood pellets. The higher the density, the longer the burning time aspect of the material (Ginting *et al.* 2018).

In the density test conducted on the four types of wood pellet, the results were obtained 1.35 g/cm$^3$ for tea pruning, 1.32 g/cm$^3$ for malakatika, 1.22 g/cm$^3$ for silver oak, and 1.27 g/cm$^3$ for lamtoro. As for the results of testing the density of 3 types of weed biomass, the results were 1.36 g/cm$^3$ for white calliandra, 1.32 g/cm$^3$ for lantana, and 1.34 g/cm$^3$ for kirinyuh. This is much larger than the wood pellets made from tapioca peel waste published by (Ginting *et al.* 2018) which is in the range of 0.82-0.86 g/cm$^3$.

In other studies, the mechanical compaction process can be carried out to increase the density and binding strength between powder particles. Increasing the density can be advantageous because it can help in the storage, handling, and transportation aspects of pellets. The high density is inversely proportional to the water content. High density makes every pore in the material narrow and forces water to come out so that the water content in the material becomes low. High density with low water content can increase the calorific value and the burning rate, and vice versa (Ginting *et al.* 2018).

High density also makes the material difficult to burn. In research by Thiffault *et al.* (2019), high density makes the material difficult to burn and vice versa, low density makes it easy to burn. This is due to air voids or gaps that oxygen can pass through during the combustion process which is quite open for the combustion process, but the low density value can have an impact on the burning of biopellets which run out quickly due to their low weight. The resulting density value is within the Indonesian standard (BSN, 2014) with a minimum of 0.8 g/cm$^3$ and several other international standards such as Germany (DIN 51731), Europe (CEN/TC 335), and Perancis (ITEBE, 2009). However, it is higher than that of Austria standard (Ö-Norm 7135).

### 3.5. Ash Content

The ash content obtained from tests carried out with different types of biomass waste slightly varies, namely 0.57% for tea pruning, 0.83% for malakatika, 0.73% for silver oak, and 0.78% lamtoro, 0.58% for calliandra white, 0.64% for lantana, and 0.48% for kirinyuh. The ash content of all the pellets produced in this study met the national standard SNI 8021 (BSN, 2014) where the ash content of biomass pellets (both for domestic and industrial use) was 1.5% maximum. Testing the ash content aims to determine the particles or parts of the material that are not burnt and do not contain carbon after being burned. The lower the ash content of the wood pellets, the less residual combustion residue will produce. The ash content of wood pellets is largely determined by the properties of the feedstock materials. The ash content values of some of these materials are less when compared to acacia wood (1.03-1.18%) and galam wood (1.03-1.15%) (Fatriani *et al*. 2018).

### 3.6. Volatile Matter Content

The content of volatile matter in a material is the amount of substance, both organic and inorganic, which is lost as a result of the evaporation of compounds during the heating process (Arisandy *et al*., 2017). The higher the volatile matter content, the faster the combustion will be and the shorter the duration of the fire (Junary *et al*., 2015). Based on SNI 8021:2014, the content of volatile matter for biomass pellet is a maximum of 80% (BSN, 2014). Kang *et al*. (2017) reported the maximum level of volatile matter is 73.98% in wood pellet analysis at the Testing and Certification Center, Korea Institute of Energy Research. Other study reported the volatile matter content of wood pellets in *Calliandra calothyrsus* is 83.13% and *Gliricidia sepium* is 82.96% (Rahayu *et al*., 2020). In the results obtained in our experiment the value of volatile matter content complied with SNI standards (less than 80%) and was also in accordance with previous studies, both wood and weed biopellets. The lowest volatile matter content was found in the results of the Lamtoro wood pellet test of 71.3% and the highest content in Lantana of 73.90%.

### 3.7. Fixed Carbon Content

Fixed carbon is pure carbon bound in a fuel. The amount of fixed carbon is determined on the value of pure carbon in the fuel (Maulana *et al*., 2017). The standard for fixed carbon content is listed in SNI 8021: 2014 which explains that the minimum fixed carbon content is 14%. Based on Kang *et al*. (2017) that the fixed carbon content is 16.89% in the analysis of wood pellets at the Korea Institute of Energy Research. The fixed carbon of wood pellet was reported 10.83% for of *Calliandra calothyrsus* and 10.31% for *Gliricidia sepium* (Rahayu *et al*., 2020). In our experimental results, the fixed carbon content has met the SNI standard (more than 14%) for each biopellet material. The highest bound carbon content was found in white Malakatika material of 20.95% and the smallest carbon content was in silver oak biopellets of 17.86%. This shows that the entire biopellet material meets the bound carbon standard, both wood and wood weed biopellets.

### 3.8. Burning Rate

The burning rate is the rate that determines the speed at which a material can be totally burnt into ash or until the fire is extinguished (Yuliati *et al*., 2022). There are differences in the results in the combustion test, such as Irawansyah *et al.* (2022) that the burning rate of wood pellets in gelam wood types ranges from 0.0026 g/s without adhesive to 0.0045 g/s with 15% tapioca adhesive. Based on Wahyullah *et al.* (2018) wood pellets based on clove waste have an average burning rate of 0.177 g/min. In addition, the burning rate of wood pellets in *Calliandra calothyrsus* is 11.73 g/min and *Gliricidia sepium* is 12.1 g/min (Rahayu *et al*., 2020). Wood pellets made from sengon (*Albizia chinensis*) mixed with rice husks have a burning rate ranging from 0.52 – 0.55 g/min depending on the amount of husk content (Yuliati *et al*., 2022). In our experimental results, it was found that the highest burning rate was in silver oak of 3.56 g/h (0.0099 g/s), while the lowest burning rate was in kirinyuh biopellets of 2.76 g/h (0.00077 g/s).. This result higher than what is reported by Irawansyah *et al.,* (2022) at 0.0026-0.0045 g/s for silver oak biopellet, while it is much less than what is repoted by Rahayu *et al.,* (2020) at 0.19-0.21 g/s. Fast or slow the rate of burning is affected by the value of volatile matter. Based on Haidar *et al*. (2022) that more volatile matter will enable a faster burning rate.

### 3.9. Calorific Value

The maximum amount of heat energy produced in complete combustion per volume or mass of the fuel, the calorific value can be determined using bomb calorimeter (Almu, 2014). In a complete combustion process this is called the enthalpy of combustion, where there is an enthalpy between the products and the reactants. This enthalpy consists of the highest heating value (HHV) and the lowest heating value (LHV) (Lestari, 2009). From the test results, the highest calorific value was found in wood pellets made from tea prunning (18.52 MJ/kg) and the lowest value was found in wood pellets made from kirinyuh (17.60 MJ/kg). The experimental results are still within the Indonesian standard (SNI 8021: 2014) with a minimum value of 16.74 MJ/kg and several other international standards such as standards from Germany (DIN 51731), Europe (CEN/TC 335), and France (ITEBE, 2009). However, in the Austrian standard (Ö-Norm 7135) the minimum calorific value is 18.00 MJ/kg, where weedy wood pellets (white calliandra, lantana, and kirinyuh) do not meet this minimum limit. The heating value and other properties of biomass pellet in several countries is shown in Table 4.

**Table 4**. Standard for biomass pellet characteristics in several countries

| Characteristic | Indonesia | Germany* | Austria* | Europe* | France* |
|---|---|---|---|---|---|
| Diameter (mm) | 4 – 10 | 4 – 10 | 4 – 10 | 6 – 25† | 6 – 25 |
| Particle density (g/cm$^3$) | > 0.8 | < 1.5 | > 1.12 | --‡ | 1.2 – 1.4 |
| Moisture content (%) | < 12 | < 12 | < 10 | < 10 | < 10 |
| Ash content (%) | < 5 | < 1.5 | < 0.5 | < 0.7 – 6† | < 10 |
| Heating value (MJ/kg) | 16.5 | 17.5 – 19.5 | > 18.0 | --‡ | > 17.0 |

* Summarized from Garcia-Maraver & Carpio (2015)
† Depending on classification
‡ Recommended value is determined by manufacturer

## 4. CONCLUSION

The implementation of the green circle economy concept in the tea plantation sector can be carried out by utilizing the potential of tea plantation biomass waste as a raw material for wood pellet production. Wood pellets themselves can be used as alternative energy in the green tea processingin the PPTK Gambung tea plantation.

Based on the analysis performed, several conclusions can be drawn, such as:

a. Quantitatively, the biomass waste of the PPTK Gambung tea plantation can be used as raw material for wood pellet production with a potential of 8,186 ton/year and is sufficient to meet the raw material needs for wood pellets for green tea processing at the PPTK Gambung tea processing factory.
b. The PPTK Gambung tea plantation biomass waste comes from tea pruning waste, branches of protective trees, weed branches, and so on.
c. From the results of the analysis of the quality of wood pellets from tea plantation biomass waste, it is concluded that the quality of the wood pellets produced can meet SNI standards and several other international standards.

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